



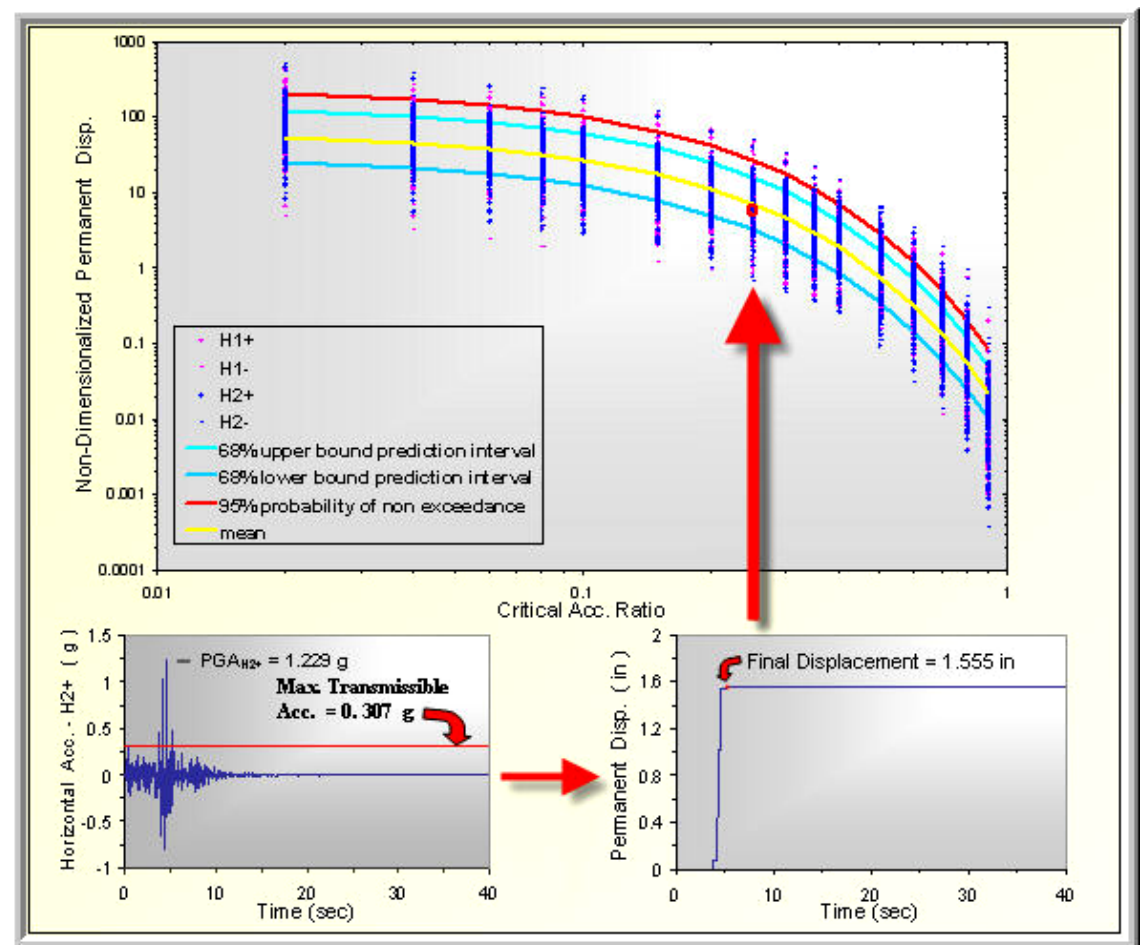
**US Army Corps  
of Engineers®**  
Engineer Research and  
Development Center

*Flood and Coastal Storm Damage Reduction Research and Development Program*

## **Permanent Seismically Induced Displacement of Rock-Founded Structures Computed by the Newmark Program**

Robert M. Ebeling, Moira T. Fong, Donald E. Yule,  
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February 2009



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Final report

Approved for public release; distribution is unlimited.

Prepared for Headquarters, U.S. Army Corps of Engineers  
Washington, DC 20314-1000

Under Work Unit 142084

**Abstract:** This research report describes the engineering formulation and corresponding software developed for the translational response of rock-founded structural systems to earthquake ground motions. The PC software Newmark and Newmark<sub>VM</sub> are developed to perform an analysis of the permanent sliding displacement response for a structural system founded on rock for a user-specified earthquake acceleration time-history via a Complete Time-History Analysis, also known as the Newmark sliding block method of analysis. The PC-based program Newmark performs a permanent sliding block displacement analysis given a baseline-corrected rock site-specific acceleration time-history. Newmark can also conduct regression analyses for sets of rock-founded acceleration time-histories in order to develop up to three user-selected forms of generalized equations of simplified permanent displacement relationships. The rock-founded structural system can be a variety of structural feature types, for example, a concrete gravity dam, a concrete monolith, or a retaining wall.

The conclusions of the regression analyses discussed in this report resulted in simplified permanent displacement relationships that were developed using data generated by Newmark for an extensive database of 122 sets of baseline-corrected rock acceleration time-histories in the range of moment magnitudes of 5 to 7. The resulting simplified permanent displacement relationships allow the engineer to rapidly determine the earthquake-induced permanent displacement for a given rock-founded structural system. This alternative procedure requires only rudimentary design/analysis ground motion characterization and use of a simplified permanent seismic displacement relationship for a sliding block (structural) system model. The resulting simplified permanent displacement relationships discussed in this report are being implemented in other Corps permanent seismically induced displacement software such as Corps<sub>WallSlip</sub> and Corps<sub>DamSlip</sub>.

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## Preface

This research report describes the engineering formulation and corresponding software developed for the translational response of U.S. Army Corps of Engineers hydraulic structures to earthquake ground motions. The PC software Newmark was developed to perform an analysis of the permanent sliding displacement response for each structural feature (e.g., a rock-founded retaining wall section or a gravity dam section) to a user-specified earthquake acceleration time-history via a complete time-history analysis. PC software Newmark is also used in this R&D effort to perform a statistical analysis of computed permanent displacements for a suite of acceleration time-histories resulting in simplified (seismic) permanent displacement relationships for use in simplified sliding block analysis. This R&D was accomplished and the results summarized in this report for use on rock-founded structural systems. Prior to this publication, the simplified permanent displacement relationships found in the technical literature are for soil-founded structures. Funding to initiate research and software development and engineering study was provided by Headquarters, U.S. Army Corps of Engineers (HQUSACE), as part of the Flood and Coastal Storm Damage Reduction Research and Development Program. The research was performed under the Dam Safety Focus Area, Work Unit 142084 entitled “Simplified Probabilistic Models for Concrete Gravity Dams” for which Dr. Robert M. Ebeling, Computational Science and Engineering (CSED), Information Technology Laboratory (ITL), U.S. Army Engineer Research and Development Center (ERDC), was the Principal Investigator. Additional funding was provided by the Engineering Risk and Reliability Directory of Expertise. Andy Harkness (of Pittsburgh District), Technical Manager of the Engineering Risk and Reliability Directory of Expertise, supervised this R&D effort.

H. Wayne Jones, ITL, was the Dam Safety Focus Area Manager. William R. Curtis, Coastal and Hydraulics Laboratory (CHL), ERDC, was the Flood and Coastal Storm Damage Reduction Research and Development Program Manager, and Dr. Michael Sharp, Geotechnical and Structures Laboratory (GSL), ERDC, was the Water Resources Infrastructure Technical Director.

The resulting engineering methodology and corresponding software is applicable to a variety of structural systems founded on rock. The main focus of this R&D effort was to develop simplified seismic permanent displacement relationships for rock-founded structures for use in a simplified sliding block analysis. Although developed for the evaluation of the permanent displacement of rock-founded structures, PC software Newmark may also be used to compute the permanent displacement of soil-founded structures during earthquake shaking.

This R&D study was conducted by Dr. Robert M. Ebeling and Moira T. Fong, ITL, Donald E. Yule, GSL, Amos Chase, Sr., Science Applications International Corporation, and Raju Kala, GSL. Dr. Ebeling was author of the scope of work for this research. The report was prepared by Dr. Ebeling, Ms. Fong, and Mr. Yule under the supervision of Dr. Robert M. Wallace, Chief, CSED, and Dr. Reed Mosher, Director, ITL.

COL Gary E. Johnston was Commander and Executive Director of ERDC. Dr. James R. Houston was Director.

## Unit Conversion Factors

| Multiply      | By         | To Obtain |
|---------------|------------|-----------|
| feet          | 0.3048     | meters    |
| inches        | 0.0254     | meters    |
| pounds (mass) | 0.45359237 | kilograms |

## Notation

|                                               |                                                                                                                         |
|-----------------------------------------------|-------------------------------------------------------------------------------------------------------------------------|
| $A$                                           | a decimal fraction                                                                                                      |
| $A \bullet g$                                 | the acceleration of the ground                                                                                          |
| angle $\beta$                                 | the direction of the resultant force $S$ of the distributed shear stresses along the interface, as shown in Figure 1.3b |
| angle $\theta$                                | the angle inclination of the resultant inertia force ( $= 0$ for horizontal accelerations only)                         |
| $Area_a$                                      | the positive area under the linear relative acceleration relationship over the time step $DT$                           |
| $Area_v$                                      | the positive area under the positive quadratic relative velocity relationship over the time step $DT$                   |
| $\beta_1, \beta_2, \beta_3, \beta_4, \beta_5$ | coefficients                                                                                                            |
| $c'$                                          | Mohr-Coulomb effective cohesion                                                                                         |
| COSMOS                                        | Consortium of strong-ground motion observation systems                                                                  |
| $\Delta t$                                    | a time increment                                                                                                        |
| DSHA                                          | a Deterministic Seismic Hazard Assessment                                                                               |
| $D, D_1, D_2, D_3$                            | the determinants of a matrix                                                                                            |
| $d_m$                                         | permanent displacement (length)                                                                                         |
| $d_s$                                         | the standardized maximum displacement                                                                                   |
| $DT, dt$                                      | time increments                                                                                                         |
| $DT_{zeroD}$                                  | a time increment                                                                                                        |
| $DT_{mid}$                                    | a time increment                                                                                                        |

|                 |                                                                                                                                                                                                                                                     |
|-----------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| $DT_{zeroV}$    | a time increment                                                                                                                                                                                                                                    |
| FLAC            | a commercially available, two-dimensional, explicit finite difference program, which has been written primarily for geotechnical applications and applied to dynamic analysis of earthen systems                                                    |
| FLUSH           | a classic example of a category of software which uses the finite element method and treats the structure and the surrounding retained soil and foundation medium in a single analysis step; used in dynamic soil-structure in interaction analyses |
| $G, g$          | the acceleration of gravity                                                                                                                                                                                                                         |
| GUI             | Graphical User Interface                                                                                                                                                                                                                            |
| $K_{AE}$        | pseudo-static active earth pressure coefficient                                                                                                                                                                                                     |
| $k_c$           | maximum transmissible acceleration capacity (decimal fraction)                                                                                                                                                                                      |
| kips            | 1,000 lbs                                                                                                                                                                                                                                           |
| $k_h$ and $k_v$ | decimal fraction that, when multiplied times the weight of some body, gives horizontal and vertical pseudo-static inertia force $S$ for use in permanent seismic deformation analyses                                                               |
| $k_m g$         | maximum horizontal ground acceleration                                                                                                                                                                                                              |
| $k_s$           | the standardized acceleration expressed as a fraction of $g$ (0.5)                                                                                                                                                                                  |
| $lhsDT$         | Left-hand side time increment                                                                                                                                                                                                                       |
| $\ln$           | the natural log                                                                                                                                                                                                                                     |
| MCE             | Maxim Credible Earthquake                                                                                                                                                                                                                           |
| MDE             | Maximum Design Earthquake                                                                                                                                                                                                                           |
| $M_s$           | surface wave                                                                                                                                                                                                                                        |

|                    |                                                                                      |
|--------------------|--------------------------------------------------------------------------------------|
| $M_w$              | moment magnitude scale                                                               |
| $N$                | a decimal fraction of the acceleration imparted to the Figure 1.3a soil sliding mass |
| $N$                | the total number of non-dimensionalized displacement terms in Figure 3.7             |
| $N^*g$             | the maximum transmissible horizontal acceleration (a constant)                       |
| OBE                | Operational Basis Earthquake                                                         |
| $P$                | the force that is a resultant of the normal forces shown in Figure 1.3b              |
| PEER               | Pacific Earthquake Engineering Research Center                                       |
| $P \bullet \Delta$ | second-order structural deformation effects                                          |
| $\phi$             | Mohr-Coulomb angle of internal friction shear strength parameter                     |
| $\phi'$            | Mohr-Coulomb effective angle of internal friction shear strength parameter           |
| PSHA               | Probabilistic Seismic Hazard Analysis                                                |
| $P_{resist}$       | a user-defined force representing the ultimate axial load resistance of a slab       |
| $relA$             | relative acceleration                                                                |
| $relA0, relA1$     | relative acceleration values at times $t_i$ and $t_{i+1}$ , respectively             |
| $relAmid$          | midrange relative acceleration                                                       |
| $relD$             | relative displacement                                                                |
| $relD0$            | from the value for relative displacement at time $t_i$                               |
| $relD1$            | the permanent relative structural displacement at time $t_{i+1}$                     |

|                          |                                                                                        |
|--------------------------|----------------------------------------------------------------------------------------|
| $relD_{mid}$             | midrange relative displacement                                                         |
| $relV$                   | relative velocity                                                                      |
| $relV_0$                 | relative velocity at time $t_i$                                                        |
| $relV_1$                 | relative velocity at time $t_{i+1}$                                                    |
| $relV_{mid}$             | midrange relative velocity                                                             |
| $rhsDT$                  | right-hand side time increment                                                         |
| $S$                      | the resultant force of the distributed shear stresses along the interface, Figure 1.3c |
| SHAKE                    | a vertical shear wave propagation program                                              |
| SOILSTRUCT               | an Incremental Construction, Soil-Structure Interaction finite element program         |
| SSI                      | a soil-structure interaction                                                           |
| $S_u$                    | undrained shear strength of soils                                                      |
| $t_i, t_{i+1}, \Delta t$ | timesteps                                                                              |
| $v_m$                    | the maximum ground velocity                                                            |
| $v_r$                    | the relative velocity of a wall                                                        |
| $v_s$                    | the standardized velocity (29.92 in./sec)                                              |
| $V_s$                    | average shear wave velocity                                                            |
| $W$                      | the weight of the sliding mass, as shown in Figure 1.3a                                |

# **1 Introduction to the Translational Response of Structures to Earthquake Ground Motions**

## **1.1 Introduction**

Engineering formulations and software provisions based on sound seismic engineering principles are needed for a wide variety of rock-founded Corps hydraulic structures that translate (i.e., slide) or rotate during earthquake shaking and for massive concrete structures constrained to rocking. The engineering formulation discussed in this report was developed to address the first of these three different modes of structural responses to earthquake shaking.

This research report describes the development of simplified permanent deformation relationships for rock-founded structures subjected to earthquake shaking. The original permanent (translational) deformation procedure of analysis, published by Newmark in 1965, required the use of an earthquake acceleration time-history in order to predict the permanent deformation of a structure (an earthen slope of an embankment in Professor Newmark's examples). This type of analysis is referred to as a "Complete Time-History Permanent (Translational) Displacement Analysis" and is a capability of the PC software developed in support of the R&D discussed in this report. The drawback to a complete time-history permanent deformation analysis is that there are many factors to consider and many stages to the selection of earthquake acceleration time histories for use on a Corps project. Additionally, the time-history selection process requires information that typically is not readily available at the beginning of a Corps project effort. Fortunately, there is an alternative procedure of seismically induced permanent deformation analysis available to District engineers for use on Corps projects. This alternative procedure requires only rudimentary design/analysis ground motion characterization and use of a simplified permanent seismic displacement relationship for a sliding block (structural) system model. This simplified seismic permanent (translational) deformation procedure of analysis was developed for the Corps in 1977 by the WES/ERDC researchers Dr. Franklin and Mr. Chang.

In a subsequent study to that conducted by Newmark (1965), Franklin and Chang (1977) expanded the use of the permanent seismically induced deformation procedure of analysis through the development of “Simplified Sliding Block” relationships. In order to use the Franklin and Chang relationships (which are for computed data presented in figure form), values for peak ground acceleration and peak ground velocity are required. A “Simplified Sliding Block” formulation has the advantage of eliminating the need for the Engineer to directly select an acceleration time-history to characterize earthquake shaking. The Franklin and Chang permanent deformation relationships are a direct product of an evaluation process involving acceleration time histories. Results of their calculations reflect the use of many acceleration time histories. Note that only acceleration time histories recorded during earthquakes occurring through 1977 were included in their study.

Two drawbacks to using the Franklin and Chang (1977) “Simplified Sliding Block” relationships for rock-founded structural systems exist; the focus of the relationships they developed is on soil sites (reflecting the early days when the permanent sliding block displacement based method of analysis was first applied to earthen “structural” systems consisting of slopes and earthen embankments); and since 1977 there have been a number of earthquake events recorded on rock as well as soil sites.

In the subsequent years there have been several studies resulting in seismically induced simplified permanent sliding block relationships, but all of these studies have been dominated by the use of soil site acceleration time-history records (e.g., Makdisi and Seed 1978; Richards and Elms 1979; Whitman and Liao 1985a, 1985b; Ambraseys and Menu 1988; Cai and Bathurst 1996). This research report summarizes the development of seismically induced, simplified sliding block permanent deformation relationships for rock-founded structures and is accomplished by processing data obtained by using a collection of acceleration time histories recorded on different “rock” sites. One hundred and twenty-two sets of horizontal “rock” acceleration time histories recorded during many different earthquake events were carefully selected, base-line corrected and processed (as discussed in Chapter 4) using the PC software Newmark to develop the simplified permanent sliding block displacement relationships summarized in Chapter 6 of this report.

The resulting simplified permanent deformation relationships for rock-founded structures summarized in this report will be implemented within CorpsWallSlip (Ebeling et al. 2007) and within CorpsDamSlip (in development by Ebeling and Chase) for the seismic Simplified Sliding Block analysis of rock-founded earth retaining structures and rock-founded concrete gravity dams, respectively.

There are three categories of analytical approaches used to perform a seismic stability analysis. They are listed in order of sophistication and complexity:

- Pseudostatic methods with a preselected seismic coefficient.
- Stress-deformation methods.
- Sliding block methods.

Each category will be subsequently discussed so as to put the Newmark sliding block method of analysis in perspective as well as understand some of the input data requirements for the PC software Newmark developed for use in this R&D effort and described in this report. Because sliding block methods are the focus of this report, it will be discussed last. The examples to be discussed will involve either embankment slopes or earth retaining structures.

#### **1.1.1 Pseudostatic methods with a preselected seismic coefficient**

Pseudostatic methods with a preselected seismic coefficient in the horizontal and in the vertical direction often require bold assumptions about the manner in which the earthquake shaking is represented and the simplifications made for their use in stability computations. Essentially, it is a force equilibrium method of analysis expressing the safety and stability of an earth retaining structure to dynamic earth forces in terms of the following:

- The factor of safety against sliding along the base of the wall,
- The ability of the wall to resist the earth forces acting to overturn the wall,
- The factor of safety against a bearing capacity failure or crushing of the concrete or rock at the toe in the case of a rock foundation.

An example using 1992 Corps criteria (now outdated) is discussed in Section 6.2 of Chapter 6 in Ebeling and Morrison (1992). Pseudostatic

methods with horizontal and vertical preselected seismic coefficients represent earthquake loading as static forces.

In these types of computations, the earthquake “demand” is represented by a horizontal seismic coefficient, and a vertical seismic coefficient (sometimes specified as zero) acting at mass centers. Values for these coefficients (typical symbols are  $k_h$  and  $k_v$ ), are dimensionless numbers that, when multiplied times the weight of some body, gives a pseudo-static inertia force for use in analysis or design. The horizontal and vertical inertia forces are applied to the mass center of the body, as shown in Figure 1.1. The coefficients  $k_h$  and  $k_v$  are, in effect, decimal fractions of the acceleration of gravity ( $g$ ). For some analyses, it is appropriate to use (acceleration) values of  $k_h g$  and  $k_v g$  smaller than the horizontal and vertical peak accelerations, respectively, anticipated during the design earthquake event. It is important to recognize that this category of method of analysis does not provide quantitative information regarding seismically-induced displacements.

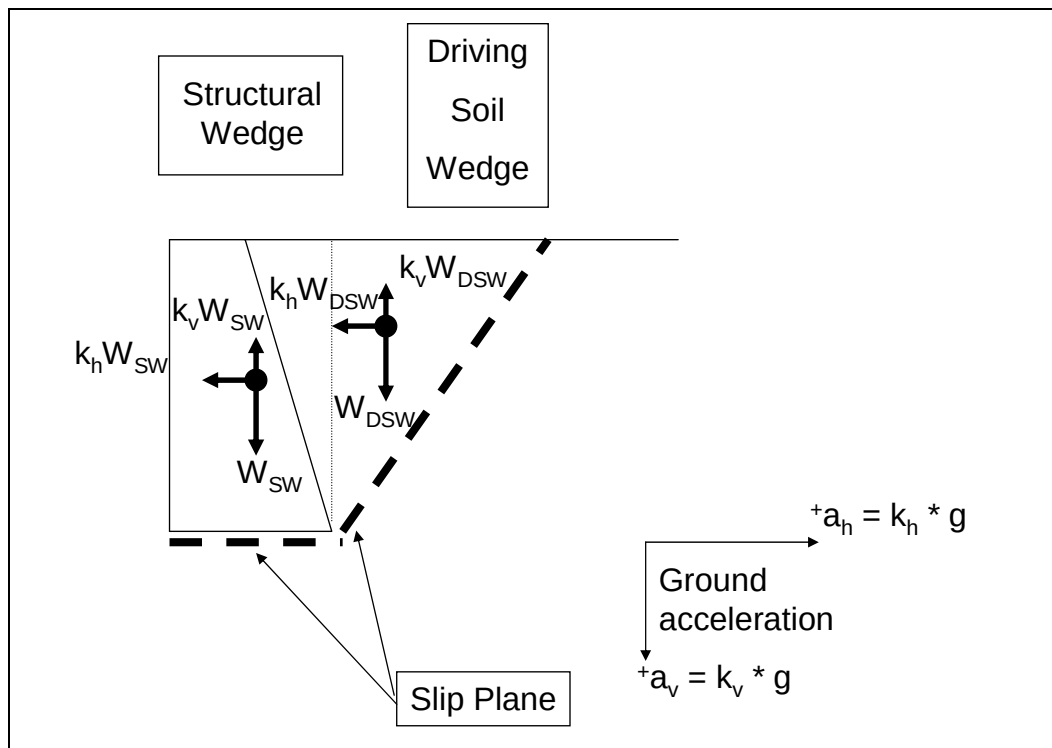


Figure 1.1. Gravity retaining wall and “driving” soil wedge treated as a rigid body.

For retaining walls in which the permanent relative motion of the retaining structure and retained soil (i.e., the backfill) are sufficient to fully mobilize the shear strength in the soil, soil wedge solutions, in which a wedge of soil bounded by the structural wedge and by an assumed failure plane within the retained soil, are considered to move as a rigid body and with the same horizontal acceleration (Figure 1.1). Table 1.1 lists the approximate magnitudes of movements required to reach minimum active earth pressure conditions. Although this Clough and Duncan (1991) guidance is for static loading, after careful evaluation Ebeling and Morrison (1992, in Section 2.2.2) concluded that the Table 1.1 values may also be used as rough guidance for minimum retained soil seismic displacement to fully mobilize a soils shear resistance, resulting in dynamic active earth pressures.

**Table 1.1. Approximate magnitudes of movements required to reach minimum active earth pressure conditions (after Clough and Duncan 1991).**

| Type of Retained Soil                                                                                                                      | Values of $Y/H^1$ |
|--------------------------------------------------------------------------------------------------------------------------------------------|-------------------|
|                                                                                                                                            | Active            |
| Dense Sand                                                                                                                                 | 0.001             |
| Medium-Loose Sand                                                                                                                          | 0.002             |
| Loose Sand                                                                                                                                 | 0.004             |
| <sup>1</sup> Y = movement of top of wall required to reach minimum active pressure, by tilting or lateral translation; H = Height of wall. |                   |

A commonly-cited expression for the forces the driving soil wedge exerts on the structural wedge was first proposed by Okabe (1924, 1926) and Mononobe and Matsuo (1929). A form of their expression for  $P_{AE}$  in use today (see Chapter 4 in Ebeling and Morrison 1992) is given in Figure 1.2. Their formulation is referred to as Mononobe-Okabe with  $P_{AE}$  expressed in terms of an active earth pressure coefficient,  $K_{AE}$ , with the subscript A designating active and the subscript E designating earthquake. The Mononobe-Okabe formulation is an extension of Coulomb's theory of static active earth pressures with a horizontal seismic coefficient and a vertical seismic coefficient acting at the center of a Coulomb's "driving" soil wedge mass of a moist retained soil (i.e., with no water table), as shown in this figure. Equation 36 in Chapter 4 of Ebeling and Morrison (1992) gives the Mononobe-Okabe relationship for  $K_{AE}$ . The general wedge solution

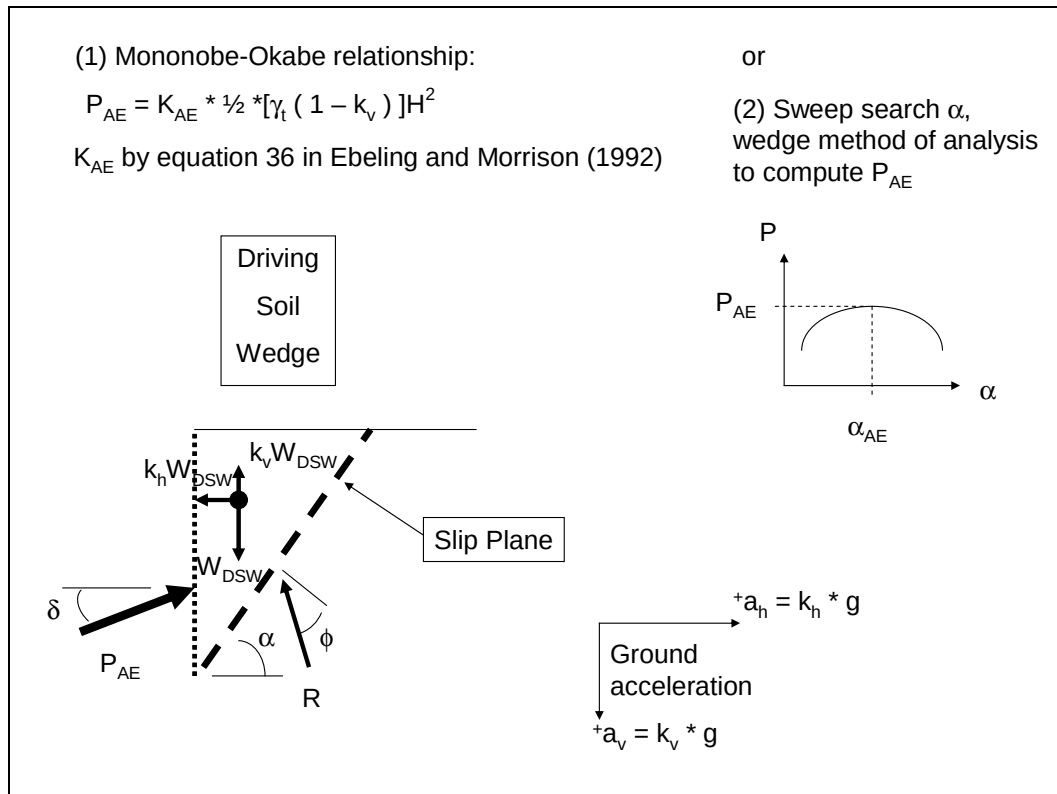


Figure 1.2. Simplified "driving" wedge method of analysis and the Mononobe-Okabe active earth pressure force relationship.

resulting in this same value for  $P_{AE}$  as can be calculated by the Mononobe-Okabe relationship is given in Appendix A of Ebeling and Morrison (1992). For retaining wall problems analyzed using the simplified wedge method, EM 1110-2-2100 in Section 5-5, part (3)b provides guidance on assumptions regarding the magnitude of the seismic coefficient  $k_h$  that may be used as a fraction of peak ground acceleration. Guidance is also given regarding the magnitude of the seismic coefficient  $k_v$ , expressed as a fraction of the value for  $k_h$ . Minimum  $k_h$  values are cited in Table G-1, Section G-4 of Appendix G, part (a) in EM 1110-2-2100, according to the seismic zone in which the project resides.

Because seismically-induced deformations are not an explicit part of this computational process and given that pseudostatic methods represent earthquake loads by static forces, the results are difficult to interpret. This is because displacement is more closely related to assessment of the seismic performance for a retaining structure than are Factors of Safety in what is fundamentally a dynamic problem where loadings are on the fraction of a second.

### 1.1.2 Stress-deformation methods

Stress-deformation methods are specialized applications of finite element or finite difference programs for the dynamic analysis of earth retaining structures to seismic loading using numerical techniques to account for the nonlinear engineering properties of soils. The problem being analyzed is often referred to as a soil-structure interaction (SSI) problem. Acceleration time histories are typically used to represent the earthquake ground motions in this type of formulation. The general procedure of stress-deformation dynamic analysis is straightforward and follows the usual engineering approach:

1. Define the problem,
2. Idealize the physical system,
3. Set up the equations of motion for the dynamic problem,
4. Characterize the dynamic engineering properties of the (structure, soil, and/or rock) materials as per the constitutive material model(s) being used,
5. Solve the equations of motion,
6. Evaluate the results.

Steps (1), (2), (4) and (6) are handled by the engineer while steps (3) and (5) are dealt with by the engineering software. A partial listing of computer-based codes for dynamic analysis of soil systems are given in Appendix D of Ebeling and Morrison (1992). Use of this type of advanced engineering software requires specialized knowledge in the fields of geotechnical and structural engineering dynamics as well as in numerical methods. Two computer programs, FLUSH and FLAC, will be discussed briefly to give the reader a sense of what is involved with the application of computationally complex numerical codes in a complete soil-structure interaction dynamic analysis and the numerous input and modeling considerations required.

#### 1.1.2.1 FLUSH

The American Society of Civil Engineers (ASCE) Standard 4-86 (1986) states that SSI denotes the phenomenon of coupling between a structure and its supporting soil or rock medium during earthquake shaking. The resulting dynamic soil pressures are a result of the degree of interactions that occur between the structure and the soil. This response is dependent on the following:

- The characteristics of the ground motion
- The retained and foundation soils (or rock)
- The structure itself.

One method of analysis for SSI is referred to as the Direct method and treats the structure and the surrounding retained soil and foundation medium in a single analysis step. FLUSH is a classic example of this category of software which uses the finite element method in this dynamic analysis (Lysmer et al. 1975).

Two-dimensional (2-D) cross-sections of the retaining structure, and portions of the retained soil and foundation, are typically modeled in the FLUSH analysis. Nonlinear soil behavior is treated through equivalent linearization of the shear stiffness of each soil element, with the effective shear strains that develop during earthquake shaking, for the user specified earthquake acceleration time-history. Material damping is assigned to each soil (and/or rock) element and to each structural element comprising the mesh. Material damping is strain-compatible for each soil, rock and structural material type. FLUSH solves the equation of motion in the frequency domain. The acceleration time-history is introduced through the base nodes of the mesh; fictitious (artificial) boundary conditions that allow for the introduction of vertically propagating shear waves resulting in horizontal motion of the nodes of the mesh during earthquake shaking, and for vertically propagating compression waves that allow for the vertical motion of the nodes. Lateral boundaries are referred to as transmitting boundaries and are imposed on the 2-D mesh to allow for energy absorbing boundary conditions to be specified. Because it is essentially a wave propagation problem being solved, great care is exercised by the seismic engineer to size the mesh so that moderate to high wave frequencies are not artificially excluded in the dynamic numerical analysis. Sizing of the 2-D mesh, as it pertains to the height of the elements and with regard to the maximum shear wave frequency vertically transmitted by the elements, first involves the analysis of representative one-dimensional (1-D) soil columns.

To assess the maximum frequency that may be transmitted by a user-proposed 2-D finite element mesh in a FLUSH analysis, representative imaginary section(s) within the 2-D model problem are first analyzed by the vertical shear wave propagation program SHAKE (Schnabel et al. 1972) and by a 1-D finite element column using FLUSH. Strain-compatible

shear stiffness results from the SHAKE analyses are used to determine the maximum height of the soil elements for the maximum frequency of the vertically propagating shear wave needed to be transmitted in the FLUSH (2-D) analysis. A 1-D soil column is then constructed using finite elements and analyzed using FLUSH to verify that the required vertically propagating shear wave frequencies are being transmitted by the FLUSH mesh. The wavelength associated with the highest frequency transmitted by the mesh is related to the heights of the elements and to the (strain compatible) shear wave velocities via the strain compatible shear stiffness of each of the elements. Recall that FLUSH accounts for nonlinear response of soils during earthquake shaking through adjustments of the soil shear stiffness and material damping parameters as a function of shear strain that develop in each element of the finite element mesh. Note that the results of this assessment are dependent on the characteristics of the acceleration time-history used in the analysis.

FLUSH output obtained via the extraction mode includes time-histories of the dynamic stresses within each element and dynamic displacements at each node in the finite element model. Time-histories of nodal point forces may also be obtained using specialized software. The computed dynamic stresses are then superimposed on the static stresses to attain the total stresses. Static stresses are typically obtained from a SOILSTRUCT finite element analysis (Ebeling et al. 1992).

In a static analysis using SOILSTRUCT, the nonlinear stress-strain behavior of soils are accounted for in an incremental, equivalent linear method of analysis in which the sequential excavation (if any), followed by sequential construction of the structure and incremental placement of retained soil, is made. Examples of this application to Corps structures for static loading(s) are given in Clough and Duncan (1969), Ebeling et al. (1993); Ebeling and Mosher (1996); Ebeling and Wahl (1997); Ebeling et al. (1997b); and Ebeling et al. (1997c). The mesh used in the FLUSH dynamic analysis will be the basis for the mesh used in the SOILSTRUCT static analysis, for the convenience of combining results.

#### *1.1.2.2 FLAC*

In 1992, the Corps completed its first research application of FLAC to the seismic analysis of a cantilever retaining wall (Green and Ebeling 2002). FLAC is a commercially available, two-dimensional, explicit finite difference program, which has been written primarily for geotechnical

applications. The basic formulation of FLAC is plane-strain. Dynamic analyses can be performed with FLAC using an optional dynamic calculation module, wherein user-specified acceleration, velocity, or stress time-histories can be input as an exterior boundary condition or as an interior excitation. FLAC allows for energy absorbing boundary conditions to be specified, which limits the numerical reflection of seismic waves at the model perimeter. The nonlinear constitutive models (10 are built-in), in conjunction with the explicit solution scheme, in FLAC give stable solutions to unstable physical processes, such as sliding or overturning of a retaining wall. FLAC solves the full dynamic equations of motion, even for essentially static systems, which enables accurate modeling of unstable processes, e.g., retaining wall failures.

FLAC, like FLUSH, has restrictions associated with the wavelength associated with the highest frequency transmitted within the grid. A procedure similar to that used to design the FLUSH mesh and involving 1-D soil column analyses, via SHAKE, is used to lay out the FLAC grid for the dynamic retaining wall problem analyzed and for the specified acceleration time-history. Section 3.3.4 of Green and Ebeling (2002) discuss the dimensions of the finite difference grid and the maximum frequency that can pass through without numerical distortion.

A disadvantage of FLAC is the long computational times, particularly when modeling stiff materials, which have large physical wave speeds. The size of the time-step depends on the dimension of the elements, the wave speed of the material, and the type of damping specified (i.e., mass proportional or stiffness proportional), where stiffness proportional, to include Rayleigh damping, requires a much smaller time step. The critical time step for numerical stability and accuracy considerations is automatically computed by FLAC, based on these factors listed. For those readers unfamiliar with the concept of critical time-step for numerical stability and accuracy considerations in a seismic time-history engineering analysis procedure, please refer to Ebeling (1992), Part V, or to Ebeling et al. (1997a). The Lagrangian formulation in FLAC updates the grid coordinates each time-step, thus allowing large cumulative deformations to be modeled. This is in contrast to Eulerian formulation in which the material moves and deforms relative to a fixed grid, and is therefore limited to small deformation analyses.

### 1.1.2.3 FLUSH versus FLAC

The advantages of FLUSH are that it has considerably faster run times than FLAC and has been applied to a number of dynamic SSI problems. FLUSH is now freely downloadable from the Internet. The major disadvantage of FLUSH is that it does not allow for permanent displacement of the wall (although strain softening associated with earthquake-induced soil or rock deformations are accounted for in the analysis). A disadvantage of FLAC is that the earthquake engineering community and the Corps is just now developing modeling procedures for the application of FLAC to dynamic SSI problems, learning how to perform the analyses and interpret the computed results.

### 1.1.3 Sliding block methods

Sliding block methods of analysis of earth retaining structures can be viewed as a compromise between the simplistic pseudostatic methods, with a preselected seismic coefficient, and the computationally complex finite element or finite-difference based stress-deformation methods of analysis. Sliding block methods of analysis calculate a permanent deformation of a retaining structural system initiated by a user specified design earthquake event.

The numerous variations of rigid sliding block methods of seismic analysis as applied to slopes, earthen dams, retaining wall systems, and foundations have their roots in the methodology outlined in Newmark (1965) and what has come to be known as the Newmark sliding block model.<sup>1</sup> This problem was first studied in detail by Newmark (1965) using the sliding block on a sloping plane analogy. Procedural refinements were contributed by Franklin and Chang (1977); Wong (1982); Whitman and Liao (1985a, 1985b); Ambraseys and Menu (1988); and others. Makdisi and Seed (1978) and Idriss (1985, Figure 47) proposed relationships based on a modification to the Newmark permanent displacement procedure to allow for dynamic response considerations.

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<sup>1</sup> An interesting footnote in seismic engineering history is given in Whitman (2000): Dr. Robert Whitman, Professor Emeritus of MIT, in 1953 performed a calculation of the permanent displacement of a slope as a result of earthquake-induced ground motions using a sliding block concept for a consulting job that Professor Donald Taylor (of MIT) had with the U.S. Army Corps of Engineers. Professor Newmark was part of the same consulting panel and sent word back to Dr. Whitman that he found this approach to be interesting, and that if he (Whitman) did not pursue it, he (Newmark) would. Dr. Whitman did not, and Professor Newmark did. Professor Newmark's research culminated in his (now classic) 1965 Geotechnique paper on this topic, the fifth Rankine lecture.

### 1.1.3.1 Concepts of Newmark's sliding (rigid) block method of analysis

Franklin and Chang (1977) and Hynes-Griffin and Franklin (1984) illustrate key concepts of a Newmark sliding block analysis using a potential sliding mass within an embankment under earthquake loading. The problems' engineering idealization is shown in Figure 1.3. The Figure 1.3a potential sliding mass is in a condition of incipient sliding with full mobilization of the shear resistance for the soil along the slip plane shown in this figure. The corresponding sliding factor of safety is equal to unity. This condition results from the acceleration of the earthen mass into the embankment (i.e., to the left) and away from the cut.  $W$  is the weight of the sliding mass. The force  $N$  times  $W$  in this figure is the inertia force required to reduce the sliding factor of safety to unity. By D'Alembert's principle, the inertia force,  $N$  times  $W$ , is applied pseudostatically to the soil mass in a direction opposite to acceleration of the mass,  $N$  times  $g$ , with  $N$  being a decimal fraction of the acceleration of gravity  $g$  (the universal gravitational constant). The acceleration of the soil mass contained within the slip plane shown in Figure 1.3a is limited to an acceleration value of  $N$  times  $g$  because the shear stress required for equilibrium along the slip plane can never be less than that of the shear strength of the soil. To state this in another way, the sliding factor of safety can never be less than 1.0. So, if the earthquake induced ground acceleration should increase to a value greater than the value  $N$  times  $g$ , the Figure 1.3a mass above this slip plane would move downhill relative to the embankment. During this permanent slope displacement, the "sliding" mass would only feel the acceleration value  $N$  times  $g$  and not the ground acceleration values. The acceleration value of  $N$  times  $g$  was referred to as the "yield acceleration" in these early publications associated with the seismically induced permanent movement of a slope.

Figure 1.3b shows the force polygon for the "sliding" soil mass. The angle inclination  $\theta$  of the inertia force may be found as the angle that is most critical; that is, the angle that minimizes  $N$ . Franklin and Chang (1977) and Hynes-Griffin and Franklin (1984) state that the angle  $\theta$  is typically set equal to zero in seismic slope stability analyses. The angle  $\beta$  is the direction of the resultant force  $S$  of the distributed shear stresses along the interface and is determined during the course of the slope stability analyses to determine the value of  $N$  that results in a sliding factor of safety of 1.0 for the slope's sliding mass. The force  $P$  is the resultant of the normal forces.

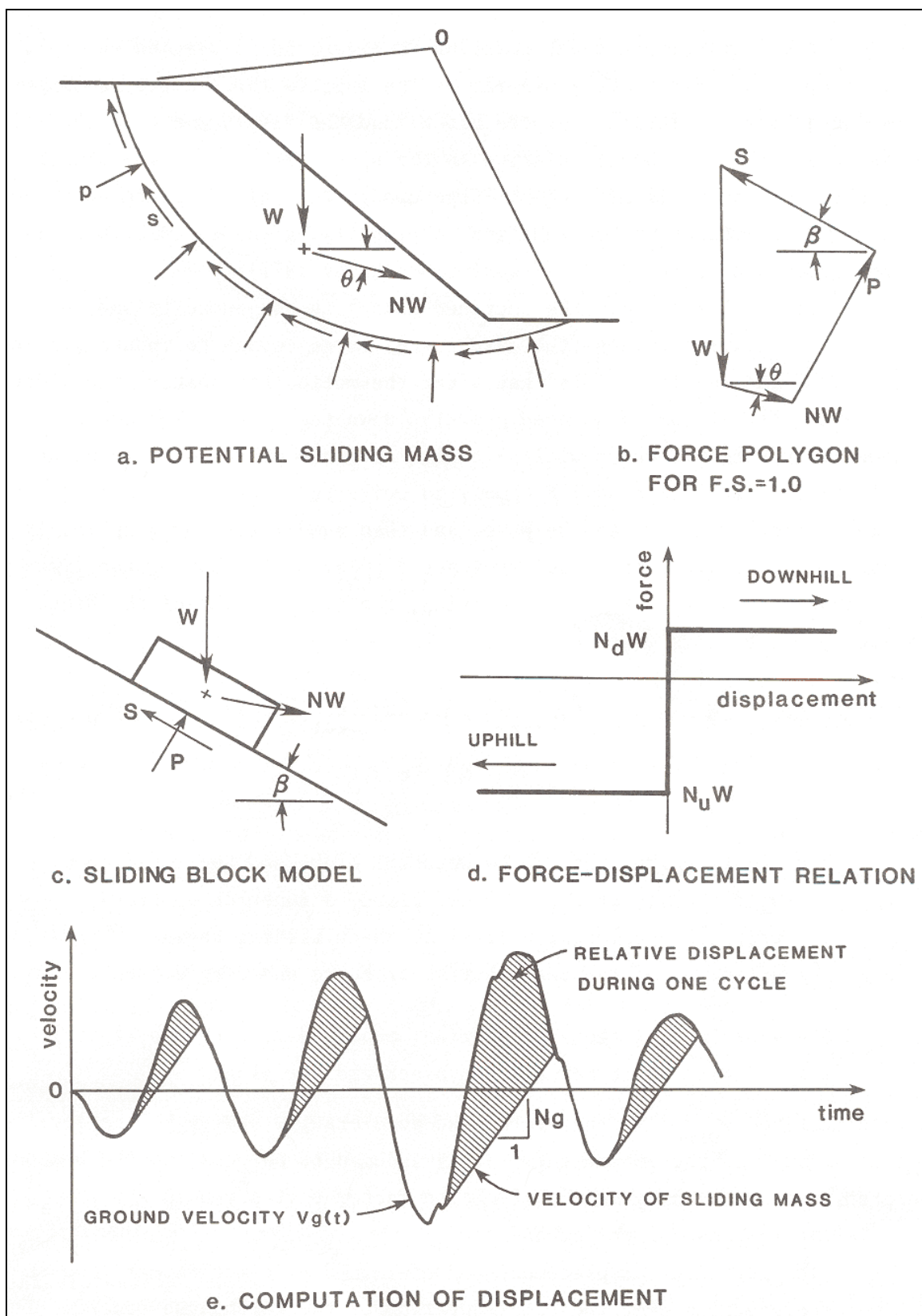


Figure 1.3. Elements of the Newmark (rigid) sliding block method of analysis  
(from Hynes-Griffin and Franklin 1984).

The Figure 1.3b force polygon for the slope mass being applied to an “idealized” sliding rigid block model on a plane inclined at an angle  $\beta$  to horizontal is illustrated in Figure 1.3c. This idealization is the basis for the designation as the Newmark’s sliding (rigid) block method of analysis, representing the sliding mass of the embankment.

Figure 1.3d is an idealization of the limiting force versus displacement relationships applied to this problem. The resistance to sliding is assumed to be rigid-plastic, as shown in this figure. This resistance to sliding is unsymmetrical because the block can slide downhill more easily than uphill. The usual practice is to assume that uphill sliding never occurs; i.e., a worst-case assumption, and results in the greatest permanent displacement (downhill).

Figure 1.3e shows a time-history plot of the velocity of the embankment during earthquake shaking. Not shown is the corresponding (ground/embankment) acceleration time-history for this particular earthquake event. (Earthquake shaking is usually represented by an acceleration time-history. Because the ground acceleration varies with time, it can be represented by variable fraction  $A$  times the constant acceleration of gravity  $g$ . Recall that the integral of the acceleration time-history is equal to the Figure 1.3e velocity time-history.) For an embankment that suffers a slope failure caused by seismic ground motions, the total permanent displacement of a sliding mass relative to the base is the sum of the increments of displacement occurring during a number of individual pulses of ground motion. These incremental relative displacements are determined as follows: For each time the acceleration of the embankment, equal to  $A$  times  $g$ , is greater than the constant  $N$  times  $g$ , relative displacements (between the slope mass and the embankment) will initiate. There are four of these incremental, permanent displacement pulses occurring in Figure 1.3e. During slope displacements, the sliding mass will move at a slower velocity than will the embankment (designated the ground velocity in this figure). The integral of the difference in velocities between the sliding mass and the embankment velocity is equal to the incremental, relative displacement of the sliding mass. The total permanent downhill displacement is the sum of the four incremental displacement cycles depicted in Figure 1.3e. Note that incremental sliding of the slope terminates when the velocities of the embankment and of the sliding mass converge to the same value.

**Summary:** The idealized engineering problem depicted in Figure 1.3 describes the essential features of the Newmark sliding (rigid) block method of analysis as first applied to slopes:

- There is a level of earthquake shaking as characterized in terms of a value of acceleration designated  $N$  times  $g$  (i.e., the yield acceleration), which fully mobilizes the shear resistance along a sliding plane of a potential sliding mass; corresponding to a factor of safety against sliding of 1.0 for that mass.
- For a given embankment (or equivalently, ground) acceleration time-history in which acceleration(s) exceed the value of  $N$  times  $g$ , incremental permanent displacements will occur.
- The magnitude of the incremental displacements may be numerically quantified using the procedure outlined in Figure 1.3e.
- Total permanent displacement is equal to the sum of the incremental displacement pulses.

Although this procedure has been applied to other types of structures, the essential features of the Newmark (rigid) sliding block method of analysis remain the same.

#### *1.1.3.2 Sliding block method of analysis applied to retaining structures*

A variation proposed on the Newmark sliding block method of analysis for earth retaining structures is the displacement controlled approach (Section 6.3 in Ebeling and Morrison 1992). It incorporates retaining wall movements explicitly determined in the stability analysis of earth retaining structures. This methodology is applied as either the displacement-controlled design of (a new) retaining wall, or as an analysis of earthquake induced displacements of an existing retaining wall.

- **The displacement controlled design of retaining wall:** In this approach, the retaining wall geometry is the primary variable. It is, in effect, a procedure for choosing a seismic coefficient based upon explicit choice of an allowable permanent displacement. Having selected the seismic coefficient, the usual stability analysis against sliding is performed, including the use of the Mononobe-Okabe equations (or, alternatively, a sweep search, soil wedge solution). The wall is proportioned to resist the applied earth and inertial force loadings. No safety factor is required to be applied to the required weight of wall evaluated by this approach; the appropriate level of

safety is incorporated into the step used to calculate the horizontal seismic coefficient. This procedure of analysis represents an improved alternative to the conventional equilibrium method of analysis that expresses the stability of a rigid wall (of prescribed geometry and material properties) in terms of a pseudostatic method with a preselected seismic coefficient and preselected factor of safety against sliding along its base, discussed in Section 1.1.1. Section 6.3.1 in Ebeling and Morrison (1992) outlines the computational steps in the (seismic) displacement controlled design of a retaining wall.

- **The analysis of earthquake induced displacements of a retaining wall:** The retaining wall geometry and material properties are typically first established for the usual, unusual and extreme load cases with non-seismic loadings. In the subsequent seismic analysis of the retaining wall using the earthquake induced displacement approach, the primary variable is the permanent displacement. The seismic inertia coefficient  $N^*$  that reduces the sliding factor of safety for the driving soil wedge and the structural wedge to unity is first determined. Ebeling and Morrison (1992), along with others, have designated the acceleration value  $N^*g$  for a retaining wall as its “maximum transmissible acceleration.” Figure 1.4 shows the driving soil wedge and structural wedge treated as a single rigid block in this approach.

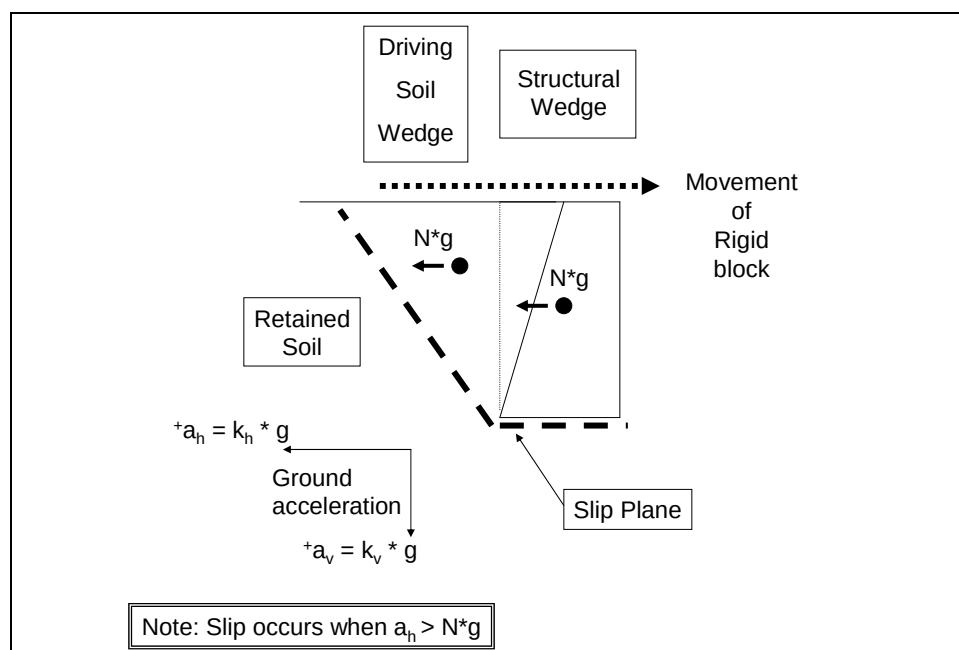


Figure 1.4. Gravity retaining wall and failure wedge treated as a sliding block (after Whitman 1990).

The resulting permanent seismic displacement of the retaining wall is subsequently determined for the earthquake specified by the design engineer. Section 6.3.2 in Ebeling and Morrison (1992) outlines the computational steps in the analysis of earthquake induced displacements of a retaining wall (with specified geometry and material properties).

The analytical procedure that was developed by Richards and Elms (1979) recognizes that for some limiting value of horizontal acceleration, i.e., the maximum transmissible acceleration identified as  $N^*g$  in Figure 1.4, the horizontal inertia force acting on a retaining wall with no toe fill will nominally exceed the shear resistance provided by the foundation along the interface between the base of the wall and the foundation.

This implies that although the soil base (i.e., the foundation to the wall) may be accelerating horizontally at values greater than  $N^*g$ , the wall will be sliding along the base under the action of the horizontal inertial force that corresponds to the horizontal acceleration  $N^*g$ . This results in movement of the soil base relative to the movement of the wall and vice-versa. The relative movement originates at the point in time designated as point  $a$  in the first time-history shown in Figure 1.5 and continues until the (absolute) velocity of the base is equal to the (absolute) velocity of the wall, designated as time point  $b$  in the second time-history of this same figure.

The (absolute) velocity of the soil base is equal to the integral over time of the soil acceleration, and the (absolute) velocity of the wall between time points  $a$  and  $b$  is equal to the integral of the wall acceleration, which is a constant  $N^*g$ . The relative velocity of the wall,  $v_r$ , shown in the third time-history is equal to the integral of the difference between the base acceleration and the constant wall acceleration  $N^*g$  between time points  $a$  and  $b$ , as shown in Figure 1.5. The relative displacement of the wall is the fourth time-history and equal to the integral of the relative velocity of the wall, which occurs between the two points in time labeled  $a$  and  $b$  in Figure 1.5. Note that at time point  $b$ , when the wall is stopping its first increment of relative movement, the acceleration is less than  $N^*g$ , as shown in the first time-history. This observation demonstrates that the relative velocity of the wall (shown in the third time-history) controls the cessation of the seismically induced incremental wall movement. Additional incremental relative displacements occur for the wall between the two latter points in time labeled  $c$  and  $d$  in Figure 1.5, with the residual relative wall displacements,  $d_r$ , equal to the cumulative relative displacements computed during

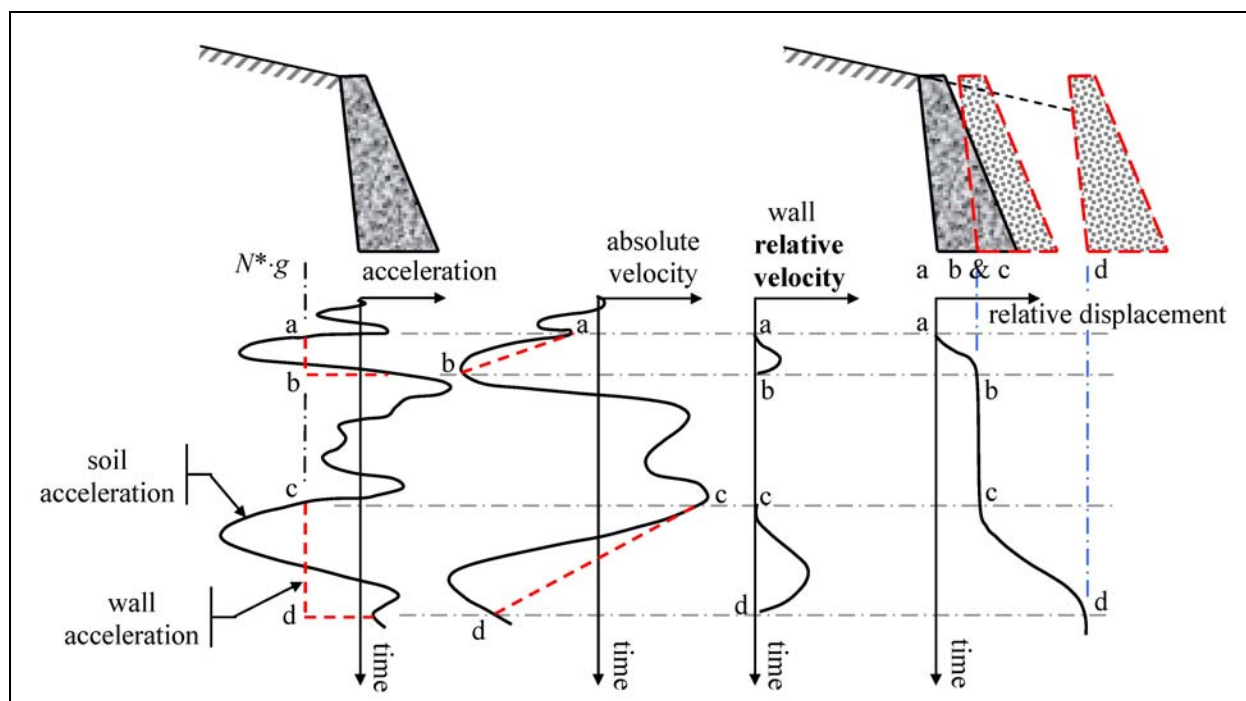


Figure 1.5. Incremental failure by base sliding (adapted from Richards and Elms 1979).

the entire time of earthquake shaking (labeled as point *d* in the fourth time-history). Lastly, although  $N \cdot g$  is referred to as the maximum transmissible acceleration in retaining structure permanent deformation problems, it is equivalent to the yield acceleration that is associated with permanent deformation problems for slopes/embankments. In the permanent deformation research conducted by Cai and Bathurst (1996), the term “critical acceleration” was used. The terms critical acceleration, maximum transmissible acceleration and yield acceleration all describe the same quantity.

Ebeling and Morrison (1992) observe that the approach has been reasonably well validated for the case of walls retaining granular, moist backfills (i.e., no water table). A key item is the selection of suitable shear strength parameters. In an effective stress analysis, the issue of the suitable friction angle is particularly troublesome when the peak friction angle is significantly greater than the residual friction angle. In the displacement controlled approach examples given in Section 6.2 of Ebeling and Morrison (1992), effective stress based shear strength parameters (i.e., effective cohesion  $c'$  and effective angle of internal friction  $\phi'$ ) were used to define the shear strength of the dilative granular backfills, with  $c'$  set equal to zero in all cases due to the level of deformations anticipated in a sliding block analysis during seismic shaking. In 1992, Ebeling and Morrison

concluded that using the residual friction angle in a sliding block analysis is conservative, and that this should be the usual practice for displacement based analysis of granular retained soils. For the Ebeling et al. (2007) report discussing CorpsWallSlip, the primary author would broaden the concept to the assignment of effective (or total) shear strength parameters for the retained soil to be consistent with the level of shearing-induced deformations encountered for each design earthquake in a sliding block analysis, and note that active earth pressures are used to define the loading imposed on the structural wedge by the driving soil wedge. (Refer to Table 1.1 for guidance regarding wall movements required to fully mobilize the shear resistance within the retained soil during earthquake shaking.)

CorpsWallSlip uses a graphical user interface for input of wall geometry, input of material properties, input/verification of earthquake time-history files, and for visualization of results. CorpsWallSlip has the ability to perform a sliding analysis of a user specified retaining wall section, such as the rock-founded retaining wall shown in Figure 1.6.

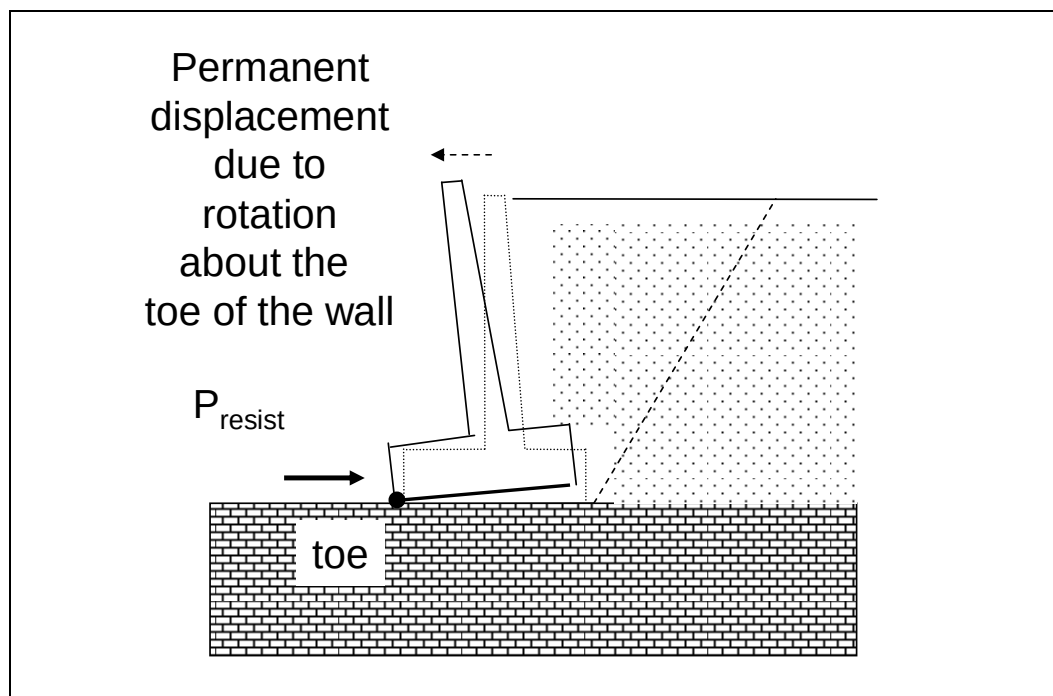


Figure 1.6. Idealized permanent, seismically induced displacement due to the rotation about the toe of a rock-founded wall retaining moist backfill, with toe restraint, computed using CorpsWallRotate.

This retaining wall is an idealization of the Figure 1.7 cantilever retaining wall problem in which the toe of the wall is buttressed by a concrete slab in a spillway channel. The engineer provides the overall wall and retained soil geometry and material properties. This PC-based software will compute for the user the value for the maximum transmissible acceleration of the retaining wall system.

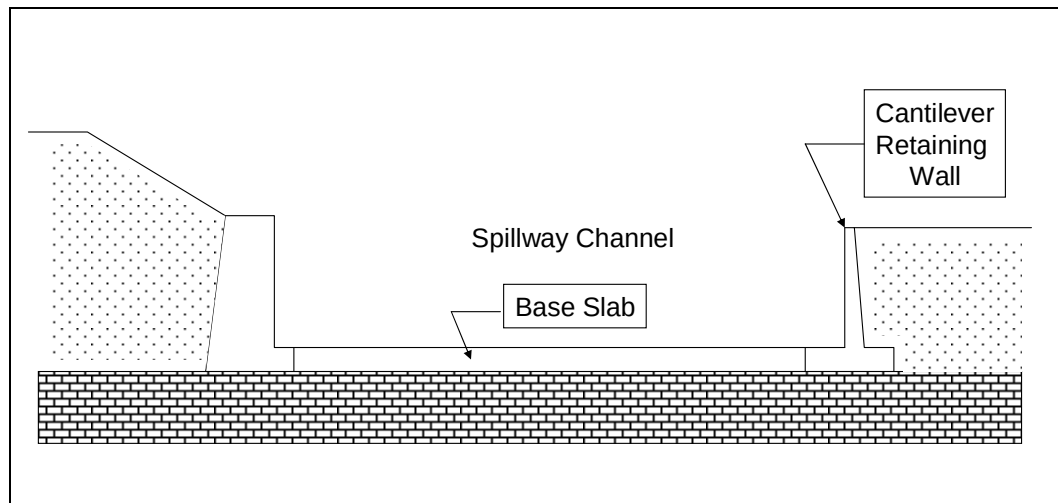


Figure 1.7. Rock-founded cantilever retaining wall bordering a spillway channel.

The PC-based program, Newmark, which is discussed in this report, requires the value for the maximum transmissible acceleration (i.e., the yield acceleration or critical acceleration) as input. For a user specified earth retaining structure, for example, the maximum transmissible acceleration (i.e., the yield acceleration or the critical acceleration) is computed using the hand-calculation procedure outlined in Ebeling and Morrison (1992).

## 1.2 New rotational analysis model based on a rigid block problem formulation

The permanent displacement of retaining structures is not restricted to walls that slide along their base as a result of inertial forces imparted during earthquake shaking. For some retaining wall system configurations and material properties, permanent displacements may instead result from the rotation of a retaining wall about a point along its wall-to-foundation interface.

The idealized permanent displacement caused by rigid body noncentroidal rotation of a retaining wall about its toe during earthquake shaking and

with toe restraint is shown in Figure 1.6. The buttressing effect of a reinforced concrete slab (Figure 1.7) is represented in this simplified dynamic model by the user-specified force  $P_{resist}$  acting on a vertical section extending upward from the toe of the wall as per, for example, Strom and Ebeling (2004).

The Figure 1.7 cantilever retaining wall that is buttressed by an invert spillway slab (which is a reinforced concrete slab), exemplify a category of Corps retaining walls that may be susceptible to earthquake induced rotation. The primary author of this report is of the opinion that the assignment of the point of rotation to the toe of the wall becomes a reasonable simplifying assumption because of the constraint provided by the Figure 1.6 invert spillway slab to lateral translations, combined with the effects of the stiff, competent rock foundation. A key result of a CorpsWallRotate analysis, idealized in Figure 1.6, is the permanent, earthquake-induced displacement of a retaining wall resulting from rotation about the toe of the wall.

Like the Zeng and Steedman (2000) rigid gravity wall formulation, discussed in Ebeling and White (2006), rotation of a rigid block model of the structural retaining wall system in this new formulation is assumed to occur about the toe of the wall (i.e., the rigid block is “pined” to the rigid base at its toe). This new Ebeling and White procedure differs from the Steedman and Zeng formulation by the following:

- Formal consideration of a toe-restraint in the analysis (due to the presence of a reinforced concrete slab against the toe of the wall)
- The ability of the user to assign a vertical acceleration time-history in addition to a horizontal acceleration time-history
- Consideration of a pool of water in front of the wall, a submerged foundation and a partially submerged retained soil (Figure 1.8)
- The implementation of this formulation within corresponding PC software CorpsWallRotate using a graphical user interface for input of geometry, input of material properties, input/verification of earthquake time-history files, and for visualization of results
- A sweep-search wedge formulation within the retained soil is used to determine the value of  $P_{AE}$  rather than relying on the Mononobe-Okabe relationship (cited in the Steedman and Zeng 1996 formulation).

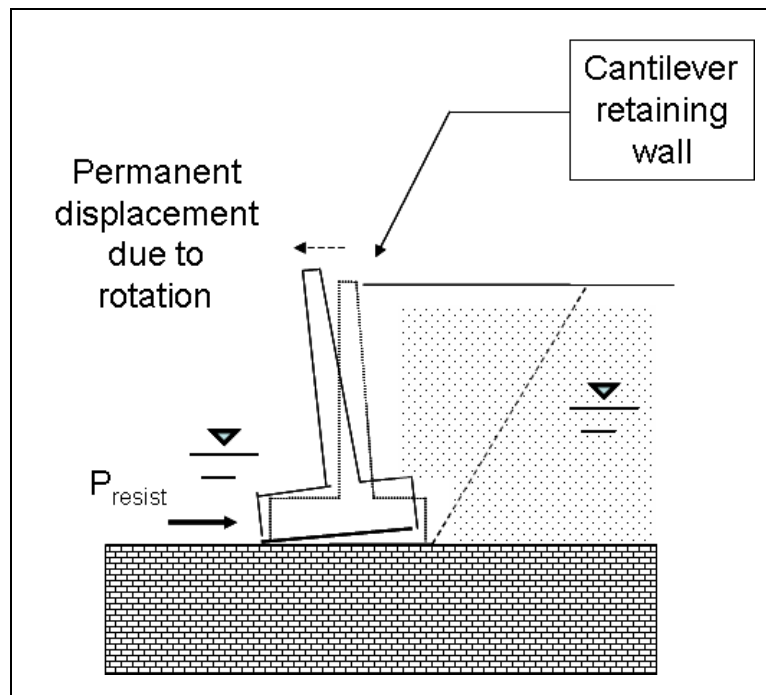


Figure 1.8. Permanent, seismically induced displacement due to the rotation about the toe of a rock-founded, partially submerged cantilever retaining wall and with toe restraint, computed using CorpsWallRotate.

Recall that the Mononobe-Okabe relationship is valid for a retained soil with a constant surface slope and whose strength is characterized by the Mohr-Coulomb shear strength parameter  $\phi$  (e.g., refer to Equations 33 through 35 in Ebeling and Morrison 1992).

The advantage of the sweep-search method, as formulated and implemented in CorpsWallRotate and in CorpsWallSlip, is that it allows for the analysis of bilinear ground surfaces (Figure 1.9) and/or the analysis of “cohesive” ( $S_u$ ) soils.<sup>1</sup>

<sup>1</sup> In the formulation described in this report, a cohesive soil refers to a total stress analysis in which the shear strength of the soil is characterized in terms of its undrained shear strength  $S_u$ . Note that minimum wall movements needed to fully mobilize the shear resistance of the soil, on the order of those listed in Table 1.1, will impact the characterization of the retained soil shear strength parameters used in the permanent displacement analysis.

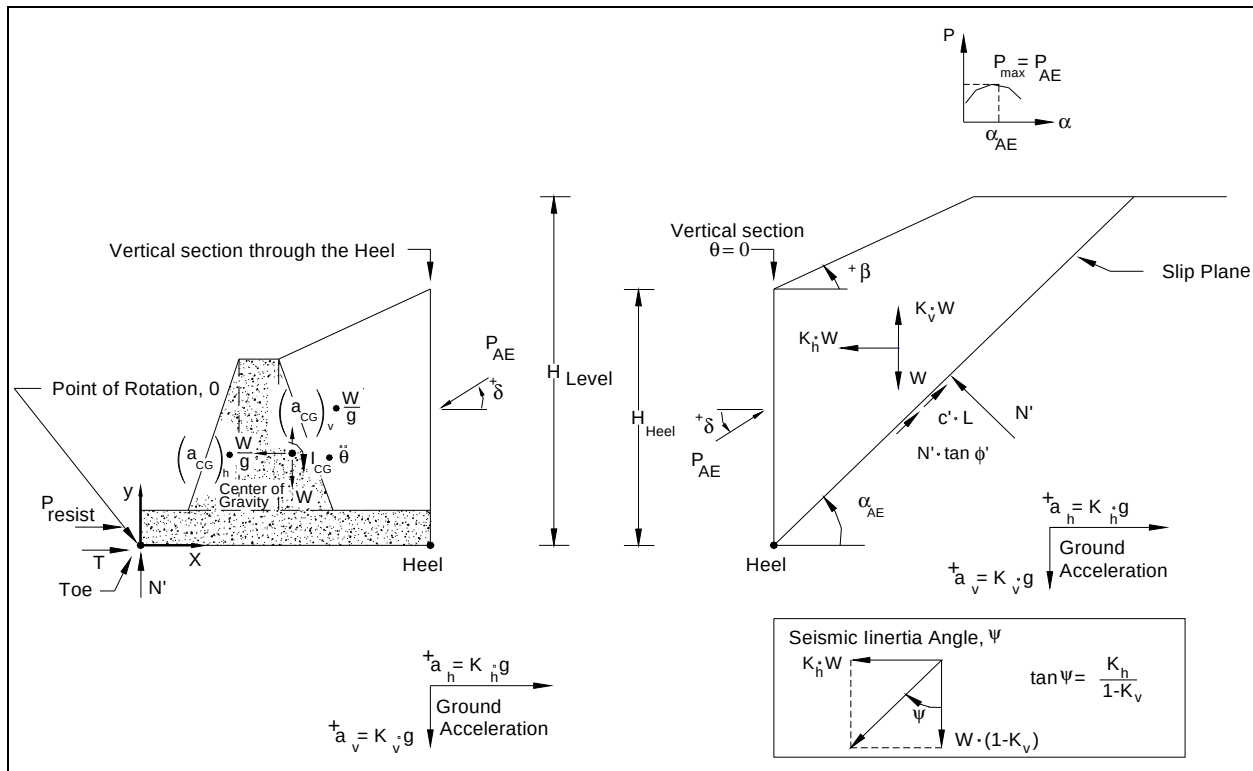


Figure 1.9. Structural wedge with toe resistance retaining a driving soil wedge with a bilinear moist slope (i.e., no water table) analyzed by effective stress analysis with full mobilization of  $(c', \phi')$  shear resistance within the backfill.

### 1.3 The tendency of a retaining wall to slide or to rotate during earthquake shaking

An important difference between the Newmark sliding block method of analysis for earth retaining structures (i.e., the displacement controlled approach that is discussed in Section 1.1.3) and the rotational analysis of a retaining structure modeled as a rigid block is the acceleration imparted to the rigid block. When a rigid block undergoes permanent sliding displacement during earthquake shaking, the largest magnitude horizontal acceleration felt by the rigid block (and the retaining structure contained within the rigid block) is  $N^*g$ , which is less than the peak value for ground acceleration. The maximum transmissible acceleration  $N^*g$  (i.e., the yield acceleration or critical acceleration) is not the horizontal ground (or, equivalently, the rigid base) acceleration representing the earthquake. For a rigid block that undergoes rotation during earthquake shaking, the accelerations felt by this rigid block during shaking are those of the ground acceleration time-history. This is because continuous contact between the rigid block undergoing rotation and the ground is maintained at the point of

rotation, i.e., the toe in Figure 1.6, during the entire earthquake shaking process.

Thus for a rigid block that undergoes rotation during earthquake shaking, the horizontal acceleration of (rigid) mass center is a function not only of the horizontal ground acceleration but it is also a function of the angular acceleration and the angular velocity during rotation (see Ebeling and White 2006). This differs from the situation of a rigid block that undergoes permanent sliding displacement during earthquake shaking; the largest magnitude horizontal acceleration felt by this rigid block is  $N*g$ . Recall that  $N*g$ , the maximum transmissible acceleration (i.e., the yield acceleration or critical acceleration) is not the user-defined, horizontal ground (or, equivalently, rigid base) acceleration. Unlike the sliding (rigid) block model, which effectively isolates the sliding block from the shaking base below, the rotating rigid block model continues to transmit horizontal acceleration through the “pin”, located at the toe of the wall, into the wall.

A key step in the evaluation process of the idealized rigid block formulations of Ebeling et al. (2007) and of Ebeling and White (2006) for translation and for rotation is the computation of the maximum transmissible acceleration and the computation of threshold value of acceleration corresponding to lift-off the base of the wall in rotation. Comparison of these values determines if the wall will tend to slide before it will rotate or visa versa. The lower of the two values dictates the kinematic mechanism for the retaining wall system model. Both of these computational steps are incorporated in both CorpsWallSlip and CorpsWallRotate. The PC-based program Newmark, described and used in the R&D of this report, does not perform this check nor does it do rotational permanent deformation analyses. For this type of rotational analysis the reader is referred to CorpsWallRotate.

## 1.4 Seismic design criteria for Corps retaining structures

Current Corps engineering methodology is to evaluate retaining walls for Usual, Unusual and Extreme Loadings. Consideration of earthquake loadings is part of the design process for Corps earth retaining structures. Engineer Regulation (ER) 1110-2-1806 (Headquarters, U.S. Army Corps of Engineers (HQUSACE) 1995) provides requirements governing the seismic design and evaluation of structures located at Corps projects. The engineering procedures outlined in this Corps document are applicable to the analysis of existing, or the design of new earth-retaining structures.

The Corps regulation for earthquake loadings, ER 1110-2-1806, specifies two project-specific earthquakes, the Operational Basis Earthquake (OBE) and the Maximum Design Earthquake (MDE).

The OBE is an earthquake that can reasonably be expected to occur within the service life of the project, that is, with a 50-percent probability of exceedance during the service life. (This corresponds to a return period of 144 years for a project with a service life of 100 years.) The associated performance requirement is that the project functions with little or no damage, and without interruption of function. The purpose of the OBE is to protect against economic losses from damage or loss of service, and therefore alternative choices of return period for the OBE may be based on economic considerations. The OBE is determined by a Probabilistic Seismic Hazard Analysis (PSHA). The OBE is classified as an Unusual event. Retaining walls are expected to remain serviceable and operable immediately following an OBE earthquake event, or immediately following any earthquake that can reasonably be expected to occur within the service life of the project.

The MDE is the maximum level of ground motion for which a structure is designed or evaluated. The associated performance requirement is that the project performs without catastrophic failure, such as an uncontrolled release of a reservoir, although severe damage or economic loss may be tolerated. For critical features, the MDE is the same as the Maximum Credible Earthquake (MCE). [Section 5(a) and Table B-1 in ER 1110-2-1806 outlines the assessment of the hazard potential classification of Civil Works projects and is related to the consequences of project failure. Critical features are the engineering structures, natural site conditions, or operating equipment and utilities at high hazard projects whose failure during earthquake could result, in loss of life.] For all other features, the MDE shall be selected as a lesser earthquake than the MCE, which provides economical designs meeting appropriate safety standards. The MDE is the maximum level of ground motion for which a structure is designed or evaluated. Although not formally stated in the ER, recent (limited) application to select, normal Corps (non-critical) structures is to assume the MDE is an earthquake that has a 10 percent chance of being exceeded in a 100-year period (or a 975-year return period). The MDE for normal structures is determined by PSHA. For critical structures, the MDE is the Maximum Credible Earthquake (MCE), which is determined by a deterministic seismic hazard assessment (DSHA). The MCE is defined as the

greatest earthquake that can reasonably be expected to be generated on a specific source, on the basis of seismological and geological evidence. Significant damage resulting from an MDE event can be considered as acceptable provided the damaged structure can be repaired and put back in service without risk to life.

Factors of safety and safety requirements for retaining walls subject to seismic loading conditions are provided in EM 1110-2-2100. This supersedes the stability guidance for retaining walls contained in EM 1110-2-2502 (but not the engineering procedures, which are based on the simplified pseudo-static procedure of analysis).

Factors of safety for sliding and flotation, and the safety provisions related to resultant location and allowable bearing capacity, contained in EM 1110-2-2100 are dependent on:

- Load condition category (usual, unusual, or extreme)
- Site information knowledge (well-defined, ordinary, or limited), and
- Structure importance (normal, or critical)

EM 1110-2-2100 associates each of the three load condition categories to a range in annual probability (or, equivalently, a range in return period). Additional “structure specific” information related to load condition categories and probabilities are contained in Appendix B of EM 1110-2-2100.

## **1.5 Axial load capacity of spillway invert slabs**

Reinforced concrete slabs provide an important contribution to the overall seismic stability of retaining walls. Figure 1.7 shows, for example, an invert spillway buttressing a cantilever retaining wall that borders the spillway channel. Key to the seismic performance of this spillway retaining wall is the stabilizing force that the channel invert slab exerts at the toe of this wall. The magnitude of this stabilizing force will depend on the limit state axial load capacity of this invert slab.

Invert slabs can be founded on earth or rock. Types of construction used by the Corps include an “independent block plan” and a “continuous reinforcing plan”. Invert slabs, when loaded axially, can exhibit either short column or long column behavior, with the later referring to slabs

whose axial capacity is reduced by second-order deformations (i.e.,  $P \bullet \Delta$  effects).

Slab capacity, in terms of axial load versus moment interaction, is determined based on ultimate strength design principles, which can be applied to both unreinforced (plain concrete) and reinforced concrete invert slab sections. Influences from the subgrade reaction, slab dead load, and axial load eccentricity, when considered in a second-order analysis, suggest the axial load capacity can be based on a short column design with second-order displacements resulting from  $P \bullet \Delta$  effects having little if any effect on column axial load capacity, according to the Strom and Ebeling (2004).

The axial load resistance  $P_{resist}$ , provided by the Figure 1.7 invert slab, is illustrated in Figure 1.6. Limited investigations, by Strom and Ebeling (2004), based on the Corps minimum thickness for invert slabs constructed on rock and earth, and for both continuous reinforcing plans and independent block plans, indicate the limit state axial load capacity, or ultimate axial load resistance of the slab ( $P_{resist}$ ) may be on the order of:

- 120 kips per foot width of slab for a 1.0 foot thick invert slab on rock
- 240 kips per foot width of slab for a 2.0 foot thick invert slab on soil

The above values are valid for both anchored and unanchored invert slabs, and for the minimum contraction joint spacings typically found on Corps projects. However, a site-specific evaluation of the limiting axial resisting force resulting from the buttressing effect of the type of slab on the toe of a retaining wall is required. Refer to Strom and Ebeling (2004) for a simplified engineering methodology for the assessment of  $P_{resist}$  for all types of slabs buttressing all types of retaining structures, including the Figure 1.7 invert spillway slab.

## 1.6 Background and research objective

EM 1110-2-2502, Retaining and Flood Walls, gives engineering procedures that are currently being used by District Engineers in their initial assessment of seismic wall performance of existing earth retaining structures and the (preliminary) sizing of new retaining structures. The engineering procedures given in EM 1110-2-2502 for retaining walls make extensive use of the simplified pseudo-static procedure of analysis of earth retaining structures and express wall performance criteria in terms of computed factors of safety against sliding and bearing failure, and base area in

compression. The simplified pseudo-static procedure of analysis makes it difficult to interpret the actual wall performance for Corps projects subjected to “strong” design ground motions because of simplifications made in the procedure of analysis. In a pseudo-static analysis, an oversimplification occurs when the engineer is forced to render the complex, horizontal and vertical earthquake acceleration time-history events to constant values of accelerations and to assume a constant direction for each. These constant values are denoted as the pseudo-static acceleration coefficients in the horizontal and vertical directions (refer to Section 1.1.1 of this report). The engineer is also required to assume a constant direction for each of these components. An acceleration time-history, in actuality, varies both in magnitude and in direction with time.

The simplified pseudo-static procedure does not allow for interpretation of actual wall performance by District Engineers. Intense shaking imparted by the OBE and MCE design events makes the interpretation of the simplified procedure of analysis even more difficult. The more important questions for the wall are whether the wall slides into the spillway basin, or rotates into the spillway basin, or even tips over onto its side during the earthquake event. The simplified pseudo-static procedure of analysis is not capable of answering these questions. The answers depend on the magnitude of the pseudo-static coefficient used in the calculations compared to the magnitude of the peak values for the acceleration pulses as well as the number and duration of these strong shaking acceleration pulses in the design earthquake event time-history. When considering both horizontal and vertical accelerations, the resulting wall response is further complicated by the time-history of phasing between the pulses of horizontal and vertical accelerations. Only the permanent wall sliding displacement/wall rotation method of time-history analysis can answer these questions. Again, wall displacements will influence the seismic earth pressure forces imparted on the wall by the retained soil.

Formal consideration of the permanent seismic wall displacement in the seismic design process for Corps-type retaining structures is given in Ebeling and Morrison (1992). The key aspect of the engineering approach presented in this Corps document is that simplified procedures for computing the seismically induced earth loads on retaining structures are also dependent upon the amount of permanent wall displacement that is expected to occur for each specified design earthquake. The Ebeling and Morrison simplified engineering procedures for Corps retaining structures

are geared toward hand calculations. The engineering formulation and corresponding PC software CorpsWallSlip (Ebeling et al. 2007) extend these simplified procedures to walls that slide during earthquake shaking and make possible the use of acceleration time-histories in the Corps design/analysis process when time-histories are made available on Corps projects. CorpsWallSlip may be used to predict permanent seismically induced translational displacements of walls retaining backfill, with or without a toe restraint. It is particularly applicable to rock-founded L-walls and T-walls (i.e., cantilever retaining walls) which border spillway channels (Figure 1.7). The PC software Newmark discussed in this report may also be used to perform the same permanent (translational) deformation analysis as CorpsWallSlip, but does require the additional step of the user computing and providing as input the maximum transmissible acceleration (i.e., the yield acceleration or the critical acceleration).

The software Newmark is also capable of performing regression analyses on multiple horizontal acceleration time histories for up to three pre-set (mathematical) formulations, for the purpose of developing simplified non-dimensional (simplified) permanent displacement relationships for use in a Simplified Sliding Block Analysis of a structural system. The main purpose of developing the software Newmark in this R&D effort is to facilitate the processing of multiple rock acceleration time histories and to perform a statistical analysis of the computed permanent displacements for multiple, user-defined critical accelerations. From these data, simplified permanent displacement relationships are derived, concluding in the selection of recommended relationships. These resulting simplified sliding block relationships based for rock-founded structures are based on data from rock acceleration time histories and will be implemented within CorpsWallSlip (Ebeling et al. 2007) for Corps earth retaining structures and within CorpsDamSlip (under development by Ebeling and Chase) for Corps rock-founded gravity dams.

## 1.7 Organization of report

Chapter 2 describes the numerical method implemented in the software Newmark for performing a translational (i.e., sliding) block analysis of a structural system model of e.g., a retaining structure or a rock-founded gravity dam, etc. The formulation used computes the permanent sliding displacement response of a structural system to an earthquake acceleration time-history via a Complete Time-History Analysis.

Chapter 3 describes three formulations used for developing simplified non-dimensional (simplified) permanent displacement relationships for use in a Simplified Sliding Block Analysis of a structural system. The regression analyses result in mean estimates and together with their standard error terms, also determine the 68 percent prediction intervals and 95 percent probability of non-exceedance upper bound estimates to seismically induced permanent (translational) displacement at the end of earthquake shaking.

Chapter 4 discusses the selection process and the characteristics of each of the 122 sets of baseline corrected “rock” acceleration time histories used in the regression analysis and the results of these analyses for the three simplified permanent (translational) displacement relationships introduced in Chapter 3.

Chapter 5 describes key aspects of the visual modeler and visual post-processor Newmark. Specifically, a description of the graphical user interface for input of value(s) of critical acceleration (i.e., the maximum transmissible acceleration or the yield acceleration), input/verification of earthquake time-history files, and for visualization of results is presented to make the user familiar with its operation.

Chapter 6 presents a summary of the recommended simplified permanent (translational) deformation relationships developed during the course of this research, conclusions and recommendations for additional research.

Appendix A is a listing and description of the Newmark ASCII input data file (file name: Newmark.in).

Appendix B is a listing and description of Newmark ASCII Data Output Files.

## 2 Translational Block Analysis of a Rock Founded Structural Model

### 2.1 Introduction

This chapter describes an engineering formulation developed for computing the permanent translational response of the Corps rock founded hydraulic structures (e.g., an earth retaining structure, a concrete gravity dam, etc.) to earthquake ground motions. The resulting engineering formulation is implemented within corresponding PC software Newmark using a graphical user interface for input/verification of earthquake time-history files, input of the hydraulic structures critical acceleration (i.e., maximum transmissible acceleration or yield acceleration) and for visualization of results. The PC software Newmark was developed to perform an analysis of the permanent sliding displacement response of a rigid block model of a structural section to a user specified earthquake acceleration time-history via a Complete Time-History Analysis. The Complete Time-History method of analysis is discussed first in this chapter. (Key aspects of the Visual Modeler, the PC-based Graphical User Interface (GUI) to Newmark are described in Chapter 5.) The main purpose of developing the software Newmark in this R&D effort is to facilitate the processing of multiple rock acceleration time histories and perform a statistical analysis (using the procedures discussed in Chapter 3) of the computed permanent displacements for multiple, user-defined critical accelerations. From this data, simplified permanent displacement relationships are derived (discussed in Chapter 4), with recommended relationships summarized in Chapter 6. These resulting simplified sliding block relationships for rock-founded structures will be implemented within CorpsWallSlip (Ebeling et al. 2007) for earth retaining structures and within CorpsDamSlip (under development by Ebeling and Chase) for Corps rock-founded gravity dams.

The software Newmark may also be used to compute the permanent (translational) displacement of a rigid block model for a single acceleration time-history. Besides an acceleration time-history, a user specified value for the structure's critical acceleration (i.e., maximum transmissible acceleration or yield acceleration) is required. Recall that the value for the critical acceleration (i.e.,  $N \cdot g$ ; the maximum transmissible acceleration in Ebeling and Morrison (1992) terminology for retaining walls) is the

horizontal acceleration imparted to the rigid body model, that will nominally exceed the shear resistance provided by the foundation along (or immediately below) the interface between the base of the rigid body and the foundation (refer to Figure 1.4). Earth retaining structures and earthen slope/embankments were discussed in Chapter 1 with regard to (Newmark) permanent displacement based sliding block analysis resulting from earthquake shaking. Hand calculations of the critical acceleration (i.e., the maximum transmissible acceleration or the yield acceleration) for a particular earth retaining structure are described in Ebeling and Morrison (1992). Alternatively, CorpsWallSlip (Ebeling et al. 2007) may be used to automatically compute the rock-founded earth retaining structure's critical acceleration using the user defined geometry, retained soil and rock foundation properties (as well as the value for the structure's critical acceleration). Several popular slope stability software programs have the capability to compute the critical acceleration for an earthen slope/embankment. The computation of the critical acceleration is done prior to executing Newmark, when evaluating a structure for its permanent displacement to a single user-specified acceleration time-history. (Note that when using the software Newmark in this fashion for a slope/embankment, the acceleration time-history used is likely to an acceleration time-history recorded on a soil site.)

## 2.2 Time-history of permanent structural displacement

Earthquake shaking of the rock foundation is represented by time histories of acceleration in the translational block formulation implemented in program Newmark for the Complete Time-History Analysis.<sup>1</sup> Since the ground acceleration varies with time, let the horizontal ground acceleration be represented by variable fraction  $A$  times the constant acceleration of gravity  $g$  in Figure 1.5. Recall that the integral of the acceleration time-history is equal to the velocity time-history and the integral of velocity is displacement (i.e., the permanent structural displacement in this case). For a "rigid block" subjected to an acceleration of value larger than the Figure 1.5 maximum transmissible acceleration, labeled  $N \cdot g$  in this figure, the rigid block will displace. When this occurs over several time steps, the total permanent displacement of a sliding block relative to the base (i.e., the rock foundation) is the sum of the increments of displacement occurring during a number of individual

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<sup>1</sup> Baseline-corrected, horizontal acceleration time histories are to be used to represent the earthquake ground motions in program Newmark.

pulses of ground motion as shown in Figure 1.5. These incremental relative displacements are determined as follows: For each time the acceleration of the ground, equal to  $A$  times  $g$ , is greater than the constant  $N^*$  times  $g$  shown in this figure, relative displacements (between the structure's mass and the rock foundation) will initiate. The integral of the difference in velocities between the sliding rigid block and the rock foundation velocity is equal to the incremental, relative displacement of the sliding structural wedge.

This section describes the numerical method implemented within program Newmark to compute the translational time-history of a rigid block model of a structure during earthquake shaking for the Complete Time-History Analysis. It mirrors the numerical procedure used to compute the translational time-history of a rigid block model of a retaining wall structural wedge, implemented in CorpsWallSlip and implemented in CorpsWallRotate, which are used in the seismic displacement analysis of retaining walls. Their numerical procedures are discussed in Section 2.4 of Ebeling et al. (2007) and Section 4.4 of Ebeling and White (2006), respectively.

### 2.2.1 Introduction to a step-by-step solution scheme

Earthquake acceleration time histories are used to represent the earthquake demand in this formulation. They are specified within the rigid base of Figures 1.4 and 1.5. It is the experience of the primary author of this report that the duration of ground acceleration time histories used on Corps projects is on the order of tens of seconds, and up to about one minute of earthquake shaking. The number of time increments (i.e., discrete acceleration point values) contained in the acceleration time-history corresponds to the number of solutions made in the translational structural analysis by program Newmark. The number of time increments is defined by the duration of earthquake shaking and the time increment  $DT$  used in digitization of the acceleration time-history. There is no standard time increment  $DT$  for the digitization and subsequent processing of acceleration time histories for Corps projects. However, Ebeling et al. (1997a) observe that a  $DT$  equal to 0.02, 0.01, or 0.005 seconds is the most common. For example, an earthquake acceleration time-history with 40 seconds of shaking and a time step of 0.02 seconds will contain 2,000 discretized acceleration points. If the acceleration time-history was processed with a  $DT$  equal to 0.01 or 0.005 seconds, then the discretized acceleration time histories would contain 4,000, and 8,000 acceleration points, respectively.

A step-by-step solution scheme is followed in order to obtain the structure's permanent translational relative velocity,  $relV$ , and displacement,  $relD$ , in the time domain by program Newmark. An overview of the characteristics of this numerical formulation is depicted in Figure 2.1. A key feature of the numerical formulation used is the assumption of a linear variation in relative acceleration  $relA$  over time step  $DT$ , from time  $t_i$  to time  $t_{i+1}$ . Values of the user-provided ground acceleration (specified within the rigid base model) are compared against the critical acceleration (i.e., maximum transmissible acceleration or yield acceleration) value at each time step.

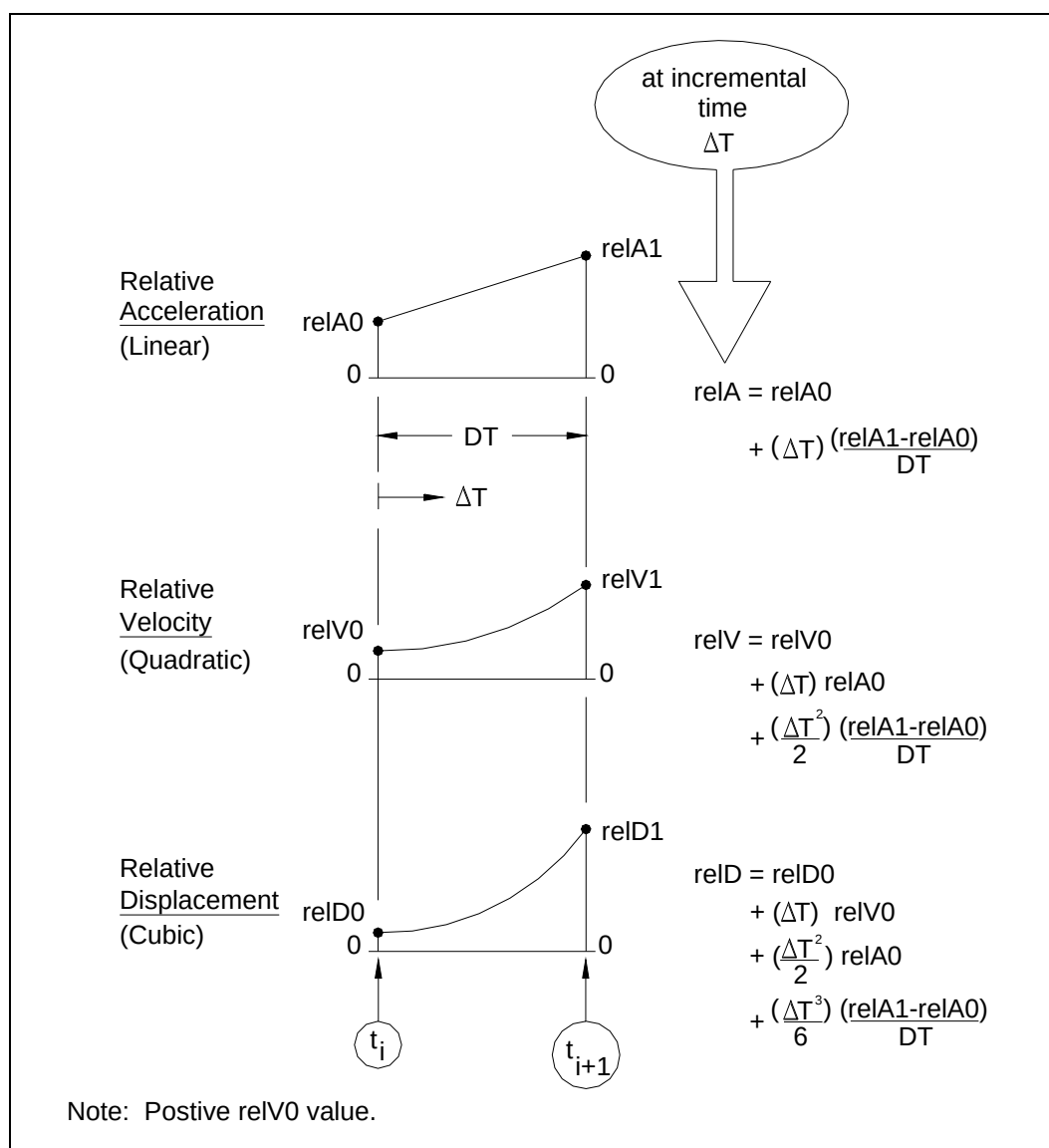


Figure 2.1. Complete equations for relative motions over time increment  $DT$  based on linearly varying acceleration.

This idealized figure assumes that the structure is undergoing positive relative acceleration (i.e., the value for acceleration of the ground is greater than the value of critical acceleration, positive relative velocity, and positive (permanent) displacement at time  $t_i$ , which continues through time  $t_{i+1}$ ). The relative acceleration values  $relA0$  and  $relA1$  are equal to the difference between the horizontal ground acceleration value minus the constant value of critical acceleration at times  $t_i$  and  $t_{i+1}$ , respectively, and are assumed positive at both time steps. (Other cases will be considered later.) The idealized figure also assumes that the relative acceleration increases in magnitude over this time step  $DT$ , as depicted in this figure. The relative velocity is computed by integrating the relative acceleration during each segment of structural translation.

$$relV = \int_0^t relA \, dt \quad \text{when } relV > 0 \quad (2.1)$$

or

$$relV = 0 \quad \text{when Equation 2.1 gives } relV \text{ less than } 0 \quad (2.2)$$

So, for a linear variation in relative acceleration over time step  $DT$ , the relative velocity,  $relV$ , is a quadratic relationship. Note that program Newmark assumes that the structure cannot slide backwards (i.e., it is impeded by the retained soil for an earth retaining structure or by the pool for a gravity dam, which is expressed by Equation 2.2. Similarly, with the permanent relative displacement of the structure being the integration of the relative velocity, the relative displacement of the structure is a cubic relationship, as listed in Figure 2.1. The permanent relative displacement of the structure is the integration of the relative velocity

$$relD = \int_0^t relV \, dt \quad (2.3)$$

This series of computations using relative accelerations and Equations 2.1 through 2.3 are repeated for each sequence of structural translations that occurs for the duration of earthquake shaking. The experience of the primary author of this report is that, when the acceleration time histories used as input to program Newmark are based on previously recorded earthquake events (a typical scenario), the permanent displacement occurs

during several, separate pulses occurring throughout the duration of shaking.

In Figure 2.1, the value for relative acceleration  $relA$ , relative velocity  $relV$  and (permanent structural) relative displacement  $relD$  at any point in time  $\Delta t$  after  $t_i$  and before time  $t_{i+1}$  are given by the linear, quadratic and cubic relationships contained on the right-hand side of these three figures (with  $\Delta t$  less than or equal to  $DT$ ).

Recall that during sliding, the acceleration felt by the structure equals the maximum transmissible acceleration. Thus, the sliding (rigid) block model effectively isolates the sliding block from the shaking (rigid) base below.

### 2.2.2 Positive relative accelerations $relA0$ and $relA1$ at times $t_i$ and $t_{i+1}$

Expanding on the details of the computations for the numerical formulation depicted in Figure 2.1, the computation of the relative acceleration,  $relA$ , relative velocity,  $relV$ , and relative displacement,  $relD$ , at time  $t_{i+1}$  are made as follows: values for  $relA$ ,  $relV$ ,  $relD$ , at time  $t_i$  are known from the previous computation step in the step-by-step solution scheme. The value for  $relA$  at time  $t_{i+1}$  (designated  $relA1$  in the figure) is computed as the difference between horizontal ground acceleration minus the constant value of critical acceleration. Referring to Figure 2.2, the relative velocity at time  $t_{i+1}$  (designated  $relV1$ ) is computed from the value for relative velocity at time  $t_i$  (designated  $relV0$ ) plus the positive area under the linear relative acceleration relationship over the time step  $DT$ , designated  $Area_a$  in this figure. By the trapezoidal rule,  $relV1$  at time  $t_{i+1}$  is

$$relV1 = relV0 + \frac{DT}{2} \bullet (relA0 + relA1) \quad (2.4)$$

with the values for  $relV0$  and  $relA0$  now being known values that were computed in the previous solution step. Note that the structure is in motion at time  $t_i$ , as reflected by a positive value for relative velocity (designated  $relV0$  in Figure 2.2). Similarly, the permanent relative structural displacement at time  $t_{i+1}$  (designated  $relD1$ ) is computed from the value for relative displacement at time  $t_i$  (designated  $relD0$ ) plus the positive area under the quadratic relative velocity relationship over the time step  $DT$ , designated  $Area_v$  in this figure. For this linear acceleration method,  $relD1$  at time  $t_{i+1}$  is

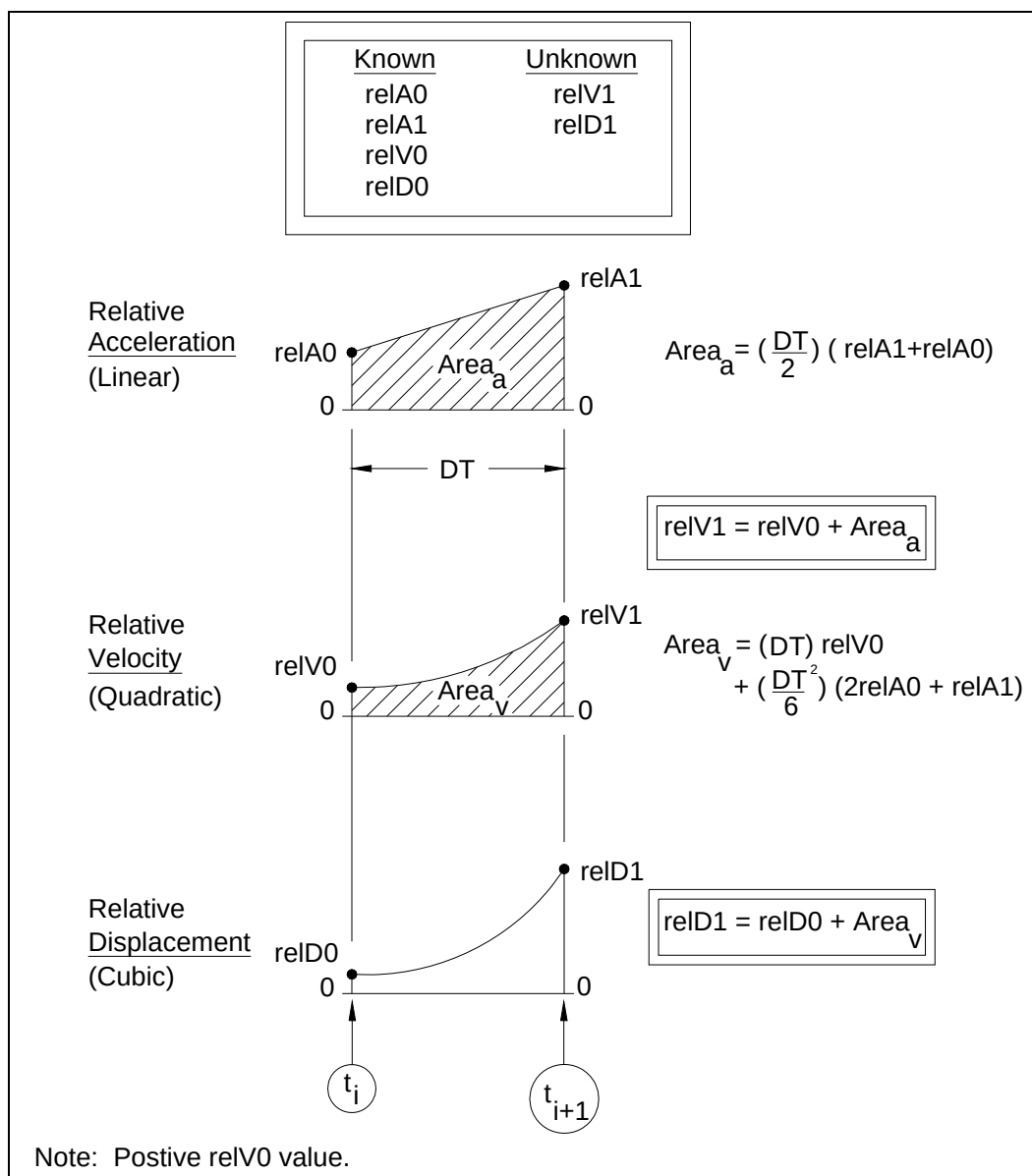


Figure 2.2. Relative Velocity and displacements at the end of time increment  $DT$  based on linearly varying relative acceleration.

$$relD1 = relD0 + DT \cdot relV0 + \frac{DT^2}{6} \cdot (2 \cdot relA0 + relA1) \quad (2.5)$$

with the value for  $relD0$  being a known value that was computed in the previous solution step. The values for relative velocity  $relV$  and (permanent structural) displacement  $relD$  at time  $t_{i+1}$  are also described in terms of the area relationships contained in Figure 2.2.

In this manor, a step-by-step solution scheme is followed throughout the entire time-history of earthquake shaking in order to obtain the structural

velocity,  $relV$ , and relative displacement,  $relD$ , at each increment in time in the Figure 2.2 case of positive values for  $relA$  at times  $t_i$  and  $t_{i+1}$ .

In summary, Figure 2.2 outlines a numerical procedure to obtain values for relative velocity and for relative displacement at time  $t_{i+1}$  in situations for which values of relative acceleration  $relA$  at times  $t_i$  and  $t_{i+1}$  are both positive.

However, there are three other situations that can arise during the step-by-step solution:

- The case of a negative value for  $relA$  at time  $t_i$  and a positive value for  $relA$  at time  $t_{i+1}$
- The case of structure decelerating over the entire time step  $DT$  for which the values of  $relA$  are negative at both times  $t_i$  and  $t_{i+1}$
- The case of a positive value for  $relA$  at time  $t_i$  and a negative value for  $relA$  at time  $t_{i+1}$ .

In all four cases, the assumption of **linear relative acceleration** over time step  $DT$  is made and the basic concept of **integrating** positive areas above and/or negative areas below the time-line of relative acceleration  $relA$  to obtain the change in relative velocity  $relV$  and then, in turn, the integration of positive and/or negative areas above and/or below the time-line of  $relV$  to obtain the change in relative displacement  $relD$  is used to determine the values for  $relV$  and  $relD$ , respectively, at time  $t_{i+1}$ . These three additional step-by-step solutions will be discussed next. Note the frequent use of the trapezoidal rule for  $relV$  and the linear acceleration method for  $relD$  in the solution processes to be described.

### 2.2.3 Positive relative acceleration $relA0$ at time $t_i$ and negative relative acceleration $relA1$ at $t_{i+1}$

Next, consider a structure in motion (i.e., with a positive value for  $relV$ ) at time  $t_i$  but with the Figure 2.3 case of a negative value for  $relA0$  computed at time step  $t_i$  and positive value for  $relA1$  computed at the next time step of  $t_{i+1}$ .<sup>1</sup> The first step is to determine the time instant  $[t_i \text{ plus } lhsDT]$  at which the relative acceleration  $relA$  is equal to zero, as labeled in the figure. By linear interpolation, this time increment  $lhsDT$  is

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<sup>1</sup> Note the assumption of a linear variation in relative acceleration over the time step  $DT$  in Figure 2.3.

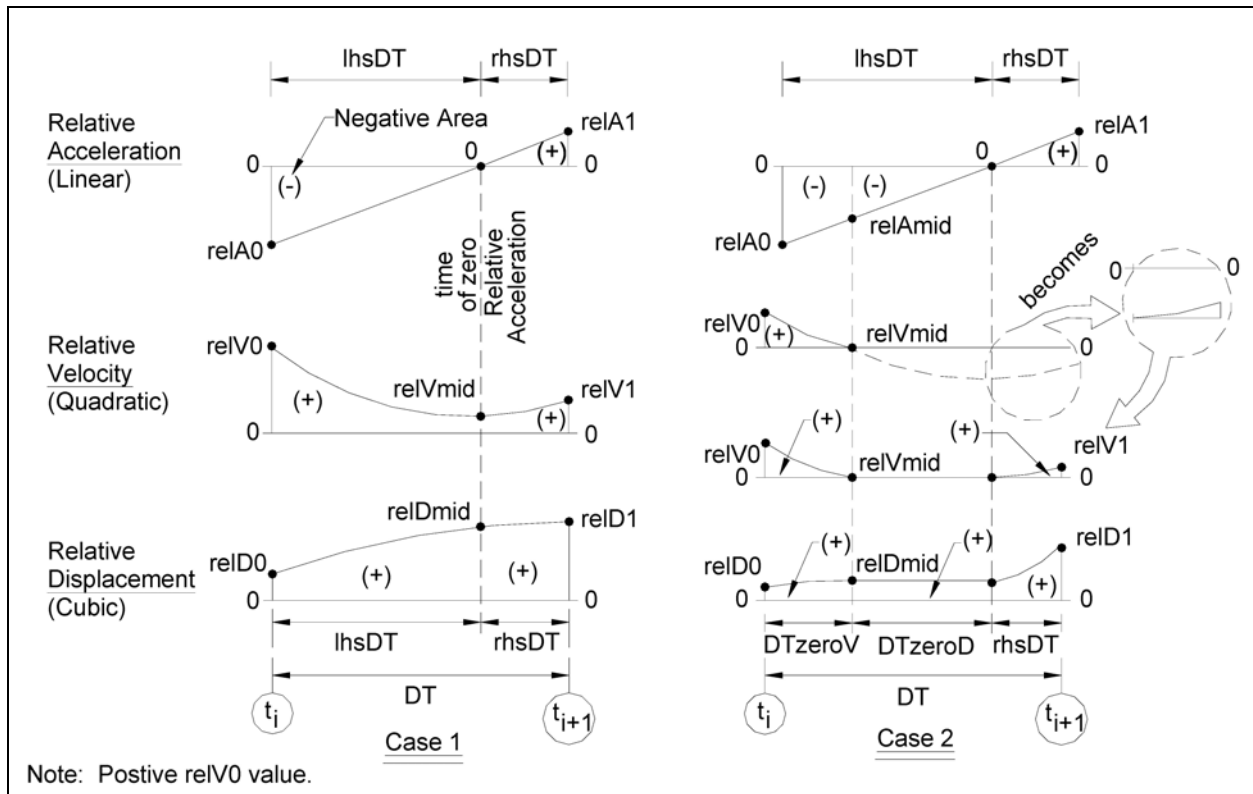


Figure 2.3. Two possible outcomes for the case of a negative relative acceleration at time  $t_i$  and a positive relative acceleration at time  $t_{i+1}$ .

$$lhsDT = \left| relA0 \cdot \left( \frac{DT}{relA1 - relA0} \right) \right| \quad (2.6)$$

The negative area between the negative portion of the linear acceleration line and the time-line over the Figure 2.3 time increment  $lhsDT$  is

$$NegativeArea_{-A+} = \frac{1}{2} \cdot lhsDT \cdot (relA0 + 0) \quad (2.7)$$

Recall that the structure is in motion at time  $t_i$  when relative velocity (designated  $relV0$  in the figure) is positive. There are two possible outcomes for the Figure 2.3 step-by-step numerical solutions for values of  $relV$  and of  $relD$  at time  $t_{i+1}$ , depending upon the magnitude of  $relV0$  relative to the magnitude of  $NegativeArea_{-A+}$ . These possible scenarios are depicted by two columns of figures in Figure 2.3, labeled as the Case 1 and Case 2 figure groups.

### 2.2.3.1 Case 1

This case results when the positive value for  $relV$  at time  $t_i$  is greater than the magnitude of  $NegativeArea_{-A+}$  (i.e., the negative area between the negative portion of the linear acceleration line and the time-line over the portion of the Figure 2.3 time increment labeled  $lhsDT$ ). The three left-hand side figures in Figure 2.3 are used to describe the Case 1 step-by-step solution scheme: The top figure describes the relative acceleration  $relA$ , the middle figure describes the relative velocity  $relV$ , and the lower figure describes the (permanent) relative structural displacement  $relD$ .

The top Case 1 figure depicts the case of a (labeled) negative triangular area between the linear relative deceleration  $relA$  line and the time-line (i.e.,  $NegativeArea_{-A+}$  by Equation 2.7), being of less magnitude than the positive value for relative velocity at time  $t_i$  (designated  $relV0$ ). Consequently, the structure will remain in displacement (i.e., sliding) during the entire time step  $DT$ . At the increment in time  $lhsDT$  after time  $t_i$ , a portion of the negative deceleration area reduces the value of relative velocity from the positive value of magnitude  $relV0$  at time  $t_i$  to a smaller magnitude value at time  $[t_i \text{ plus } lhsDT]$ , as shown in this figure. The relative velocity at time  $[t_i \text{ plus } lhsDT]$  is

$$relVmid = relV0 + \frac{1}{2} \bullet lhsDT \bullet (relA0 + 0) \quad (2.8)$$

The change in relative displacement from time  $t_i$  to time  $[t_i \text{ plus } lhsDT]$  is equal to the labeled positive area between the quadratic relative velocity curve and the time-line. At time  $[t_i \text{ plus } lhsDT]$  the relative structural displacement increases in magnitude from  $relD0$  to  $relDmid$ .

$$relDmid = relD0 + lhsDT \bullet relV0 + \frac{(lhsDT)^2}{6} \bullet (2 \bullet relA0 + 0) \quad (2.9)$$

The structure continues in motion, with positive relative velocity and with additional permanent deformation after time  $[t_i \text{ plus } lhsDT]$  when the relative acceleration of the structure is positive. At time  $[t_i \text{ plus } lhsDT]$  the magnitude of structure's relative velocity begins to increase in magnitude as a result of the positive relative acceleration of the structure. The positive (labeled) triangular area between the time-line and the linear acceleration line, shown in the top Case 1 figure, equals the change in relative velocity

and for the structure, consequently, the value for relative velocity at time  $t_{i+1}$  (labeled  $relV1$  in the Case 1 middle figure) is

$$relV1 = relVmid + \frac{1}{2} \bullet rhsDT \bullet (0 + relA1) \quad (2.10)$$

The change in structural displacement from time  $[t_i \text{ plus } lhsDT]$  to time  $t_{i+1}$  is equal to the integral of the positive relative velocity of the middle  $relV$ -figure. The permanent structural displacement increases in value from  $relDmid$  to  $relD1$ , as depicted in the bottom figure.

$$relD1 = relDmid + rhsDT \bullet relVmid + \frac{(rhsDT)^2}{6} \bullet (2 \bullet 0 + relA1) \quad (2.11)$$

### 2.2.3.2 Case 2

This case results when the positive value for relative velocity at time  $t_i$  is less than the magnitude of  $NegativeArea_{-A+}$  (i.e., the negative area between the negative portion of the linear acceleration line and the time-line over the portion of the Figure 2.3 time increment labeled  $lhsDT$ ). The four right-hand side figures in Figure 2.3 are used to describe the Case 2 step-by-step solution scheme. From the top to bottom, one figure describes the relative acceleration, two figures describe the relative velocity, and one figure describes the permanent relative structural displacement.

The top, right-hand side, Case 2 figure depicts the case of a (labeled) negative triangular area between the linear relative deceleration line and the time-line, being of greater magnitude than the positive value for relative velocity at time  $t_i$  (designated  $relV0$ ). Consequently, the structure will come to rest before time  $t_{i+1}$  is achieved. At an increment in time  $DTzeroV$  after time  $t_i$ , a portion of the negative deceleration area reduces the value of relative velocity from the positive value of magnitude  $relV0$  at time  $t_i$  to a value of 0 at time  $[t_i \text{ plus } DTzeroV]$ , as shown in this figure. At time  $[t_i \text{ plus } DTzeroV]$  the relative acceleration is

$$relA_{mid} = DTzeroD \bullet \left( \frac{relA0}{lhsDT} \right) \quad (2.12)$$

where  $DTzeroD$  is the time increment shown in Figure 2.3. The Figure 2.3 negative (relative) deceleration area below time increment  $DTzeroV$  is

$$AreaTrapezoid_{-A+} = \frac{1}{2} \bullet DTzeroV \bullet (relAO + relAmid) \quad (2.13)$$

The Figure 2.3 negative relative deceleration area below time increment  $DTzeroD$  is

$$AreaTriangle_{-A+} = \frac{1}{2} \bullet DTzeroD \bullet (relAmid + 0) \quad (2.14)$$

Thus, the total Figure 2.3 negative relative deceleration area below time increment  $lhsDT$  is

$$NegativeArea_{-A+} = AreaTrapezoid_{-A+} + AreaTriangle_{-A+} \quad (2.15)$$

The relative velocity at time  $[t_i \text{ plus } DTzeroV]$  is

$$relVmid = relV0 + AreaTrapezoid_{-A+} \quad (2.16)$$

With a value for  $relVmid$  equal to zero, Equation 2.16 becomes

$$0 = relV0 + AreaTrapezoid_{-A+} \quad (2.17)$$

Expanding by adding the term  $AreaTriangle_{-A+}$  to both sides, Equation 2.17 becomes

$$AreaTriangle_{-A+} = relV0 + AreaTrapezoid_{-A+} + AreaTriangle_{-A+} \quad (2.18)$$

Which by introducing Equation 2.15, becomes

$$AreaTriangle_{-A+} = relV0 + NegativeArea_{-A+} \quad (2.19)$$

Introducing Equations 2.14 and 2.12 and solving for  $DTzeroD$ , Equation 2.19 becomes

$$DTzeroD = \sqrt{2 \bullet \left( \frac{lhsDT}{relAO} \right) \bullet (relV0 + NegativeArea_{-A+})} \quad (2.20)$$

Recognizing the time increment  $lhsDT$  is equivalent to

$$lhsDT = DTzeroV + DTzeroD \quad (2.21)$$

and by introducing Equations 2.21 and 2.13 into Equation 2.20 and solving for  $DTzeroV$ ,

$$DTzeroV = lhsDT - \sqrt{2 \bullet \left( \frac{lhsDT}{relA0} \right) \bullet (relV0 + NegativeArea_{-A+})} \quad (2.22)$$

The change in relative displacement from time  $t_i$  to time  $[t_i \text{ plus } DTzeroV]$  is equal to the labeled positive area between the quadratic relative velocity curve and the time-line. At time  $[t_i \text{ plus } DTzeroV]$  the structural displacement increases in magnitude from  $relD0$  to  $relDmid$ . The relative velocity at time  $[t_i \text{ plus } DTzeroV]$ , expressed in terms of  $DTzeroV$ , is

$$relVmid = relV0 + \frac{1}{2} \bullet DTzeroV \bullet (relA0 + relA_{mid}) \quad (2.23)$$

with the relative acceleration at time  $[t_i \text{ plus } DTzeroV]$  equal to

$$relA_{mid} = relA0 + \left( \frac{relA1 - relA0}{DT} \right) \bullet DTzeroV \quad (2.24)$$

The change in relative displacement from time  $t_i$  to time  $[t_i \text{ plus } DTzeroV]$  is equal to the labeled positive area between the quadratic relative velocity curve and the time-line. At time  $[t_i \text{ plus } DTzeroV]$  the structural displacement increases in magnitude from  $relD0$  to  $relDmid$ .

$$\begin{aligned} relDmid = relD0 + DTzeroV \bullet relV0 \\ + \frac{(DTzeroV)^2}{6} \bullet (2 \bullet relA0 + relA_{mid}) \end{aligned} \quad (2.25)$$

The structure remains at rest with zero relative velocity and with no additional permanent relative displacement from time  $[t_i \text{ plus } DTzeroV]$  until time  $[t_i \text{ plus } lhsDT]$  when the relative acceleration of the structure begins (again). At time  $[t_i \text{ plus } lhsDT]$  the structure begins to develop further permanent displacement as a result of the positive relative reacceleration of the structure. The positive (labeled) triangular area between the

time-line and the linear relative acceleration line, shown in the right-hand side of the top figure, equals the change in relative velocity and with the structure at rest, consequently, the value for relative velocity at time  $t_{i+1}$  (labeled  $relV1$  in the lower relative velocity figure) is

$$relV1 = \frac{1}{2} \bullet rhsDT \bullet (0 + relA1) \quad (2.26)$$

The change in structural displacement from time  $[t_i \text{ plus } lhsDT]$  to time  $t_{i+1}$  is equal to the integral of the positive relative velocity, as depicted in the middle two, right-hand side  $relV$ -figures. The top  $relV$  figure is a computational figure, and the bottom  $relV$  figure is the  $relV$  curve-shift figure that properly accounts for zero structural relative velocity over time increment  $DT_{zeroD}$ , with an insert detailed, curve-shift figure for  $relV$  shown of this computational  $relV$  figure in Figure 2.3. The permanent relative structural displacement increases in value from  $relDmid$  to  $relD1$ , as depicted in the bottom figure.

$$relD1 = relDmid + rhsDT \bullet 0 + \frac{(rhsDT)^2}{6} \bullet (2 \bullet 0 + relA1) \quad (2.27)$$

#### 2.2.4 Negative relative accelerations $relA0$ and $relA1$ at times $t_i$ and $t_{i+1}$

Next, consider a structure in motion (i.e., with a positive value for relative velocity) at time  $t_i$  but with the Figure 2.4 case of a negative values for relative acceleration computed at time steps  $t_i$  and  $t_{i+1}$ .<sup>1</sup>

The first step is to determine if the structure, which is in motion at time  $t_i$ , comes to rest during the time step  $DT$ .

The negative area between the negative portion of the linear acceleration line and the time-line over the Figure 2.4 time increment  $DT$  is

$$NegativeArea_{-A-} = \frac{1}{2} \bullet DT \bullet (relA0 + relA1) \quad (2.28)$$

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<sup>1</sup> Again, note the assumption of a linear variation in relative acceleration over the time step  $DT$  shown in Figure 2.4.

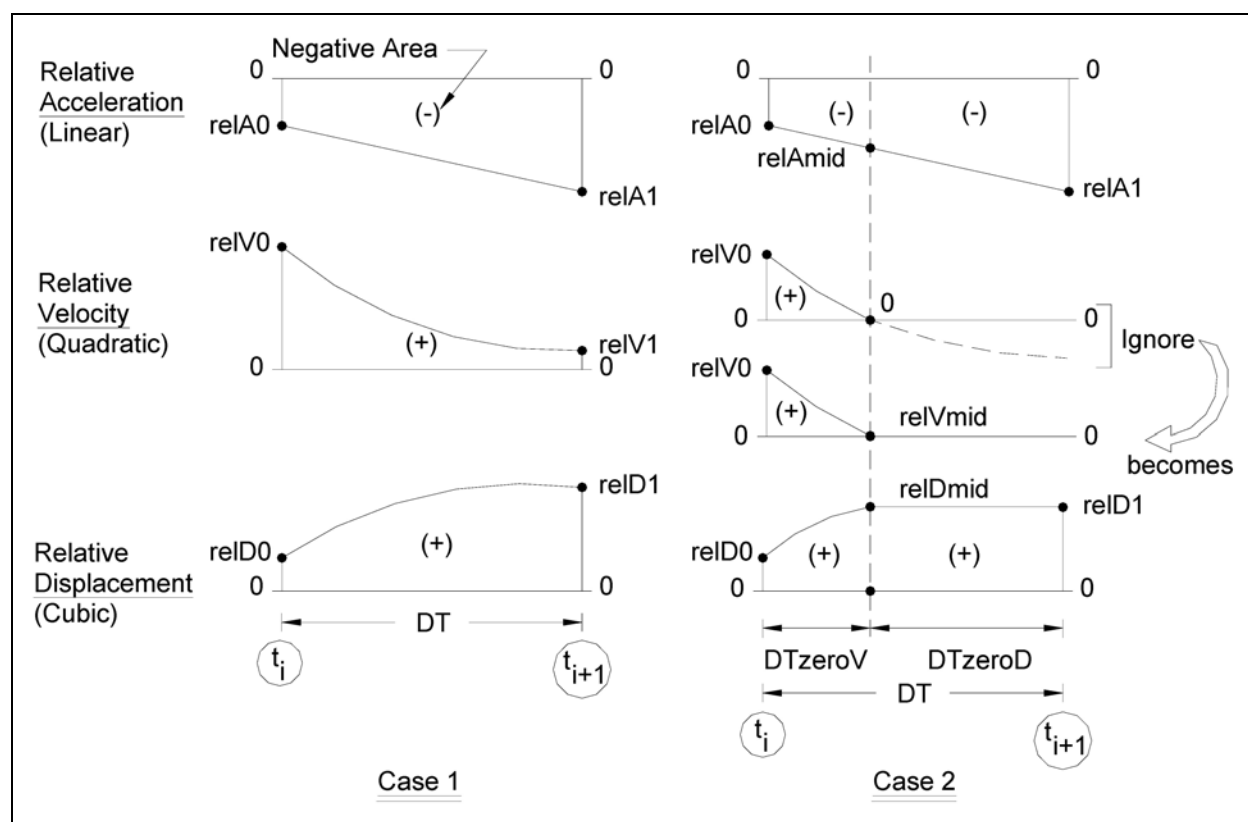


Figure 2.4. Two possible outcomes for the case of negative relative accelerations at times  $t_i$  and  $t_{i+1}$ .

There are two possible outcomes for the Figure 2.4 step-by-step numerical solution for relative velocity and relative displacement at time  $t_{i+1}$ , depending upon the magnitude of  $relV0$  relative to the magnitude of Equation 2.28  $NegativeArea_{-A-}$ . These possible scenarios are depicted by two columns of figures in Figure 2.4, labeled as Case 1 and Case 2 figure groups.

#### 2.2.4.1 Case 1

This case results when the positive value for relative velocity at time  $t_i$  is greater than the magnitude of  $NegativeArea_{-A-}$  (i.e., the negative area between the negative portion of the linear acceleration line and the time-line over the Figure 2.4 time step  $DT$ ). The three left-hand side figures in Figure 2.4 are used to describe the Case 1 step-by-step solution scheme: The top figure describes the relative acceleration, the middle figure describes the relative velocity, and the lower figure describes the permanent relative structural displacement.

The top Case 1 figure depicts the case of a (labeled) negative area between the linear relative deceleration line and the time-line (i.e.,  $NegativeArea_{-A}$  by Equation 2.28), being of less magnitude than the positive value for relative velocity at time  $t_i$  (designated  $relV0$ ). Consequently, the structure will remain in motion during the entire time step  $DT$ . At the time step  $DT$  after time  $t_i$ , the negative deceleration area reduces the value of relative velocity from the positive value of magnitude  $relV0$  at time  $t_i$  to a smaller magnitude value at time  $[t_i \text{ plus } DT]$ , as shown in this figure. The relative velocity at time  $[t_i \text{ plus } DT]$  is

$$relV1 = relV0 + \frac{1}{2} \bullet DT \bullet (relA0 + relV1) \quad (2.29)$$

The change in relative displacement from time  $t_i$  to time  $[t_i \text{ plus } DT]$  is equal to the labeled positive area between the quadratic relative velocity curve and the time-line. At time  $[t_i \text{ plus } DT]$  the structural displacement increases in magnitude from  $relD0$  to  $relD1$ .

$$relD1 = relD0 + DT \bullet relV0 + \frac{(DT)^2}{6} \bullet (2 \bullet relA0 + relA1) \quad (2.30)$$

#### 2.2.4.2 Case 2

This case results when the positive value for relative velocity at time  $t_i$  is less than the magnitude of  $NegativeArea_{-A}$  (i.e., the negative area between the negative portion of the linear acceleration line and the time-line over the portion of the Figure 2.4 time increment labeled  $lhsDT$ ). The four right-hand side figures in Figure 2.4 are used to describe the Case 2 step-by-step solution scheme. From the top to bottom, one figure describes the relative acceleration, two figures describe the relative velocity, and one figure describes the permanent relative structural displacement.

The top, right-hand side, Case 2 figure depicts the case of a (labeled) negative area between the linear relative deceleration line and the time-line (i.e.,  $NegativeArea_{-A}$  by Equation 2.28), being of greater magnitude than the positive value for relative velocity at time  $t_i$  (designated  $relV0$ ). Consequently, the structure will come to rest before time  $t_{i+1}$  is achieved. At an increment in time  $DT_{zeroV}$  after time  $t_i$ , a portion of the negative deceleration area reduces the value of relative velocity from the positive

value of magnitude  $relV0$  at time  $t_i$  to a value of 0 at time  $[t_i \text{ plus } DTzeroV]$ , as shown in this figure. At time  $[t_i \text{ plus } DTzeroV]$  the relative acceleration is

$$relA_{mid} = relA0 + DTzeroV \cdot \left( \frac{relA1 - relA0}{DT} \right) \quad (2.31)$$

where  $DTzeroV$  is the time increment shown in Figure 2.4. The Figure 2.4 negative relative deceleration area below time increment  $DTzeroV$  is

$$AreaTrapezoid_{-A-} = \frac{1}{2} \cdot DTzeroV \cdot (relA0 + relA_{mid}) \quad (2.32)$$

Introducing Equation 2.31, Equation 2.32 becomes

$$AreaTrapezoid_{-A-} = \left\{ \begin{array}{l} \frac{1}{2} \cdot DTzeroV \cdot relA0 \\ + \frac{DTzeroV}{2} \\ \cdot \left[ relA0 + DTzeroV \cdot \left( \frac{relA1 - relA0}{DT} \right) \right] \end{array} \right\} \quad (2.33)$$

This simplifies to

$$AreaTrapezoid_{-A-} = DTzeroV \cdot relA0 + \frac{(DTzeroV)^2}{2} \cdot \left( \frac{relA1 - relA0}{DT} \right) \quad (2.34)$$

The change in rotation from time  $t_i$  to time  $[t_i \text{ plus } DTzeroV]$  is equal to the labeled positive area between the quadratic relative velocity curve and the time-line. At time  $[t_i \text{ plus } DTzeroV]$  the structural displacement increases in magnitude from  $relD0$  to  $relD_{mid}$ . The relative velocity at time  $[t_i \text{ plus } DTzeroV]$  is

$$relV_{mid} = relV0 + AreaTrapezoid_{-A-} \quad (2.35)$$

With a value for  $relV_{mid}$  equal to zero, Equation 2.35 becomes

$$0 = \left[ \frac{1}{2} \bullet \left( \frac{relA1 - relA0}{DT} \right) \right] \bullet (DTzeroV)^2 + relA0 \bullet DTzeroV + relV0 \quad (2.36)$$

This quadratic equation has a general solution of

$$DTzeroV = \frac{-relA0 \pm \sqrt{(relA0)^2 - 4 \bullet \left[ \frac{1}{2} \bullet \left( \frac{relA1 - relA0}{DT} \right) \right] \bullet relV0}}{2 \bullet \left[ \frac{1}{2} \bullet \left( \frac{relA1 - relA0}{DT} \right) \right]} \quad (2.37)$$

Even though this solution provides for two possible values for  $DTzeroV$ , only the positive value is assigned to  $DTzeroV$  in program Newmark.

The change in displacement from time  $t_i$  to time  $[t_i \text{ plus } DTzeroV]$  is equal to the labeled positive area between the quadratic relative velocity curve and the time-line. At time  $[t_i \text{ plus } DTzeroV]$  the relative structural displacement increases in magnitude from  $relD0$  to  $relDTmid$ .

$$relDmid = relD0 + DTzeroV \bullet relV0 + \frac{(DTzeroV)^2}{6} \bullet (2 \bullet relA0 + relA_{mid}) \quad (\text{bis 2.25})$$

The structure remains at rest with zero relative velocity and with no additional permanent displacement from time  $[t_i \text{ plus } DTzeroV]$  until time  $[t_i \text{ plus } DT]$ . Consequently, at time  $t_{i+1}$  the permanent relative structural displacement is constant, as depicted in the bottom figure.

$$relD1 = relDmid \quad (2.38)$$

with the value for  $relDmid$  given by Equation 2.25.

### 2.2.5 Positive relative acceleration $relA0$ at time $t_i$ and negative relative acceleration $relA1$ at $t_{i+1}$

Next, consider a structure in motion (i.e., with a positive value for relative velocity) at time  $t_i$ , but with the Figure 2.5 case of a positive value for relative acceleration at time step  $t_i$  and negative value for relative acceleration

at the next time step of  $t_{i+1}$ .<sup>1</sup> The first step is to determine the time instant  $[t_i \text{ plus } lhsDT]$  at which the relative acceleration is equal to zero, as labeled in the figure. By linear interpolation, this time increment  $lhsDT$  is

$$lhsDT = \left| relA0 \bullet \left( \frac{DT}{relA1 - relA0} \right) \right| \quad (\text{bis 2.6})$$

The positive area between the positive portion of the linear acceleration line and the time-line over the Figure 2.5 time increment  $lhsDT$  is

$$PositiveArea_{+A-} = \frac{1}{2} \bullet lhsDT \bullet (relA0 + 0) \quad (2.39)$$

The Figure 2.5 time increment  $rhsDT$  is given by

$$rhsDT = DT - lhsDT \quad (2.40)$$

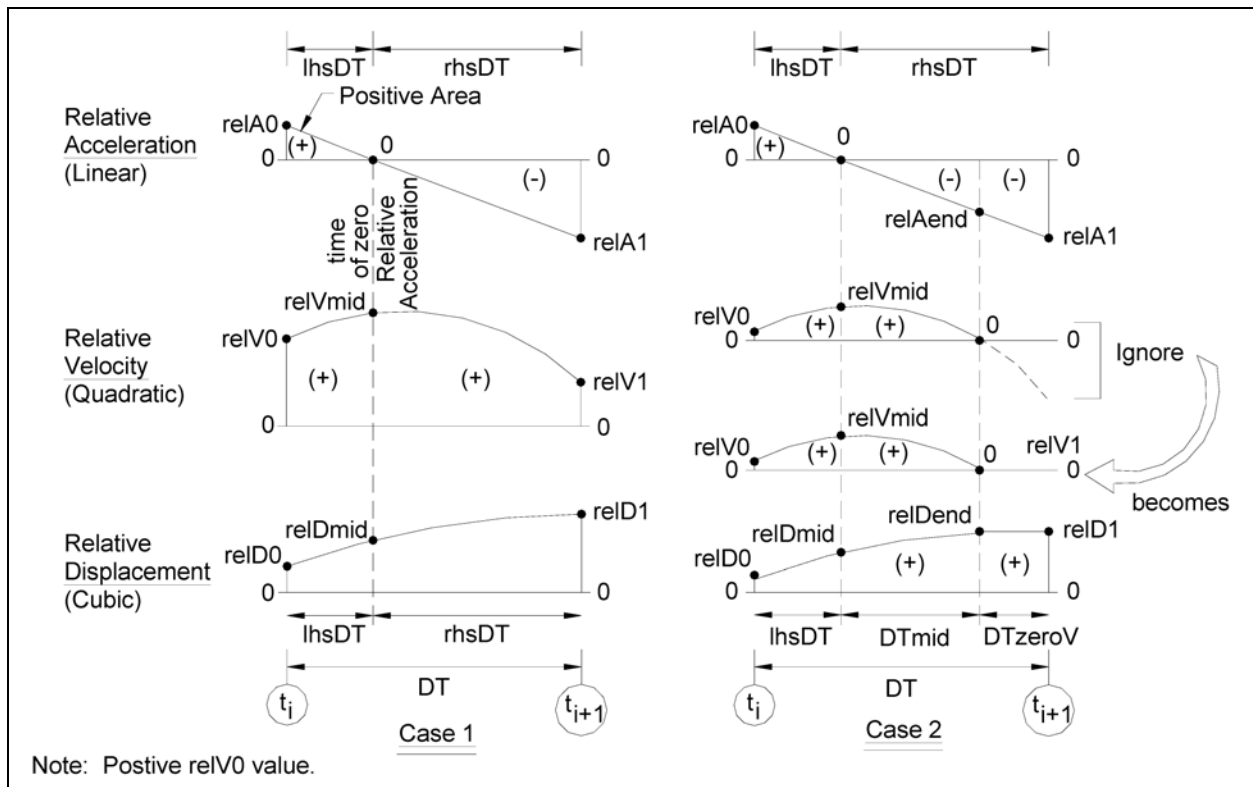


Figure 2.5. Two possible outcomes for the case of a positive relative acceleration at time  $t_i$  and a negative relative acceleration at time  $t_{i+1}$ .

<sup>1</sup> Again, observe the assumption of a linear variation in relative acceleration over the time step  $DT$  shown in Figure 2.5.

The negative area between the negative portion of the linear acceleration line and the time-line over the Figure 2.5 time increment  $rhsDT$  is

$$NegativeArea_{+A-} = \frac{1}{2} \bullet rhsDT \bullet (0 + relA1) \quad (2.41)$$

There are two possible outcomes for the Figure 2.5 step-by-step numerical solution for relative velocity and relative displacement at time  $t_{i+1}$ , depending upon the magnitude of  $relV0$  relative to the magnitude of the sum of the  $PositiveArea_{+A-}$  plus the  $NegativeArea_{+A-}$ . These possible scenarios are depicted by two columns of figures in Figure 2.5, labeled as Case 1 and Case 2 figure groups.

#### 2.2.5.1 Case 1

This case results if the  $NegativeArea_{+A-}$  exceeds  $PositiveArea_{+A-}$  but the positive value for relative velocity at time  $t_i$  is greater than the magnitude of the negative sum of  $PositiveArea_{+A-}$  plus  $NegativeArea_{+A-}$ , or if the  $NegativeArea_{+A-}$  is less than  $PositiveArea_{+A-}$ , consequently, the positive value for  $relV0$  at time  $t_i$  will increase to a larger value of  $relV1$  at time  $t_{i+1}$  (with an increase equal to the positive sum of  $PositiveArea_{+A-}$  plus  $NegativeArea_{+A-}$ ). The three left-hand side figures in Figure 2.5 are used to describe the Case 1 step-by-step solution scheme: The top figure describes the relative acceleration, the middle figure describes the relative velocity, and the lower figure describes the permanent relative structural displacement.

The top Case 1 figure depicts the case of a structure sliding during the entire time step  $DT$  because either the  $NegativeArea_{+A-}$  exceeds  $PositiveArea_{+A-}$  but the positive value for relative velocity at time  $t_i$  is greater than the magnitude of the sum of  $PositiveArea_{+A-}$  plus  $NegativeArea_{+A-}$ , or because the  $NegativeArea_{+A-}$  is less than  $PositiveArea_{+A-}$ . At the increment in time  $lhsDT$  after time  $t_i$ , the positive acceleration area increases the value of relative velocity from the positive value of magnitude  $relV0$  at time  $t_i$  to a larger magnitude value at time  $[t_i \text{ plus } lhsDT]$ , as shown in this figure. The relative velocity at time  $[t_i \text{ plus } lhsDT]$  is

$$relVmid = relV0 + \frac{1}{2} \bullet lhsDT \bullet (relA0 + 0) \quad (\text{bis 2.8})$$

The change in displacement from time  $t_i$  to time  $[t_i \text{ plus } lhsDT]$  is equal to the labeled positive area between the quadratic relative velocity curve and the time-line. At time  $[t_i \text{ plus } lhsDT]$  the structural displacement increases in magnitude from  $relD0$  to  $relDmid$ .

$$relDmid = relD0 + lhsDT \bullet relV0 + \frac{(lhsDT)^2}{6} \bullet (2 \bullet relA0 + 0) \quad (\text{bis 2.9})$$

The structure continues in motion, with positive relative velocity and with additional permanent relative displacement after time  $[t_i \text{ plus } lhsDT]$ , when the relative acceleration of the structure is positive. At time  $[t_i \text{ plus } lhsDT]$ , the magnitude of the structure's relative velocity begins to decrease in magnitude as a result of the relative deceleration of the structure. The negative (labeled) triangular area between the time-line and the linear relative deceleration line, shown in the top Case 1 figure, equals the change in relative velocity and for the structure. Consequently, the value for relative velocity at time  $t_{i+1}$  (labeled  $relV1$  in the Case 1 middle figure) is

$$relV1 = relVmid + \frac{1}{2} \bullet rhsDT \bullet (0 + relA1) \quad (\text{bis 2.10})$$

The change in structural displacement from time  $[t_i \text{ plus } lhsDT]$  to time  $t_{i+1}$  is equal to the integral of the positive relative velocity of the middle  $relV$ -figure. The permanent relative structural displacement increases in value from  $relDmid$  to  $relD1$ , as depicted in the bottom figure.

$$relD1 = relDmid + rhsDT \bullet relVmid + \frac{(rhsDT)^2}{6} \bullet (2 \bullet 0 + relA1) \quad (\text{bis 2.11})$$

#### 2.2.5.2 Case 2

This case results when the  $NegativeArea_{+A-}$  exceeds  $PositiveArea_{+A-}$  and the positive value for relative velocity at time  $t_i$  is less than the magnitude of the sum of  $PositiveArea_{+A-}$  plus  $NegativeArea_{+A-}$ . The four right-hand side figures in Figure 2.5 are used to describe the Case 2 step-by-step solution scheme. From the top to bottom, one figure describes the relative acceleration, two figures describe the relative velocity, and one figure describes the permanent relative structural displacement.

The top, right-hand side, Case 2 figure depicts the case of the sum of a (labeled) positive triangular area between the linear relative deceleration line and the time-line (i.e.,  $PositiveArea_{+A-}$  by Equation 2.39) plus a (labeled) negative triangular area between the linear relative deceleration line and the time-line (i.e.,  $NegativeArea_{+A-}$  by Equation 2.41), being negative and of greater magnitude than the positive value for relative velocity at time  $t_i$  (designated  $relV0$ ). Consequently, the structure will come to rest before time  $t_{i+1}$  is achieved.

At time  $[t_i \text{ plus } lhsDT]$ , the structure's relative velocity increases in magnitude from  $relV0$  to  $relVmid$ . The relative velocity at time  $[t_i \text{ plus } lhsDT]$  is

$$relVmid = relV0 + \frac{1}{2} \bullet lhsDT \bullet (relA0 + 0) \quad (\text{bis 2.8})$$

with the relative acceleration at time  $[t_i \text{ plus } lhsDT]$  equal to zero.

The change in displacement from time  $t_i$  to time  $[t_i \text{ plus } lhsDT]$  is equal to the labeled positive area between the quadratic relative velocity curve and the time-line. At time  $[t_i \text{ plus } lhsDT]$ , the structural displacement increases in magnitude from  $relD0$  to  $relDmid$ .

$$relDmid = relD0 + lhsDT \bullet relV0 + \frac{(lhsDT)^2}{6} \bullet (2 \bullet relA0 + 0) \quad (2.42)$$

At an increment in time  $[lhsDT + DTmid]$  after time  $t_i$ , a portion of the negative deceleration area reduces the value of relative velocity from the positive value of magnitude  $relVmid$  at time  $[t_i \text{ plus } lhsDT]$  to a value of 0 at time  $[t_i \text{ plus } (lhsDT + DTmid)]$ , as shown in this figure. At time  $[t_i \text{ plus } (lhsDT + DTmid)]$ , the relative acceleration is

$$relAend = DTmid \bullet \left( \frac{relA1}{rhsDT} \right) \quad (2.43)$$

where  $DTmid$  is the time increment shown in Figure 2.5. The Figure 2.5 negative relative acceleration area below time increment  $DTmid$  is

$$AreaTriangle_{+A-} = \frac{1}{2} \bullet DTmid \bullet (0 + relAend) \quad (2.44)$$

The Figure 2.5 negative relative acceleration area below time increment  $DT_{zeroV}$  is

$$AreaTrapezoid_{+A-} = \frac{1}{2} \bullet DT_{zeroV} \bullet (relA_{end} + relA1) \quad (2.45)$$

Thus, the total Figure 2.5 negative relative acceleration area below time increment  $rhsDT$  is

$$NegativeArea_{+A-} = AreaTrapezoid_{+A-} + AreaTriangle_{+A-} \quad (2.46)$$

With the relative velocity at time  $[t_i \text{ plus } (lhsDT + DT_{mid})]$  equal to zero,

$$0 = relV_{mid} + AreaTriangle_{+A-} \quad (2.47)$$

By introducing Equations 2.8, 2.39, 2.43, and 2.44, and solving for  $DT_{mid}$ , Equation 2.47 becomes

$$DT_{mid} = \sqrt{-2 \bullet \left( \frac{rhsDT}{relA1} \right) \bullet (relV0 + PositiveArea_{+A-})} \quad (2.48)$$

At time  $[t_i \text{ plus } (lhsDT + DT_{mid})]$ , the relative structural displacement comes to rest with

$$\begin{aligned} relD_{end} &= relD_{mid} + DT_{mid} \bullet relV_{mid} \\ &+ \frac{(DT_{mid})^2}{6} \bullet (2 \bullet 0 + relA_{end}) \end{aligned} \quad (2.49)$$

The structure remains at rest with zero relative velocity and with no additional permanent relative displacement from time  $[t_i \text{ plus } (lhsDT + DT_{mid})]$  until time  $t_{i+1}$ . The permanent relative structural displacement at this time  $t_{i+1}$  is

$$relD1 = relD_{end} \quad (2.50)$$

### 2.2.6 Starting the program Newmark analysis and the initiation of structural translation during a $DT$ time step

**Start of the step-by-step time-history analysis:** The numerical formulation used in the step-by-step time-history analysis by program Newmark assumes that the structure is at rest at the start of the analysis (i.e., at time  $t_i$  equal to 0 and with  $i = 1$ ). Consequently, relative acceleration, relative velocity and relative displacement are equal to zero as an initial boundary condition at the first time step (i.e., with  $i = 1$ ). Recall the relative acceleration at time  $t_i$  is equal to the difference between the horizontal ground acceleration value at time  $t_i$  minus the constant value of critical acceleration (i.e., maximum transmissible acceleration or yield acceleration).

**Initiation of structural displacement during the first  $DT$  time step:** At the end of the first  $DT$  time step, at time increment  $t_2$  (i.e.,  $t_{i+1}$  and with  $i = 1$  so the subscript  $i + 1$  becomes 2), a relative acceleration value is computed by program Newmark. If a positive value for relative acceleration is computed at time increment  $t_2$  then the system is in motion (i.e., sliding) during this first time step  $DT$ .

However, if a negative value for relative acceleration is computed and the system has been at rest and with zero relative acceleration at time  $t_i = 0$  (i.e.,  $t_i$  and for  $i = 1$ ) then the system is at rest at time  $t_2$ . This means that the correct value for relative acceleration is zero at time  $t_2$ .

**Initiation of structural displacement during a  $DT$  time step:** A structure is at rest at the beginning of any  $DT$  time step (designated time  $t_i$  in Figures 2.1 through 2.5) when relative velocity and relative displacement are equal to zero. At all  $DT$  time steps other than the first time step, the values at time  $t_i$  for relative acceleration, relative velocity and relative displacement were computed during the previous time step and then assigned as known values for this next time step. The step-by-step numerical procedure implemented in program Newmark allows for structural displacement to initiate during any  $DT$  time step during earthquake shaking. This will occur for a structure at rest at time  $t_i$ , i.e., the start of the time step, when a positive value is computed for relative acceleration at time  $t_{i+1}$ . The numerical procedure outlined in Figure 2.2 allows for the computation of relative velocity and relative displacement at time  $t_{i+1}$  for this case.

### 2.2.7 Cessation of structural translation

A structure is in motion at the start of any  $DT$  time step (designated time  $t_i$  in Figures 2.1 through 2.5) when relative velocity (i.e.,  $relV$ ) is nonzero. The step-by-step numerical procedure implemented in program Newmark allows for structural translation (i.e., sliding) to terminate during any  $DT$  time step during earthquake shaking. This occurs when the deceleration of the structure is sufficiently large during time step  $DT$ . The applicable numerical procedures are labeled as Case 2 in Figures 2.4 and 2.5.

In the case of structural translation decelerating and with negative values for relative acceleration at times  $t_i$  and  $t_{i+1}$  during time step  $DT$ , the relative velocity at time  $t_{i+1}$  (designated  $relV1$ ) and the relative structural displacement at time  $t_{i+1}$  (designated  $relD1$ ) are made using the Case 2 approach outlined in Figure 2.4. Note the relative velocity reduces to zero at a time increment  $DTzeroV$  after time  $t_i$ . The structure remains at rest and with zero relative velocity over time increment  $DTzeroD$ , as shown in this figure.

In the case of structural translation decelerating and with a positive value for relative acceleration at time  $t_i$  and a negative value for relative acceleration at time  $t_{i+1}$  during time step  $DT$ , the relative velocity at time  $t_{i+1}$  (designated  $relV1$ ) and the relative structural displacement at time  $t_{i+1}$  (designated  $relD1$ ) are made using the Case 2 approach outlined in Figure 2.5. Note the relative velocity reduces to zero at a time increment  $[lhsDT + DTmid]$  after time  $t_i$ . The structure remains at rest and with zero relative velocity over time increment  $DTzeroV$ , as shown in this figure.

Note that structural translation can begin again at a later point in time, as described in the subsection 2.2.6 paragraph entitled “Starting the program Newmark analysis and the initiation of structural translation during a  $DT$  time step.”

### 3 Regression Analysis

#### 3.1 Introduction

This chapter describes three formulations for developing simplified non-dimensionalized permanent displacement relationships. These relationships as illustrated in Table 3.1 are described in detail at each following section, respectively. The derivations of these mean estimates, together with their standard error terms, also determine the 68 percent prediction intervals and 95 percent probability of non-exceedance upper bound estimates.

**Table 3.1. Forms of simplified non-dimensionalized permanent displacement relationships.**

|                                                                                                            |                                                                                                                                                          |
|------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Equation Form Three</b><br>Three-term Regression Analysis                                               | $\frac{d_m \bullet k_m g}{v_m^2} = \beta_1 \bullet \exp \left( \beta_2 \bullet \frac{k_c}{k_m} \right) \bullet \left( \frac{k_c}{k_m} \right)^{\beta_3}$ |
| <b>Equation Form Two</b><br>Two-term Regression Analysis,<br>Linear in Natural Logarithm<br>Transformation | $\frac{d_m \bullet k_m g}{v_m^2} = \beta_1 \bullet \exp \left( \beta_2 \bullet \frac{k_c}{k_m} \right)$                                                  |
| <b>Equation Form One</b><br>Two-term Regression Analysis,<br>Linear in Common Logarithm<br>Transformation  | $\frac{d_m \bullet k_m g}{v_m^2} = \beta_4 \bullet \left( \frac{k_c}{k_m} \right)^{\beta_5}$                                                             |

#### 3.2 Three-term regression analysis (Equation Form Three)

As noted earlier, Newmark (1965) first proposed the sliding block theory to estimate the permanent displacement of a sliding soil mass subjected to earthquake loading. Cai and Bathurst (1995) presented several simplified permanent displacement relationships that were developed by themselves as well as by others [e.g., Newmark (1965); Franklin and Chang (1977); Richards and Elms (1979); Whitman and Liao (1985a, 1985b); etc.], all of which are based on the Newmark sliding block method of analysis. These simplified permanent seismic displacement relationships use values of peak acceleration and peak velocity as a means to characterize earthquake demands on earthen and/or earth retaining structures founded on soil. All were derived using acceleration time-history records recorded on soil sites.

This subsection discusses one general form of a simplified permanent displacement relationship first proposed by Cai and Bathurst (1995).

One form of a simplified permanent seismic displacement relationship attributed to Cai and Bathurst (1995) and for a soil site, is of the form,

$$d_m = 35 \bullet \frac{v_m^2}{k_m g} \bullet \exp \left( -6.91 \bullet \frac{k_c}{k_m} \right) \bullet \left( \frac{k_c}{k_m} \right)^{-0.38} \quad (3.1)$$

Newmark (1965) introduced the peak ground acceleration and the peak ground velocity as characteristic soil parameters. Collecting these parameters, along with the permanent seismic displacement, the left-hand side becomes what is termed a non-dimensionalized displacement, which for the Cai and Bathurst relationship becomes,

$$\frac{d_m \bullet k_m g}{v_m^2} = 35 \bullet \exp \left( -6.91 \bullet \frac{k_c}{k_m} \right) \bullet \left( \frac{k_c}{k_m} \right)^{-0.38} \quad (3.2)$$

When discussing nonlinear regression, Equation 3.2 may be written in the general form of

$$y = \beta_1 \bullet \exp(\beta_2 \bullet x) \bullet x^{\beta_3} \quad (3.3)$$

with

$$y = \frac{d_m \bullet k_m g}{v_m^2}; \quad \text{non-dimensionalized displacement, and}$$

$$x = \frac{k_c}{k_m}; \quad \text{critical acceleration ratio}$$

where:

- $d_m$  = permanent displacement
- $k_m g$  = maximum horizontal ground acceleration
- $v_m$  = maximum ground velocity
- $k_c$  = maximum transmissible acceleration capacity

for which  $\beta_1$ ,  $\beta_2$ , and  $\beta_3$  are constants and the equation is nonlinear in  $\beta_2$ .

The form of Equation 3.3 is now  $[x, y]$  as compared to the original form

$$\left[ \frac{k_c}{k_m}, \frac{d_m \bullet k_m g}{v_m^2} \right] \text{ of Equation 3.2.}$$

Taking the natural log ( $\ln$ ) of both sides, Equation 3.3 becomes

$$\ln(y) = \ln(\beta_1) + \beta_2 \bullet x + \beta_3 \bullet \ln(x) \quad (3.4)$$

which simplifies to

$$\ln(y) = \beta_1^* + \beta_2 \bullet x + \beta_3 \bullet \ln(x) \quad (3.5)$$

with  $\beta_1^*$  equal to  $\ln(\beta_1)$ , or  $\beta_1 = \exp(\beta_1^*)$ .

The transformation of Equation 3.3 to Equations 3.4 and 3.5 resulted in the altered form of the equation from  $(x, y)$  to  $(x, \ln(y))$  or specifically,  $(x, y^*)$  with  $y^* = \ln(y)$ , such that Equation 3.5 becomes,

$$y^* = \beta_1^* + \beta_2 \bullet x + \beta_3 \bullet \ln(x) \quad (3.6)$$

From Equation 3.6, the set of basis functions  $(1, x, \ln(x))$  have a nonlinear term,  $\ln(x)$ ; however, the parameters  $(\beta_1^*, \beta_2, \text{ and } \beta_3)$  are constant and not part of any nonlinear term.

Regression models which are a linear function of the parameters are called linear regression models. Therefore, a linear regression analysis can be applied to solve for these constant parameters.

The least squares fitting method is one of the simplest and most common applied forms of linear regression. This method will be used to estimate the parameters which will minimize the sum of squares of the y-distance from the specified, or produce the least possible value of  $S$ ,

$$S = \sum_{i=1}^N e_i^2 = \sum_{i=1}^N \left[ y_i^* - (\beta_1^* + \beta_2 x_i + \beta_3 x_i^*) \right]^2 \quad (3.7)$$

with

$N$  = the total number of non-dimensionalized displacement terms  
 $x^* = \ln(x)$ .

We can estimate the parameters by taking the partial derivatives of Equation 3.7 with respect to  $\beta_1^*$ ,  $\beta_2$ , and  $\beta_3$ , and setting the resultant equal to zero.

$$\begin{aligned}\frac{\partial S}{\partial \beta_1} &= \sum_{i=1}^N 2 \left[ y_i^* - (\beta_1^* + \beta_2 x_i + \beta_3 x_i^*) \right] (-1) = 0 \\ \frac{\partial S}{\partial \beta_2} &= \sum_{i=1}^N 2 \left[ y_i^* - (\beta_1^* + \beta_2 x_i + \beta_3 x_i^*) \right] (-x_i) = 0 \\ \frac{\partial S}{\partial \beta_3} &= \sum_{i=1}^N 2 \left[ y_i^* - (\beta_1^* + \beta_2 x_i + \beta_3 x_i^*) \right] (-x_i^*) = 0\end{aligned}\tag{3.8}$$

The estimates of  $\beta_1^*$ ,  $\beta_2$ , and  $\beta_3$  are then represented by 3 linear equations in 3 unknowns,

$$\begin{aligned}\beta_1^*(N) + \beta_2 \sum_{i=1}^N x_i + \beta_3 \sum_{i=1}^N x_i^* &= \sum_{i=1}^N y_i^* \\ \beta_1^* \sum_{i=1}^N x_i + \beta_2 \sum_{i=1}^N (x_i)^2 + \beta_3 \sum_{i=1}^N x_i x_i^* &= \sum_{i=1}^N x_i y_i^* \\ \beta_1^* \sum_{i=1}^N x_i^* + \beta_2 \sum_{i=1}^N x_i x_i^* + \beta_3 \sum_{i=1}^N (x_i^*)^2 &= \sum_{i=1}^N x_i^* y_i^*\end{aligned}\tag{3.9}$$

The linear system of Equation 3.9 can be reduced to the equivalent system expressed in matrix form,  $M \cdot \beta = Y$ , with matrix  $M$ , vector  $Y$ , and solving for vector  $\beta$ ,

$$\underbrace{\begin{bmatrix} N & \sum_{i=1}^N x_i & \sum_{i=1}^N x_i^* \\ \sum_{i=1}^N x_i & \sum_{i=1}^N (x_i)^2 & \sum_{i=1}^N x_i x_i^* \\ \sum_{i=1}^N x_i^* & \sum_{i=1}^N x_i x_i^* & \sum_{i=1}^N (x_i^*)^2 \end{bmatrix}}_M \cdot \underbrace{\begin{bmatrix} \beta_1^* \\ \beta_2 \\ \beta_3 \end{bmatrix}}_{\beta} = \underbrace{\begin{bmatrix} \sum_{i=1}^N y_i^* \\ \sum_{i=1}^N x_i y_i^* \\ \sum_{i=1}^N x_i^* y_i^* \end{bmatrix}}_Y \quad (3.10)$$

The solution for  $\beta = [\beta_1^*, \beta_2, \text{ and } \beta_3]$  to the linear system  $M \cdot \beta = Y$  can be determined with Cramer's formulas in terms of determinants. Solving for third order determinants, we have,

$$\beta_1^* = \frac{D_1}{D} \quad \beta_2 = \frac{D_2}{D} \quad \beta_3 = \frac{D_3}{D} \quad (3.11)$$

where  $D$  is the determinant of the matrix  $M$  and  $D_1, D_2, D_3$  are each obtained by replacing the first, second and third columns of  $D$ , respectively, with the elements of the column  $Y$ . The determinants  $D, D_1, D_2$ , and  $D_3$  of the system can now be simply expressed as follows,

$$\begin{aligned}
 D = N \cdot & \left( \sum_{i=1}^N (x_i)^2 \cdot \sum_{i=1}^N (x_i^*)^2 - \sum_{i=1}^N x_i x_i^* \cdot \sum_{i=1}^N x_i x_i^* \right) \\
 & - \sum_{i=1}^N x_i \cdot \left( \sum_{i=1}^N x_i \cdot \sum_{i=1}^N (x_i^*)^2 - \sum_{i=1}^N x_i x_i^* \cdot \sum_{i=1}^N x_i^* \right) \\
 & + \sum_{i=1}^N x_i^* \cdot \left( \sum_{i=1}^N x_i \cdot \sum_{i=1}^N x_i x_i^* - \sum_{i=1}^N (x_i)^2 \cdot \sum_{i=1}^N x_i^* \right) \quad (3.12)
 \end{aligned}$$

$$\begin{aligned}
D_1 = & \sum_{i=1}^N y_i^* \cdot \left( \sum_{i=1}^N (x_i)^2 \cdot \sum_{i=1}^N (x_i^*)^2 - \sum_{i=1}^N x_i x_i^* \cdot \sum_{i=1}^N x_i x_i^* \right) \\
& - \sum_{i=1}^N x_i y_i^* \cdot \left( \sum_{i=1}^N x_i \cdot \sum_{i=1}^N (x_i^*)^2 - \sum_{i=1}^N x_i x_i^* \cdot \sum_{i=1}^N x_i^* \right) \\
& + \sum_{i=1}^N x_i^* y_i^* \cdot \left( \sum_{i=1}^N x_i \cdot \sum_{i=1}^N x_i x_i^* - \sum_{i=1}^N (x_i)^2 \cdot \sum_{i=1}^N x_i^* \right)
\end{aligned} \tag{3.13}$$

$$\begin{aligned}
D_2 = & - \sum_{i=1}^N y_i^* \cdot \left( \sum_{i=1}^N x_i \cdot \sum_{i=1}^N (x_i^*)^2 - \sum_{i=1}^N x_i^* \cdot \sum_{i=1}^N x_i x_i^* \right) \\
& + \sum_{i=1}^N x_i y_i^* \cdot \left( N \cdot \sum_{i=1}^N (x_i^*)^2 - \sum_{i=1}^N x_i^* \cdot \sum_{i=1}^N x_i^* \right) \\
& - \sum_{i=1}^N x_i^* y_i^* \cdot \left( N \cdot \sum_{i=1}^N x_i x_i^* - \sum_{i=1}^N x_i \cdot \sum_{i=1}^N x_i^* \right)
\end{aligned} \tag{3.14}$$

$$\begin{aligned}
D_3 = & \sum_{i=1}^N y_i^* \cdot \left( \sum_{i=1}^N x_i \cdot \sum_{i=1}^N x_i x_i^* - \sum_{i=1}^N x_i^* \cdot \sum_{i=1}^N (x_i)^2 \right) \\
& - \sum_{i=1}^N x_i y_i^* \cdot \left( N \cdot \sum_{i=1}^N x_i x_i^* - \sum_{i=1}^N x_i^* \cdot \sum_{i=1}^N x_i \right) \\
& + \sum_{i=1}^N x_i^* y_i^* \cdot \left( N \cdot \sum_{i=1}^N (x_i)^2 - \sum_{i=1}^N x_i \cdot \sum_{i=1}^N x_i \right)
\end{aligned} \tag{3.15}$$

From Cramer's rule (Equation 3.11), the coefficients,  $\beta_1^*$ ,  $\beta_2$ , and  $\beta_3$  can now be determined. These parameters were originally estimated with the assumption that the sums of many independent and identically-distributed random variables possess a finite variance. With this in mind,

the residual error term or the variance, Equation 3.7, can be applied to determine the error in the estimates, the standard error (*Std. error*), defined as square root of the ratio of the square of the difference and the difference between  $N$  data points and the number of parameters (3),

$$Std. error = \sqrt{\frac{\sum_{i=1}^N [y_i^* - (\beta_1^* + \beta_2 x_i + \beta_3 x_i^*)]^2}{N - 3}} \quad (3.16)$$

Typically, the smaller the *Std. error*, the more accurate the parameter estimation. As can be noted, the *Std. error* term will tend to get smaller with the increase in the number of data points. A 95 percent probability of non-exceedance will be used as an upper bound estimate. For a normally distributed variable, this value can be calculated by taking the product of the *Std. error* and 1.65, specifically from Equation 3.6 we can show that,

$$y^* = \beta_1^* + \beta_2 \bullet x + \beta_3 \bullet \ln(x) + 1.65 \bullet Std. error \quad (3.17)$$

Recalling that  $\beta_1^* = \ln(\beta_1)$  and  $y^* = \ln(y)$ ; taking the exponential of both sides of Equation 3.6 and the residual error term, reintroduces a form of Equation 3.3, namely,

$$y = \beta_1 \bullet \exp(\beta_2 \bullet x) \bullet x^{\beta_3} \bullet \exp(1.65 \bullet Std. error) \quad (3.18)$$

with  $\beta_1 = \exp(\beta_1^*)$ .

Finally, restoring to the original form of  $\left[ \frac{k_c}{k_m}, \frac{d_m \bullet k_m g}{v_m^2} \right]$  gives us the non-dimensionalized displacement equation for a 95 percent probability of non-exceedance,

$$\frac{d_m \bullet k_m g}{v_m^2} = \beta_1 \bullet \exp\left(\beta_2 \bullet \frac{k_c}{k_m}\right) \bullet \left(\frac{k_c}{k_m}\right)^{\beta_3} \bullet \exp(1.65 \bullet Std. error) \quad (3.19)$$

and the non-dimensionalized displacement equation of the mean of the estimate as presented in row one of Table 3.1,

$$\frac{d_m \bullet k_m g}{v_m^2} = \beta_1 \bullet \exp\left(\beta_2 \bullet \frac{k_c}{k_m}\right) \bullet \left(\frac{k_c}{k_m}\right)^{\beta_3} \quad (3.20)$$

The estimate and its *Std. error* can also be used to construct prediction intervals about the mean estimate. These prediction intervals reflect ranges that limit the average of the estimated value with a known probability for a known distribution (a normal distribution for the transformed coordinate system in this case). For a selected  $N$  data set that is normally distributed, there is approximately a 68 percent probability that the average result will fall between one *Std. error* above the mean estimate and one *Std. error* below the mean estimate. The 68 percent prediction interval can be determined by modifying Equation 3.6 and adding/subtracting the *Std. error* as follows,

$$y^* = \beta_1^* + \beta_2 \bullet x + \beta_3 \bullet \ln(x) \pm \text{Std. error} \quad (3.21)$$

or specifically,

$$y^* = \beta_1^* + \beta_2 \bullet x + \beta_3 \bullet \ln(x) + \text{Std. error} \quad (3.21a)$$

and

$$y^* = \beta_1^* + \beta_2 \bullet x + \beta_3 \bullet \ln(x) - \text{Std. error} \quad (3.21b)$$

Recalling that  $\beta_1^* = \ln(\beta_1)$  and  $y^* = \ln(y)$ ; taking the exponential of both sides of Equations 3.21a and 3.21b reintroduces a form of Equation 3.3, namely,

$$y = \beta_1 \bullet \exp(\beta_2 \bullet x) \bullet x^{\beta_3} \bullet \exp(\text{Std. error}) \quad (3.22a)$$

and

$$y = \beta_1 \bullet \exp(\beta_2 \bullet x) \bullet x^{\beta_3} \bullet \exp(-\text{Std. error}) \quad (3.22b)$$

with  $\beta_1 = \exp(\beta_1^*)$ .

Finally, restoring to the original form of  $\left[ \frac{k_c}{k_m}, \frac{d_m \bullet k_m g}{v_m^2} \right]$  gives us the non-dimensionalized displacement equations

$$\frac{d_m \bullet k_m g}{v_m^2} = \beta_1 \bullet \exp \left( \beta_2 \bullet \frac{k_c}{k_m} \right) \bullet \left( \frac{k_c}{k_m} \right)^{\beta_3} \bullet \exp(\text{Std. error}) \quad (3.23a)$$

$$\frac{d_m \bullet k_m g}{v_m^2} = \beta_1 \bullet \exp \left( \beta_2 \bullet \frac{k_c}{k_m} \right) \bullet \left( \frac{k_c}{k_m} \right)^{\beta_3} \bullet \exp(-\text{Std. error}) \quad (3.23b)$$

such that, there is a 68 percent probability that the mean of the estimate will fall between the 68 percent prediction intervals of Equations 3.23a and 3.23b.

### 3.3 Two-term regression analysis, linear in natural logarithm transformation (Equation Form Two)

A second form of a simplified permanent seismic displacement relationship attributed to Wong (1982) [reported in Whitman and Liao (1985)] for a soil site, is of the following form,

$$d_m = 37 \bullet \frac{v_m^2}{k_m g} \bullet \exp \left( -9.4 \bullet \frac{k_c}{k_m} \right) \quad (3.24)$$

Recall that Newmark (1965) introduced the peak ground acceleration and the peak ground velocity as characteristic soil parameters. Collecting these parameters, along with the permanent seismic displacement, the left-hand side becomes what is termed a non-dimensionalized displacement, which for the Wong relationship becomes,

$$\frac{d_m \bullet k_m g}{v_m^2} = 37 \bullet \exp \left( -9.4 \bullet \frac{k_c}{k_m} \right) \quad (3.25)$$

When discussing nonlinear regression, Equation 3.25 may be written in the general form of

$$y = \beta_1 \bullet \exp(\beta_2 \bullet x) \quad (3.26)$$

with

$$y = \frac{d_m \bullet k_m g}{v_m^2}; \quad \text{non-dimensionalized displacement, and}$$

$$x = \frac{k_c}{k_m}; \quad \text{critical acceleration ratio}$$

where:

$$\begin{aligned} d_m &= \text{permanent displacement,} \\ k_m g &= \text{maximum horizontal ground acceleration} \\ v_m &= \text{maximum ground velocity} \\ k_c &= \text{maximum transmissible acceleration capacity} \end{aligned}$$

for which  $\beta_1$  and  $\beta_2$  are constants and the equation is nonlinear in  $\beta_2$ .

The form of Equation 3.26 is now  $[x, y]$  as compared to the original form  $\left[ \frac{k_c}{k_m}, \frac{d_m \bullet k_m g}{v_m^2} \right]$  of Equation 3.25.

Taking the natural log (ln) of both sides, Equation 3.26 becomes

$$\ln(y) = \ln(\beta_1) + \beta_2 \bullet x \quad (3.27)$$

which simplifies to

$$\ln(y) = \beta_1^* + \beta_2 \bullet x \quad (3.28)$$

with  $\beta_1^*$  equal to  $\ln(\beta_1)$ , or  $\beta_1 = \exp(\beta_1^*)$ .

The transformation of Equation 3.26 to Equations 3.27 and 3.28 resulted in the altered form of the equation from  $(x, y)$  to  $(x, \ln(y))$  or specifically,  $(x, y^*)$  with  $y^* = \ln(y)$ , such that Equation 3.28 becomes,

$$y^* = \beta_1^* + \beta_2 \bullet x \quad (3.29)$$

From Equation 3.29, the set of basis functions  $(1, x)$  are linear and the parameters  $(\beta_1^*$  and  $\beta_2)$  are constant. A linear regression analysis can be applied to solve for these constant parameters.

The least squares fitting method will be used to estimate the parameters  $(\beta_1^*$  and  $\beta_2)$  which will minimize the sum of squares of the distance from the specified curve, or produce the least possible value of  $S$ ,

$$S = \sum_{i=1}^N e_i^2 = \sum_{i=1}^N \left[ y_i^* - (\beta_1^* + \beta_2 x_i) \right]^2 \quad (3.30)$$

with

$N$  = the total number of non-dimensionalized displacement terms.

We can estimate the parameters by taking the partial derivatives of Equation 3.30 with respect to  $\beta_1^*$  and  $\beta_2$ , and setting the resultant equal to zero.

$$\frac{\partial S}{\partial \beta_1^*} = \sum_{i=1}^N 2 \left[ y_i^* - (\beta_1^* + \beta_2 x_i) \right] (-1) = 0 \quad (3.31)$$

$$\frac{\partial S}{\partial \beta_2} = \sum_{i=1}^N 2 \left[ y_i^* - (\beta_1^* + \beta_2 x_i) \right] (-x_i) = 0$$

The estimates of  $\beta_1^*$  and  $\beta_2$  are then represented by 2 linear equations in 2 unknowns,

$$\beta_1^*(N) + \beta_2 \sum_{i=1}^N x_i = \sum_{i=1}^N y_i^* \quad (3.32)$$

$$\beta_1^* \sum_{i=1}^N x_i + \beta_2 \sum_{i=1}^N x_i^2 = \sum_{i=1}^N x_i y_i^*$$

The solution for  $\beta_1^*$  and  $\beta_2$  to the linear system of Equation 3.32 can be numerically computed by applying the formula,

$$\beta_2 = \frac{\sum_{i=1}^N (x_i \bullet y_i^*) - \frac{\left( \sum_{i=1}^N x_i \bullet \sum_{i=1}^N y_i^* \right)}{N}}{\sum_{i=1}^N x_i^2 - \frac{\left( \sum_{i=1}^N x_i \right)^2}{N}}$$

$$\text{or} \quad (3.33)$$

$$\frac{\sum_{i=1}^N \left[ (x_i - \bar{x}) \bullet (y_i^* - \bar{y}^*) \right]}{\sum_{i=1}^N (x_i - \bar{x})^2}$$

$$\beta_1^* = \bar{y}^* - \beta_2 \bar{x} \quad (3.34)$$

with

$$\bar{y}^* = \frac{\sum_{i=1}^N y_i^*}{N}; \text{ the mean of } y^*$$

$$\bar{x} = \frac{\sum_{i=1}^N x_i}{N}; \text{ the mean of } x.$$

The parameters  $\beta_1^*$  and  $\beta_2$  were originally estimated with the assumption that the sums of many independent and identically-distributed random variables possess a finite variance. With this in mind, the residual error term or the variance, Equation 3.30 can be applied to determine the error in the estimates, the standard error (*Std. error*), defined as the square root of the ratio of the square of the difference and the difference between  $N$  data points and the number of parameters (2),

$$\text{Std. error} = \sqrt{\frac{\sum_{i=1}^N \left[ y_i^* - (\beta_1^* + \beta_2 x_i) \right]^2}{N - 2}} \quad (3.35)$$

Typically, the smaller the *Std. error*, the more accurate the parameter estimation. As can be noted, the *Std. error* term will tend to get smaller with the increase in the number of data points. A 95 percent probability of non-exceedance will be used as an upper bound estimate. For a normally distributed variable, this value can be calculated by taking the product of the *Std. error* and 1.65, specifically from Equation 3.29 we can show that,

$$y^* = \beta_1^* + \beta_2 \bullet x + 1.65 \bullet \text{Std. error} \quad (3.36)$$

Recalling that  $\beta_1^* = \ln(\beta_1)$  and  $y^* = \ln(y)$ ; taking the exponential of both sides of Equation 3.29 and the residual error term, reintroduces a form of Equation 3.26, namely,

$$y = \beta_1 \bullet \exp(\beta_2 \bullet x) \bullet \exp(1.65 \bullet \text{Std. error}) \quad (3.37)$$

with  $\beta_1 = \exp(\beta_1^*)$ .

Finally, restoring to the original form of  $\left[ \frac{k_c}{k_m}, \frac{d_m \bullet k_m g}{v_m^2} \right]$  gives us the non-dimensionalized displacement equation for a 95 percent probability of non-exceedance,

$$\frac{d_m \bullet k_m g}{v_m^2} = \beta_1 \bullet \exp\left(\beta_2 \bullet \frac{k_c}{k_m}\right) \bullet \exp(1.65 \bullet \text{Std. error}) \quad (3.38)$$

and the non-dimensionalized displacement equation of the mean of the estimate, as presented in row two of Table 3.1,

$$\frac{d_m \bullet k_m g}{v_m^2} = \beta_1 \bullet \exp\left(\beta_2 \bullet \frac{k_c}{k_m}\right) \quad (3.39)$$

The estimate and its *Std. error* can also be used to construct prediction intervals about the mean estimate. These prediction intervals reflect ranges that limit the average of the estimated value with a known probability for a known distribution (a normal distribution for the transformed coordinate system in this case). For a selected  $N$  data set that is normally distributed, there is approximately a 68 percent probability that the average result will fall between one *Std. error* above the mean estimate

and one *Std. error* below the mean estimate. The 68 percent prediction interval can be determined by modifying Equation 3.39 and adding/subtracting the *Std. error* as follows,

$$y^* = \beta_1^* + \beta_2 \bullet x \pm \text{Std. error} \quad (3.40)$$

or specifically,

$$y^* = \beta_1^* + \beta_2 \bullet x + \text{Std. error} \quad (3.40a)$$

and

$$y^* = \beta_1^* + \beta_2 \bullet x - \text{Std. error} \quad (3.40b)$$

Recalling that  $\beta_1^* = \ln(\beta_1)$  and  $y^* = \ln(y)$ ; taking the exponential of both sides of Equations 3.40a and 3.40b reintroduces a form of Equation 3.26, namely,

$$y = \beta_1 \bullet \exp(\beta_2 \bullet x) \bullet \exp(\text{Std. error}) \quad (3.41a)$$

and

$$y = \beta_1 \bullet \exp(\beta_2 \bullet x) \bullet \exp(-\text{Std. error}) \quad (3.41b)$$

with  $\beta_1 = \exp(\beta_1^*)$ .

Finally, restoring to the original form of  $\left[ \frac{k_c}{k_m}, \frac{d_m \bullet k_m g}{v_m^2} \right]$  gives us the non-dimensionalized displacement equations

$$\frac{d_m \bullet k_m g}{v_m^2} = \beta_1 \bullet \exp\left(\beta_2 \bullet \frac{k_c}{k_m}\right) \bullet \exp(\text{Std. error}) \quad (3.42a)$$

$$\frac{d_m \bullet k_m g}{v_m^2} = \beta_1 \bullet \exp\left(\beta_2 \bullet \frac{k_c}{k_m}\right) \bullet \exp(-\text{Std. error}) \quad (3.42b)$$

such that, there is a 68 percent probability that the mean of the estimate will fall between the 68 percent prediction intervals of Equations 3.42a and 3.42b.

### 3.4 Two-term regression analysis, linear in common logarithm transformation (Equation Form One)

A third form of a simplified permanent seismic displacement relationship attributed to Richards and Elms (1979) for a soil site, is of the following form,

$$d_m = 0.087 \cdot \frac{v_m^2}{k_m g} \cdot \left( \frac{k_c}{k_m} \right)^{-4} \quad (3.43)$$

Recall that Newmark (1965) introduced the peak ground acceleration and the peak ground velocity as characteristic soil parameters. Collecting these parameters, along with the permanent seismic displacement, the left-hand side becomes what is termed a non-dimensionalized displacement, which for the Richards and Elms relationship becomes,

$$\frac{d_m \cdot k_m g}{v_m^2} = 0.087 \cdot \left( \frac{k_c}{k_m} \right)^{-4} \quad (3.44)$$

When discussing nonlinear regression, this Equation 3.44 may be written in the general form of

$$y = \beta_4 \cdot x^{\beta_5} \quad (3.45)$$

with

$$y = \frac{d_m \cdot k_m g}{v_m^2}; \quad \text{non-dimensionalized displacement, and}$$

$$x = \frac{k_c}{k_m}; \quad \text{critical acceleration ratio}$$

where:

$d_m$  = permanent displacement,  
 $k_m g$  = maximum horizontal ground acceleration

$v_m$  = maximum ground velocity  
 $k_c$  = maximum transmissible acceleration capacity

for which  $\beta_4$  and  $\beta_5$  are constants.

The form of Equation 3.45 is now  $[x, y]$  as compared to the original form  $\left[ \frac{k_c}{k_m}, \frac{d_m \bullet k_m g}{v_m^2} \right]$  of Equation 3.2.

Taking the common log ( $\log_{10}$  or  $\log$ ) of both sides, Equation 3.45 becomes

$$\log(y) = \log(\beta_4) + \beta_5 \bullet \log(x) \quad (3.46)$$

which simplifies to

$$\log(y) = \beta_4^{**} + \beta_5 \bullet \log(x) \quad (3.47)$$

with  $\beta_4^{**}$  equal to  $\log(\beta_4)$ , or  $\beta_4 = 10^{(\beta_4^{**})}$ .

The transformation of Equation 3.45 to Equations 3.46 and 3.47 resulted in the altered form of the equation from  $(x, y)$  to  $(x, \log(y))$  or specifically,  $(x, y^{**})$  with  $y^{**} = \log(y)$ , such that Equation 3.47 becomes,

$$y^{**} = \beta_4^{**} + \beta_5 \bullet \log(x) \quad (3.48)$$

From Equation 3.48, the set of basis functions  $(1, \log(x))$  have a nonlinear term,  $\log(x)$ ; however, the parameters  $\beta_4^{**}$  and  $\beta_5$  are constant and not part of any nonlinear term. Regression models which are a linear function of the parameters are called linear regression models. Therefore, a linear regression analysis can be applied to solve for these constant parameters.

The least squares fitting method will be used to estimate the parameters  $\beta_4^{**}$  and  $\beta_5$  which will minimize the sum of squares of the distance from the specified curve, or produce the least possible value of  $S$ ,

$$S = \sum_{i=1}^N e_i^2 = \sum_{i=1}^N \left[ y_i^{**} - (\beta_4^{**} + \beta_5 \bullet x_i^{**}) \right]^2 \quad (3.49)$$

with

$N$  = the total number of non-dimensionalized displacement terms.  
 $x^{**} = \log(x)$ .

We can estimate the parameters by taking the partial derivatives of Equation 3.49 with respect to  $\beta_4^{**}$  and  $\beta_5$ , and setting the resultant equal to zero.

$$\frac{\partial S}{\partial \beta_4^{**}} = \sum_{i=1}^N 2 \left[ y_i^{**} - (\beta_4^{**} + \beta_5 \bullet x_i^{**}) \right] (-1) = 0 \quad (3.50)$$

$$\frac{\partial S}{\partial \beta_5} = \sum_{i=1}^N 2 \left[ y_i^{**} - (\beta_4^{**} + \beta_5 \bullet x_i^{**}) \right] (-x_i^{**}) = 0$$

The estimates of  $\beta_4^{**}$  and  $\beta_5$  are then represented by 2 linear equations in 2 unknowns,

$$\beta_4^{**} (N) + \beta_5 \sum_{i=1}^N x_i^{**} = \sum_{i=1}^N y_i^{**} \quad (3.51)$$

$$\beta_4^{**} \sum_{i=1}^N x_i^{**} + \beta_5 \sum_{i=1}^N (x_i^{**})^2 = \sum_{i=1}^N x_i^{**} \bullet y_i^{**}$$

The solution for  $\beta_4^{**}$  and  $\beta_5$  to the linear system of Equation 3.51 can be numerically computed by applying the formulae,

$$\beta_5 = \frac{\sum_{i=1}^N (x_i^{**} \bullet y_i^{**}) - \frac{\left( \sum_{i=1}^N x_i^{**} \bullet \sum_{i=1}^N y_i^{**} \right)}{N}}{\sum_{i=1}^N (x_i^{**})^2 - \frac{\left( \sum_{i=1}^N x_i^{**} \right)^2}{N}}$$

$$\text{or} \quad (3.52)$$

$$= \frac{\sum_{i=1}^N \left[ \left( x_i^{**} - \overline{x^{**}} \right) \bullet \left( y_i^{**} - \overline{y^{**}} \right) \right]}{\sum_{i=1}^N \left( x_i^{**} - \overline{x^{**}} \right)^2}$$

$$\beta_4^{**} = \overline{y^{**}} - \beta_5 \overline{x^{**}} \quad (3.53)$$

with

$$\overline{y^{**}} = \frac{\sum_{i=1}^N y_i^{**}}{N}; \quad \text{the mean of } y^{**}$$

$$\overline{x^{**}} = \frac{\sum_{i=1}^N x_i^{**}}{N}; \quad \text{the mean of } x^{**}$$

The parameters  $\beta_4^{**}$  and  $\beta_5$  were originally estimated with the assumption that the sums of many independent and identically-distributed random variables possess a finite variance. With this in mind, the residual error term or the variance, Equation 3.49 can be applied to determine the error in the estimates, the standard error (*Std. error*), defined as the square root of the ratio of the square of the difference and the difference between  $N$  data points and the number of parameters (2),

$$\text{Std. error} = \sqrt{\frac{\sum_{i=1}^N \left[ y_i^{**} - (\beta_4^{**} + \beta_5 x_i^{**}) \right]^2}{N - 2}} \quad (3.54)$$

Typically, the smaller the *Std. error*, the more accurate the parameter estimation. As can be noted, the *Std. error* term will tend to get smaller with the increase in the number of data points. A 95 percent probability of non-exceedance will be used as an upper bound estimate. For a normally distributed variable, this value can be calculated by taking the product of the *Std. error* and 1.65, specifically from Equation 3.48 we can show that,

$$y^{**} = \beta_4^{**} + \beta_5 \bullet \log(x) + 1.65 \bullet \text{Std. error} \quad (3.55)$$

Recalling that  $\beta_4^{**} = \log(\beta_4)$  and  $y^{**} = \log(y)$ ; taking the antilog of both sides of Equation 3.55 with the residual error term, reintroduces a form of Equation 3.45, namely,

$$y = \beta_4 \bullet x^{\beta_5} \bullet 10^{(1.65 \bullet \text{Std. error})} \quad (3.56)$$

with  $\beta_4 = 10^{(\beta_4^{**})}$ .

Finally, restoring to the original form of  $\left[ \frac{k_c}{k_m}, \frac{d_m \bullet k_m g}{v_m^2} \right]$  gives us the non-dimensionalized displacement equation for a 95 percent probability of non-exceedance,

$$\frac{d_m \bullet k_m g}{v_m^2} = \beta_4 \bullet \left( \frac{k_c}{k_m} \right)^{\beta_5} \bullet 10^{(1.65 \bullet \text{Std. error})} \quad (3.57)$$

and the non-dimensionalized displacement equation of the mean of the estimate, as presented in row three of Table 3.1,

$$\frac{d_m \bullet k_m g}{v_m^2} = \beta_4 \bullet \left( \frac{k_c}{k_m} \right)^{\beta_5} \quad (3.58)$$

The estimate and its *Std. error* can also be used to construct prediction intervals about the mean estimate. These prediction intervals reflect ranges that limit the average of the estimated value with a known probability for a known distribution (a normal distribution for the transformed coordinate system in this case). For a selected  $N$  data set that is normally distributed, there is approximately a 68 percent probability that the

average result will fall between one *Std. error* above the mean estimate and one *Std. error* below the mean estimate. The 68 percent prediction interval can be determined by modifying Equation 3.48 and adding/subtracting the *Std. error* as follows,

$$y^{**} = \beta_4^{**} + \beta_5 \bullet \log(x) \pm \text{Std. error} \quad (3.59)$$

or specifically,

$$y^{**} = \beta_4^{**} + \beta_5 \bullet \log(x) + \text{Std. error} \quad (3.59a)$$

and

$$y^{**} = \beta_4^{**} + \beta_5 \bullet \log(x) - \text{Std. error} \quad (3.59b)$$

Recalling that  $\beta_4^{**} = \log(\beta_4)$  and  $y^{**} = \log(y)$ ; taking the antilog of both sides of Equations 3.59a and 3.59b reintroduces a form of Equation 3.45, namely,

$$y = \beta_4 \bullet x^{\beta_5} \bullet 10^{\text{Std. error}} \quad (3.60a)$$

and

$$y = \beta_4 \bullet x^{\beta_5} \bullet 10^{-\text{Std. error}} \quad (3.60b)$$

with  $\beta_4 = 10^{(\beta_4^{**})}$ .

Finally, restoring to the original form of  $\left[ \frac{k_c}{k_m}, \frac{d_m \bullet k_m g}{v_m^2} \right]$  gives us the non-dimensionalized displacement equations

$$\frac{d_m \bullet k_m g}{v_m^2} = \beta_4 \bullet \left( \frac{k_c}{k_m} \right)^{\beta_5} \bullet 10^{\text{Std. error}} \quad (3.61a)$$

$$\frac{d_m \bullet k_m g}{v_m^2} = \beta_4 \bullet \left( \frac{k_c}{k_m} \right)^{\beta_5} \bullet 10^{-\text{Std. error}} \quad (3.61b)$$

such that, there is a 68 percent probability that the mean of the estimate will fall between the 68 percent prediction intervals of Equations 3.61a and 3.61b.

## 4 Regression results for ground motions recorded on rock

### 4.1 Introduction

This chapter discusses the regression analysis of the permanent displacement of rock acceleration time histories.

A rock site acceleration time-history database developed for use with the permanent displacement regression analysis involved selecting, documenting, processing, and archiving engineering significant data from rock or stiff soil sites. One goal was to collect sufficient data to capture the inherent variability of earthquake ground response. Practically, this goal is not fully realizable due to the limited data set compared to an ideal complete set of data which would represent all combinations of tectonic settings, earthquake sizes, source to site distances, and site conditions. For example, large magnitude earthquake data at near distances, while increasing as strong ground motion monitoring is improving, is still limited resulting from the rareness of large earthquakes coupled with near field recording sites. This limited data aspect is the rationale for including stiff soil site records to build a sufficiently large rock site data set to support robust analyses applicable to a reasonable range of engineering significant situations with insight into its variability. Conversely, since the effort to build a large data set from a limited basis may tend to create bias, in order to counteract this data from different earthquakes, in different regions at a spread of ranges were selected.

To manage the data collection and follow-on analysis, three data sets were developed applicable for nominally small (Magnitude 5), medium (Magnitude 6), and large (Magnitude 7) earthquake sizes. The overall size range for the three sets was set at  $M_w = 4.9$  at the low end and open ended for large size earthquakes. These three datasets are completely described within Tables 4.1, 4.2, and 4.3, respectively. The largest earthquake magnitude is  $M_w = 8.1$  for these data. Table 4.4 describes the classifications of the three data sets. This cutoff on the low end was necessary based on the number of available records from the more frequent small magnitude events and the engineering significance of strong ground motions.

In addition to a minimum magnitude restriction in the data search, an additional lower bound constraint was set at  $0.007\ g$  for the peak ground acceleration. The magnitude boundaries between the three earthquake data sets was arbitrary in the sense that there is not an implied physical basis for these separations at or near these magnitude boundaries of 4.9, 6.1, and 6.9, but were chosen based on populating a sufficient number in each set. In this respect, one should not expect to find different results in using data from either set near the dividing magnitudes.

Important to the documentation and use of these data are the definitions for the parameters of earthquake magnitude and site conditions. Interestingly, earthquake magnitude is not a simple data parameter because of the historical development of various earthquake magnitude scales and now backwards application of new magnitude scales to historical events. Earthquake magnitude scale to assess the size of an earthquake was initially based on resulting levels of damage before seismic instrumentation was developed to measure ground motions. The initial use of the damage-based Mercalli Intensity scale had evolved to determinations based on measured response of earthquake accelerographs and most recently to current use of a magnitude scale based on a mechanical concept based energy released, estimated on the area of the ruptured crust and the strength of crust. This current preferred scale in engineering seismology is the moment magnitude scale ( $M_w$ ) and necessarily involves backwards assignment to historical data collected prior to its accepted and now routine use. Table 4.5 is provided to illustrate this backward application and how the assigned earthquake magnitudes have changed for a few historically significant earthquakes.

The  $M_w$  is a standard magnitude scale that is completely independent of the type of instrument such as Richter ( $M$ ) and surface wave ( $M_s$ ), which are indirect estimations of strain energy based on measured displacement amplitudes of seismic waves of certain periods and at certain distances from sources. The  $M_w$  is a more direct measure of energy since it is based on calculated frictional resistance over the area of fault slippage.

Table 4.1. Master accelerograph table of magnitude 6.9 – 8.1.

| M7 Master Accelerograph Table |      |                   |     |                         |       |        |      |        |          |        |         |       |          |       |           |                       |               |        |      |     |                   |                   |            |                                  |
|-------------------------------|------|-------------------|-----|-------------------------|-------|--------|------|--------|----------|--------|---------|-------|----------|-------|-----------|-----------------------|---------------|--------|------|-----|-------------------|-------------------|------------|----------------------------------|
| Set                           | Rec# | Filename          | Mw  | Distance<br>(hyp)<br>km | PGA   |        | PGV  |        | PGD      |        | Ratio 1 |       | Ratio 2  |       | AI<br>95% | Duration<br>bracketed | Site<br>Class | Region | Comp | deg | Setting &<br>Mech | Earthquake        | Date       | Station                          |
|                               |      |                   |     |                         | +     | -      | +    | -      | Lin Disp |        | vm/km   |       | d*km/vm² |       |           |                       |               |        |      |     |                   |                   |            |                                  |
|                               |      |                   |     |                         |       |        |      |        | +        | -      | +       | -     | +        | -     |           |                       |               |        |      |     |                   |                   |            |                                  |
|                               |      |                   |     |                         |       |        |      |        |          |        |         |       |          |       |           |                       |               |        |      |     |                   |                   |            |                                  |
| 1                             | 1    | 101_lpg1_090a.dat | 7.0 | 33                      | 0.442 | -0.418 | 27.0 | -33.8  | 8.50     | -2.90  | 24.1    | 31.8  | 5.04     | 1.04  | 151       | 9.7                   | Rock(a)       | WUS    | H1   | 90  | XX-RO-17          | Loma Prieta       | 10/18/1989 | Gilroy Array #1                  |
|                               | 2    | 102_lpg1_000a.dat | 7.0 | 33                      | 0.435 | -0.375 | 32.5 | -11.2  | 4.28     | -9.49  | 29.4    | 11.8  | 1.73     | 27.71 | 95        | 13.2                  | Rock(a)       | WUS    | H2   | 0   | XX-RO-17          | Loma Prieta       | 10/18/1989 | Gilroy Array #1                  |
|                               | 3    | 103_lpg1_Oupa.dat | 7.0 | 33                      | 0.178 | -0.210 | 8.3  | -15.3  | 8.29     | -3.79  | 18.4    | 28.6  | 20.99    | 3.36  | 26        | 4.3                   | Rock(a)       | WUS    | V    | UP  | XX-RO-17          | Loma Prieta       | 10/18/1989 | Gilroy Array #1                  |
| 2                             | 4    | 104_hmjt_360a.dat | 7.1 | 52                      | 0.168 | -0.190 | 14.0 | -23.2  | 5.40     | -5.00  | 32.8    | 48.1  | 4.54     | 1.73  | 56        | 13.1                  | Rock(w/s)     | WUS    | H1   | 360 | MF-SS-05          | Hector Mine       | 10/16/1999 | Joshua Tree Fire Sta             |
|                               | 5    | 105_hmjt_090a.dat | 7.1 | 52                      | 0.102 | -0.146 | 17.6 | -17.1  | 7.00     | -5.00  | 68.1    | 46.1  | 2.25     | 2.46  | 31        | 12.5                  | Rock(w/s)     | WUS    | H2   | 90  | MF-SS-05          | Hector Mine       | 10/16/1999 | Joshua Tree Fire Sta             |
|                               | 6    | 106_hmjt_Oupa.dat | 7.1 | 52                      | 0.102 | -0.121 | 9.0  | -8.0   | 4.12     | -4.16  | 34.7    | 25.9  | 5.10     | 7.77  | 27        | 14.0                  | Rock(w/s)     | WUS    | V    | UP  | MF-SS-05          | Hector Mine       | 10/16/1999 | Joshua Tree Fire Sta             |
| 3                             | 7    | 107_lpld_000a.dat | 7.1 | 26                      | 0.388 | -0.442 | 38.0 | -84.3  | 12.03    | -16.01 | 38.6    | 75.1  | 3.17     | 0.98  | 168       | 6.7                   | Rock          | WUS    | H1   | 0   | XX-RO-17          | Loma Prieta       | 10/18/1989 | Lexington Dam -Abut              |
|                               | 8    | 108_lpld_090a.dat | 7.1 | 26                      | 0.297 | -0.409 | 31.9 | -95.5  | 32.44    | -10.98 | 42.3    | 91.9  | 9.27     | 0.48  | 158       | 7.1                   | Rock          | WUS    | H2   | 90  | XX-RO-17          | Loma Prieta       | 10/18/1989 | Lexington Dam -Abut              |
|                               | 9    | 109_lpld_Oupa.dat | 7.1 | 26                      | 0.117 | -0.133 | 25.9 | -16.8  | 11.86    | -16.77 | 87.1    | 49.8  | 2.03     | 7.74  | 18        | 5.2                   | Rock          | WUS    | V    | UP  | XX-RO-17          | Loma Prieta       | 10/18/1989 | Lexington Dam -Abut              |
| 4                             | 10   | 110_inut_075a.dat | 7.0 | 34                      | 0.310 | -0.224 | 15.8 | -18.7  | 1.57     | -2.32  | 20.1    | 32.8  | 1.90     | 1.46  | 87        | 8.3                   | Rock          | India  | H1   | 0   | XX-XX-10          | Uttarakshi, India | 10/19/1991 | IIT Roorkee, India               |
|                               | 11   | 111_inut_345a.dat | 7.0 | 34                      | 0.227 | -0.242 | 17.1 | -9.6   | 1.82     | -3.51  | 29.6    | 15.6  | 1.38     | 9.06  | 68        | 8.9                   | Rock          | India  | H2   | 345 | XX-XX-10          | Uttarakshi, India | 10/19/1991 | IIT Roorkee, India               |
|                               | 12   | 112_inut_Oupa.dat | 7.0 | 34                      | 0.189 | -0.197 | 13.2 | -7.6   | 2.93     | -2.12  | 27.6    | 15.2  | 3.10     | 7.04  | 48        | 10.4                  | Rock          | India  | V    | V   | XX-XX-10          | Uttarakshi, India | 10/19/1991 | IIT Roorkee, India               |
| 5                             | 13   | 113_dz65_00xa.dat | 7.1 | 23                      | 0.496 | -0.332 | 15.5 | -16.5  | 1.58     | -2.24  | 12.3    | 19.6  | 3.22     | 2.67  | 180       | 21.2                  | Rock          | Turkey | H1   | EW  | XX-SS-10          | Duzce, Turkey     | 11/12/1999 | LEDO Sta 6500                    |
|                               | 14   | 114_dz65_00ya.dat | 7.1 | 23                      | 0.619 | -0.920 | 39.0 | -27.1  | 2.76     | -3.05  | 24.8    | 11.6  | 1.10     | 3.74  | 885       | 23.8                  | Rock          | Turkey | H2   | NS  | XX-SS-10          | Duzce, Turkey     | 11/12/1999 | LEDO Sta 6501                    |
|                               | 15   | 115_dz65_Oupa.dat | 7.1 | 23                      | 0.182 | -0.151 | 5.0  | -5.3   | 1.32     | -1.55  | 10.8    | 13.8  | 9.36     | 8.23  | 39        | 17.3                  | Rock          | Turkey | V    | V   | XX-SS-10          | Duzce, Turkey     | 11/12/1999 | LEDO Sta 6502                    |
| 6                             | 16   | 116_kbku_000a.dat | 6.9 | 31                      | 0.290 | -0.239 | 42.3 | -54.8  | 8.92     | -13.59 | 57.5    | 90.2  | 1.41     | 1.06  | 110       | 9.5                   | Rock          | Japan  | H1   | 0   | XX-SS-18          | Kobe, Japan       | 1/16/1995  | Kobe University                  |
|                               | 17   | 117_kbku_090a.dat | 6.9 | 31                      | 0.310 | -0.196 | 34.2 | -20.2  | 7.17     | -6.21  | 43.5    | 40.6  | 1.86     | 2.92  | 74        | 7.4                   | Rock          | Japan  | H2   | 90  | XX-SS-18          | Kobe, Japan       | 1/16/1995  | Kobe University                  |
|                               | 18   | 118_kbku_Oupa.dat | 6.9 | 31                      | 0.380 | -0.324 | 16.5 | -20.2  | 5.17     | -6.55  | 17.1    | 24.5  | 7.06     | 5.12  | 59        | 6.8                   | Rock          | Japan  | V    | UP  | XX-SS-18          | Kobe, Japan       | 1/16/1995  | Kobe University                  |
| 7                             | 19   | 119_kbch_000a.dat | 6.9 | 65                      | 0.079 | -0.093 | 5.9  | -4.8   | 1.83     | -2.90  | 29.4    | 20.3  | 4.08     | 11.51 | 11        | 6.2                   | Rock          | Japan  | H1   | 0   | XX-SS-18          | Kobe, Japan       | 1/20/1995  | Chihaya                          |
|                               | 20   | 120_kbch_090a.dat | 6.9 | 65                      | 0.102 | -0.108 | 3.4  | -4.7   | 0.83     | -1.08  | 13.0    | 17.1  | 7.25     | 5.19  | 14        | 8.5                   | Rock          | Japan  | H2   | 90  | XX-SS-18          | Kobe, Japan       | 1/20/1995  | Chihaya                          |
|                               | 21   | 121_kbch_Oupa.dat | 6.9 | 65                      | 0.067 | -0.080 | 2.0  | -2.4   | 1.14     | -1.52  | 11.5    | 12.0  | 19.46    | 20.35 | 8         | 8.7                   | Rock          | Japan  | V    | UP  | XX-SS-18          | Kobe, Japan       | 1/20/1995  | Chihaya                          |
| 8                             | 22   | 122_lpuc_000a.dat | 7.0 | 66                      | 0.120 | -0.157 | 17.2 | -13.1  | 6.78     | -5.20  | 56.6    | 33.1  | 2.68     | 4.62  | 26        | 9.8                   | Rock          | WUS    | H1   | 0   | XX-RO-17          | Loma Prieta       | 10/18/1989 | Up. Crystal Spr Pulgas           |
|                               | 23   | 123_lpuc_090a.dat | 7.0 | 66                      | 0.083 | -0.086 | 10.3 | -14.1  | 4.54     | -5.85  | 48.9    | 64.3  | 3.46     | 2.49  | 16        | 7.8                   | Rock          | WUS    | H2   | 90  | XX-RO-17          | Loma Prieta       | 10/18/1989 | Up. Crystal Spr Pulgas           |
|                               | 24   | 124_lpuc_Oupa.dat | 7.0 | 66                      | 0.041 | -0.061 | 6.2  | -4.3   | 2.51     | -2.22  | 58.9    | 27.9  | 2.67     | 7.14  | 5         | 2.9                   | Rock          | WUS    | V    | UP  | XX-RO-17          | Loma Prieta       | 10/18/1989 | Up. Crystal Spr Pulgas           |
| 9                             | 25   | 125_saak_090a.dat | 7.1 | 79                      | 0.208 | -0.173 | 5.0  | -4.6   | 0.70     | -0.57  | 9.5     | 10.5  | 5.69     | 4.53  | 22        | 9.2                   | Rock          | Alaska | H1   | 90  | XX-XX-43          | Southeast Alaska  | 5/2/1971   | Adak AK Naval Base               |
|                               | 26   | 126_saak_180a.dat | 7.1 | 79                      | 0.099 | -0.117 | 3.2  | -2.2   | 0.38     | -0.57  | 13.0    | 7.5   | 3.48     | 13.10 | 6         | 3.7                   | Rock          | Alaska | H2   | 180 | XX-XX-43          | Southeast Alaska  | 5/2/1971   | Adak AK Naval Base               |
|                               | 27   | 127_saak_Oupa.dat | 7.1 | 79                      | 0.065 | -0.063 | 2.0  | -2.6   | 0.77     | -0.51  | 12.4    | 16.3  | 11.75    | 4.61  | 4         | 1.1                   | Rock          | Alaska | V    | UP  | XX-XX-43          | Southeast Alaska  | 5/2/1971   | Adak AK Naval Base               |
| 10                            | 28   | 128_cmpt_090a.dat | 7.0 | 16                      | 1.040 | -1.017 | 37.5 | -42.4  | 12.59    | -25.15 | 14.2    | 16.4  | 9.11     | 13.96 | 217       | 34.2                  | Rock          | WUS    | H2   | 90  | XX-RV-10          | Cape Mendocino    | 4/25/1992  | Cape Mendocino - Petrolia        |
|                               | 29   | 129_cmpt_000a.dat | 7.0 | 16                      | 1.498 | -0.494 | 38.2 | -129.2 | 11.80    | -54.21 | 10.0    | 103.0 | 11.89    | 1.57  | 543       | 37.9                  | Rock          | WUS    | H1   | 180 | XX-RV-10          | Cape Mendocino    | 4/25/1992  | Cape Mendocino - Petrolia        |
|                               | 30   | 130_cmpt_Oupa.dat | 7.0 | 16                      | 0.514 | -0.755 | 70.0 | -54.7  | 133.42   | -13.94 | 53.6    | 28.5  | 13.73    | 3.45  | 125       | 7.9                   | Rock          | WUS    | V    | UP  | XX-RV-10          | Cape Mendocino    | 4/25/1992  | Cape Mendocino - Petrolia        |
| 11                            | 31   | 131_inbb_360a.dat | 7.3 | 46                      | 0.170 | -0.192 | 14.0 | -10.9  | 7.86     | -9.44  | 32.3    | 22.4  | 6.71     | 14.89 | 56.64     | 25.1                  | Rock          | WUS    | H1   | 360 | XX-SS-05          | Landers           | 6/28/1992  | Big Bear Lake - Civic Center     |
|                               | 32   | 132_inbb_270a.dat | 7.3 | 46                      | 0.165 | -0.116 | 7.2  | -7.6   | 3.43     | -3.31  | 17.3    | 25.8  | 10.55    | 6.52  | 50.35     | 21.6                  | Rock          | WUS    | H2   | 270 | XX-SS-05          | Landers           | 6/28/1992  | Big Bear Lake - Civic Center     |
|                               | 33   | 133_inbb_Oupa.dat | 7.3 | 46                      | 0.064 | -0.081 | 4.0  | -4.1   | 1.18     | -1.54  | 24.3    | 20.2  | 4.72     | 7.10  | 13.29     | 15.6                  | Rock          | WUS    | V    | UP  | XX-SS-05          | Landers           | 6/28/1992  | Big Bear Lake - Civic Center     |
| 12                            | 34   | 134_tbir_190a.dat | 7.4 | 18                      | 0.401 | -0.277 | 16.5 | -25.0  | 9.86     | -8.78  | 16.2    | 35.5  | 14.30    | 3.83  | 152.85    | 36.9                  | Rock          | Iran   | H1   | 190 | XX-XX-XX          | Tabas, Iran       | 9/16/1978  | Ministry of Housing & Urban Dev. |
|                               | 35   | 135_tbir_080a.dat | 7.4 | 18                      | 0.371 | -0.290 | 24.5 | -24.4  | 22.29    | -23.32 | 25.9    | 33.1  | 13.58    | 11.15 | 160.34    | 36.8                  | Rock          | Iran   | H2   | 80  | XX-XX-XX          | Tabas, Iran       | 9/16/1978  | Ministry of Housing & Urban Dev. |
|                               | 36   | 136_tbir_Oupa.dat | 7.4 | 18                      | 0.180 | -0.189 | 12.1 | -10.7  | 10.22    | -6.28  | 26.4    | 22.3  | 12.38    | 10.17 | 84.9      | 35.7                  | Rock          | Iran   | V    | UP  | XX-XX-XX          | Tabas, Iran       | 9/16/1978  | Ministry of Housing & Urban Dev. |

| M7 Master Accelerograph Table |      |                   |     |                         |       |        |      |       |          |        |         |      |          |       |           |                       |               |               |      |      |                   |               |            |                       |          |  |  |  |
|-------------------------------|------|-------------------|-----|-------------------------|-------|--------|------|-------|----------|--------|---------|------|----------|-------|-----------|-----------------------|---------------|---------------|------|------|-------------------|---------------|------------|-----------------------|----------|--|--|--|
| Set                           | Rec# | Filename          | Mw  | Distance<br>(hyp)<br>km | PGA   |        | PGV  |       | PGD      |        | Ratio 1 |      | Ratio 2  |       | AI<br>95% | Duration<br>bracketed | Site<br>Class | Region        | Comp | deg  | Setting &<br>Mech | Earthquake    | Date       | Station               |          |  |  |  |
|                               |      |                   |     |                         | +     | -      | +    | -     | Lin Disp |        | vm/km   |      | d*km/vm² |       |           |                       |               |               |      |      |                   |               |            |                       |          |  |  |  |
|                               |      |                   |     |                         |       |        |      |       | g%       |        | cm/s    |      | cm       |       |           |                       |               |               |      |      |                   |               |            |                       | in./s/%g |  |  |  |
|                               |      |                   |     |                         |       |        |      |       |          |        |         |      |          |       |           |                       |               |               |      |      |                   |               |            |                       |          |  |  |  |
| 13                            | 37   | 137_elob_180a.dat | 7.6 | 109                     | 0.428 | -0.404 | 35.7 | -38.4 | 8.68     | -4.12  | 32.8    | 37.4 | 2.86     | 1.11  | 346.19    | 33.7                  | Rock          | El Salvador   | H1   | 180  | XX-XX-60          | El Salvador   | 1/13/2001  | Observatorio          |          |  |  |  |
|                               | 38   | 138_elob_090a.dat | 7.6 | 109                     | 0.349 | -0.379 | 24.6 | -26.1 | 4.63     | -5.82  | 27.7    | 27.1 | 2.62     | 3.17  | 225.96    | 31.0                  | Rock          | El Salvador   | H2   | 90   | XX-XX-60          | El Salvador   | 1/13/2001  | Observatorio          |          |  |  |  |
|                               | 39   | 139_elob_Oupa.dat | 7.6 | 109                     | 0.253 | -0.306 | 13.0 | -11.6 | 6.33     | -5.38  | 20.2    | 14.9 | 9.28     | 12.07 | 156.2     | 33.9                  | Rock          | El Salvador   | V    | UP   | XX-XX-60          | El Salvador   | 1/13/2001  | Observatorio          |          |  |  |  |
| 14                            | 40   | 140_elsm_360a.dat | 7.6 | 80                      | 0.581 | -0.881 | 26.6 | -27.8 | 4.06     | -5.95  | 18.0    | 12.4 | 3.26     | 6.65  | 866.49    | 33.3                  | Rock          | El Salvador   | H1   | 360  | XX-XX-60          | El Salvador   | 1/13/2001  | Santiago de Maria     |          |  |  |  |
|                               | 41   | 141_elsm_090a.dat | 7.6 | 80                      | 0.646 | -0.716 | 40.4 | -40.1 | 8.41     | -6.70  | 24.6    | 22.0 | 3.27     | 2.93  | 1057.8    | 35.2                  | Rock          | El Salvador   | H2   | 90   | XX-XX-60          | El Salvador   | 1/13/2001  | Santiago de Maria     |          |  |  |  |
|                               | 42   | 142_elsm_Oupa.dat | 7.6 | 80                      | 0.440 | -0.402 | 14.0 | -16.1 | 6.88     | -4.66  | 12.5    | 15.7 | 15.18    | 7.10  | 302       | 31.1                  | Rock          | El Salvador   | V    | UP   | XX-XX-60          | El Salvador   | 1/13/2001  | Santiago de Maria     |          |  |  |  |
| 15                            | 43   | 143_itst_000a.dat | 6.9 | 32                      | 0.251 | -0.231 | 36.4 | -27.7 | 10.61    | -11.37 | 57.2    | 47.2 | 1.97     | 3.36  | 107.28    | 17.3                  | Rock          | Iprina, Italy | H1   | 0    | XX-XX-9.5         | Iprina, Italy | 11/23/1980 | ENEL, Struno, Italy   |          |  |  |  |
|                               | 44   | 144_itst_270a.dat | 6.9 | 32                      | 0.287 | -0.358 | 49.2 | -51.8 | 17.54    | -32.36 | 67.5    | 57.0 | 2.04     | 4.23  | 127.08    | 23.7                  | Rock          | Iprina, Italy | H2   | 270  | XX-XX-9.5         | Iprina, Italy | 11/23/1980 | ENEL, Struno, Italy   |          |  |  |  |
|                               | 45   | 145_itst_Oupa.dat | 6.9 | 32                      | 0.260 | -0.166 | 16.7 | -25.6 | 10.29    | -6.36  | 25.3    | 60.8 | 9.41     | 1.58  | 46.52     | 11.6                  | Rock          | Iprina, Italy | V    | UP   | XX-XX-9.5         | Iprina, Italy | 11/23/1980 | ENEL, Struno, Italy   |          |  |  |  |
| 16                            | 46   | 146_itba_000a.dat | 6.9 | 25                      | 0.133 | -0.139 | 22.1 | -15.8 | 7.96     | -9.24  | 65.2    | 44.6 | 2.14     | 5.07  | 30.35     | 9.1                   | Rock          | Iprina, Italy | H1   | 0    | XX-XX-9.5         | Iprina, Italy | 11/23/1980 | ENEL, Bagnoli, Italy  |          |  |  |  |
|                               | 47   | 147_itba_270a.dat | 6.9 | 25                      | 0.202 | -0.177 | 31.9 | -17.8 | 9.59     | -9.24  | 62.1    | 39.5 | 1.87     | 5.07  | 38.97     | 10.6                  | Rock          | Iprina, Italy | H2   | 270  | XX-XX-9.5         | Iprina, Italy | 11/23/1980 | ENEL, Bagnoli, Italy  |          |  |  |  |
|                               | 48   | 148_itba_Oupa.dat | 6.9 | 25                      | 0.108 | -0.090 | 11.8 | -14.1 | 4.80     | -5.75  | 43.0    | 61.9 | 3.65     | 2.54  | 15.66     | 7.2                   | Rock          | Iprina, Italy | V    | UP   | XX-XX-9.5         | Iprina, Italy | 11/23/1980 | ENEL, Bagnoli, Italy  |          |  |  |  |
| 17                            | 49   | 149_itbi_000a.dat | 6.9 | 25                      | 0.061 | -0.100 | 23.4 | -14.4 | 14.03    | -12.65 | 152.2   | 56.7 | 1.52     | 5.96  | 16.91     | 9.9                   | Rock          | Iprina, Italy | H1   | 0    | XX-XX-9.5         | Iprina, Italy | 11/23/1980 | ENEL, Bisaccia, Italy |          |  |  |  |
|                               | 50   | 150_itbi_270a.dat | 6.9 | 25                      | 0.083 | -0.057 | 11.9 | -12.5 | 2.89     | -2.93  | 56.6    | 86.9 | 1.65     | 1.04  | 12.46     | 2.1                   | Rock          | Iprina, Italy | H2   | 270  | XX-XX-9.5         | Iprina, Italy | 11/23/1980 | ENEL, Bisaccia, Italy |          |  |  |  |
|                               | 51   | 151_itbi_Oupa.dat | 6.9 | 25                      | 0.055 | -0.067 | 14.1 | -11.6 | 11.12    | -9.09  | 100.9   | 68.1 | 3.02     | 4.46  | 10.49     | 0.8                   | Rock          | Iprina, Italy | V    | UP   | XX-XX-9.5         | Iprina, Italy | 11/23/1980 | ENEL, Bisaccia, Italy |          |  |  |  |
| 18                            | 52   | 152_tasm_Oewa.dat | 7.3 | 73                      | 0.112 | -0.136 | 13.5 | -9.5  | 5.90     | -4.77  | 47.3    | 27.4 | 3.57     | 7.11  | 28.95     | 9.1                   | Rock          | Taiwan        | H1   | EW   | XX-XX-15          | Smart, Taiwan | 11/14/1986 | Smart, Taiwan         |          |  |  |  |
|                               | 53   | 153_tasm_Onsa.dat | 7.3 | 73                      | 0.139 | -0.143 | 12.4 | -10.5 | 3.43     | -6.06  | 35.2    | 29.0 | 3.02     | 7.67  | 33.87     | 37.6                  | Rock          | Taiwan        | H2   | NS   | XX-XX-15          | Smart, Taiwan | 11/14/1986 | Smart, Taiwan         |          |  |  |  |
|                               | 54   | 154_tasm_Odna.dat | 7.3 | 73                      | 0.042 | -0.052 | 4.8  | -5.4  | 1.96     | -3.05  | 45.3    | 40.8 | 3.49     | 5.33  | 6.44      | 0.0                   | Rock          | Taiwan        | V    | DN   | XX-XX-15          | Smart, Taiwan | 11/14/1986 | Smart, Taiwan         |          |  |  |  |
| 19                            | 55   | 155_tach_45ea.dat | 7.6 | 78                      | 0.401 | -0.474 | 36.6 | -32.7 | 21.51    | -50.39 | 35.9    | 27.1 | 6.32     | 21.95 | 125.55    | 21.7                  | Rock          | Taiwan        | H1   | E    | XX-XX-6.8         | ChiChi        | 9/20/1999  | ChiChi, Taiwan        |          |  |  |  |
|                               | 56   | 156_tach_45na.dat | 7.6 | 78                      | 0.512 | -0.250 | 27.8 | -39.1 | 13.59    | -14.20 | 21.4    | 61.5 | 8.81     | 2.28  | 105.88    | 14.2                  | Rock          | Taiwan        | H2   | N    | XX-XX-6.8         | ChiChi        | 9/20/1999  | ChiChi, Taiwan        |          |  |  |  |
|                               | 57   | 157_tach_45va.dat | 7.6 | 78                      | 0.181 | -0.361 | 21.4 | -15.9 | 12.43    | -22.90 | 46.6    | 17.3 | 4.81     | 32.27 | 33.95     | 12.6                  | Rock          | Taiwan        | V    | V    | XX-XX-6.8         | ChiChi        | 9/20/1999  | ChiChi, Taiwan        |          |  |  |  |
| 20                            | 58   | 158_tach_71ea.dat | 7.6 | 17                      | 0.567 | -0.524 | 37.6 | -44.5 | 13.76    | -12.62 | 26.1    | 33.4 | 5.40     | 3.28  | 839.55    | 58.2                  | Rock          | Taiwan        | H1   | E    | XX-XX-6.8         | ChiChi        | 9/20/1999  | ChiChi, Taiwan        |          |  |  |  |
|                               | 59   | 159_tach_71na.dat | 7.6 | 17                      | 0.567 | -0.655 | 47.0 | -69.4 | 48.34    | -49.53 | 32.6    | 41.7 | 12.17    | 6.60  | 855.32    | 58.7                  | Rock          | Taiwan        | H2   | N    | XX-XX-6.8         | ChiChi        | 9/20/1999  | ChiChi, Taiwan        |          |  |  |  |
|                               | 60   | 160_tach_71va.dat | 7.6 | 17                      | 0.449 | -0.348 | 31.3 | -34.8 | 23.33    | -31.34 | 27.4    | 39.4 | 10.50    | 8.83  | 248.74    | 30.0                  | Rock          | Taiwan        | V    | V    | XX-XX-6.8         | ChiChi        | 9/20/1999  | ChiChi, Taiwan        |          |  |  |  |
| 21                            | 61   | 261_mhlu_000a.dat | 8.1 | 84                      | 0.164 | -0.169 | 21.6 | -21.0 | 22.52    | -14.68 | 51.8    | 48.9 | 7.78     | 5.53  | 91.67     | 31.8                  | Rock          | Mexico        | H1   | N00W | Su-IT-27          | Michoacan     | 9/19/1985  | La Union, Mexico      |          |  |  |  |
|                               | 62   | 262_mhli_090a.dat | 8.1 | 84                      | 0.151 | -0.141 | 10.3 | -13.2 | 8.59     | -5.23  | 27.0    | 36.8 | 11.88    | 4.16  | 81.12     | 31.8                  | Rock          | Mexico        | H2   | N90W | Su-IT-27          | Michoacan     | 9/19/1985  | La Union, Mexico      |          |  |  |  |
|                               | 63   | 263_mhlu_Oupa.dat | 8.1 | 84                      | 0.107 | -0.132 | 14.4 | -15.0 | 13.15    | -16.03 | 52.8    | 44.8 | 6.69     | 9.20  | 36.94     | 23.7                  | Rock          | Mexico        | V    | V    | Su-IT-27          | Michoacan     | 9/19/1985  | La Union, Mexico      |          |  |  |  |
| 22                            | 64   | 264_pich_000a.dat | 7.8 | 84                      | 0.259 | -0.205 | 9.6  | -11.7 | 3.72     | -2.76  | 14.6    | 22.5 | 10.31    | 4.06  | 140.48    | 23.2                  | Rock          | Chile         | H1   | 0    | Su-IT-33          | Valparaiso    | 3/3/1985   | Pichemu, Chile        |          |  |  |  |
|                               | 65   | 265_pich_090a.dat | 7.8 | 84                      | 0.151 | -0.178 | 12.4 | -12.4 | 3.63     | -3.92  | 32.5    | 27.5 | 3.47     | 4.43  | 76.65     | 22.5                  | Rock          | Chile         | H2   | 90   | Su-IT-33          | Valparaiso    | 3/3/1985   | Pichemu, Chile        |          |  |  |  |
|                               | 66   | 266_pich_Oupa.dat | 7.8 | 84                      | 0.107 | -0.121 | 5.1  | -5.9  | 1.95     | -1.77  | 18.8    | 19.3 | 7.81     | 5.95  | 24.04     | 18.2                  | Rock          | Chile         | V    | UP   | Su-IT-33          | Valparaiso    | 3/3/1985   | Pichemu, Chile        |          |  |  |  |
| 23                            | 67   | 267_pach_140a.dat | 7.8 | 84                      | 0.231 | -0.230 | 12.4 | -11.3 | 1.67     | -1.88  | 21.1    | 19.4 | 2.47     | 3.31  | 254.62    | 59.1                  | Rock          | Chile         | H    | 140  | Su-IT-33          | Valparaiso    | 3/3/1985   | Papudo Chile          |          |  |  |  |
|                               | 68   | 268_pach_Oupa.dat | 7.8 | 84                      | 0.197 | -0.177 | 6.2  | -5.2  | 1.17     | -1.12  | 12.5    | 11.6 | 5.79     | 7.22  | 93.93     | 50.3                  | Rock          | Chile         | V    | UP   | Su-IT-33          | Valparaiso    | 3/3/1985   | Papudo Chile          |          |  |  |  |

Table 4.2. Master accelerograph table of magnitude 6.1 – 6.8 earthquakes.

| M6 Master Accelerograph Table |      |                   |     |                         |       |        |       |       |          |        |         |      |           |       |            |                       |               |        |      |     |                   |                  |           |                                |
|-------------------------------|------|-------------------|-----|-------------------------|-------|--------|-------|-------|----------|--------|---------|------|-----------|-------|------------|-----------------------|---------------|--------|------|-----|-------------------|------------------|-----------|--------------------------------|
| Set                           | Rec# | Filename          | Mw  | Distance<br>(hyp)<br>km | PGA   |        | PGV   |       | PGD      |        | Ratio 1 |      | Ratio 2   |       | AI<br>0.95 | Duration<br>bracketed | Site<br>Class | Region | Comp | deg | Setting &<br>Mech | Earthquake       | date      | Station                        |
|                               |      |                   |     |                         | +     | -      | +     | -     | Lin Disp |        | vm/km   |      | d*km/vm^2 |       |            |                       |               |        |      |     |                   |                  |           |                                |
|                               |      |                   |     |                         |       |        |       |       | +        | -      | +       | -    | +         | -     |            |                       |               |        |      |     |                   |                  |           |                                |
|                               |      |                   |     |                         |       |        |       |       |          |        |         |      |           |       |            |                       |               |        |      |     |                   |                  |           |                                |
| 24                            | 69   | 301_bbrc_090a.dat | 6.5 | 70                      | 0.051 | -0.043 | 3.0   | -3.4  | 0.51     | -0.61  | 23.2    | 31.1 | 2.82      | 2.20  | 6          | 0                     | Rock(a)       | WUS    | H1   | 90  | XX-RO-13          | Big Bear         | 6/28/1992 | Rancho Cucamonga - Deer Canyon |
|                               | 70   | 302_bbrc_180a.dat | 6.5 | 70                      | 0.032 | -0.029 | 2.0   | -1.9  | 0.43     | -0.32  | 24.4    | 26.2 | 3.48      | 2.46  | 2          | 0                     | Rock(a)       | WUS    | H2   | 180 | XX-RO-13          | Big Bear         | 6/28/1992 | Rancho Cucamonga - Deer Canyon |
|                               | 71   | 303_bbrc_Oupa.dat | 6.5 | 70                      | 0.021 | -0.017 | 1.2   | -1.1  | 0.20     | -0.21  | 22.5    | 25.2 | 2.86      | 2.97  | 1          | 0                     | Rock(a)       | WUS    | V    | UP  | XX-RO-13          | Big Bear         | 6/28/1992 | Rancho Cucamonga - Deer Canyon |
| 25                            | 72   | 304_clpv_065a.dat | 6.4 | 33                      | 0.161 | -0.147 | 13.3  | -16.2 | 3.32     | -2.94  | 32.7    | 43.4 | 2.94      | 1.62  | 35         | 9                     | Rock(a)       | WUS    | H1   | 65  | MF-SS-05          | Coalinga         | 5/2/1983  | Parkfield Vineyard Canyon      |
| 26                            | 73   | 305_clsc_045a.dat | 6.4 | 34                      | 0.166 | -0.158 | 14.9  | -16.1 | 4.18     | -2.58  | 35.2    | 40.1 | 3.08      | 1.54  | 26         | 7                     | Rock(a)       | WUS    | H1   | 45  | XX-RO-13          | Coalinga         | 5/2/1983  | Slack Canyon                   |
|                               | 74   | 306_clsc_315a.dat | 6.4 | 34                      | 0.111 | -0.153 | 11.7  | -13.3 | 2.64     | -2.71  | 41.6    | 34.2 | 2.10      | 2.30  | 21         | 4                     | Rock(a)       | WUS    | H2   | 315 | XX-RO-13          | Coalinga         | 5/2/1983  | Slack Canyon                   |
|                               | 75   | 307_clsc_Oupa.dat | 6.4 | 34                      | 0.044 | -0.053 | 5.4   | -6.8  | 2.05     | -2.45  | 48.3    | 50.8 | 3.02      | 2.73  | 4          | 0                     | Rock(a)       | WUS    | V    | UP  | XX-RO-13          | Coalinga         | 5/2/1983  | Slack Canyon                   |
| 27                            | 76   | 308_vmcp_045a.dat | 6.3 | 34                      | 0.291 | -0.621 | 31.8  | -24.9 | 12.82    | -7.10  | 43.0    | 15.8 | 3.62      | 6.98  | 177        | 13                    | Rock(a)       | Mexico | H1   | 45  | XX-XX-11          | Victoria, Mexico | 6/9/1980  | UNAMUCSD Cerro Prieto          |
|                               | 77   | 309_vmcp_315a.dat | 6.3 | 34                      | 0.294 | -0.587 | 19.9  | -16.8 | 9.43     | -7.77  | 26.7    | 11.3 | 6.86      | 15.78 | 90         | 12                    | Rock(a)       | Mexico | H2   | 315 | XX-XX-11          | Victoria, Mexico | 6/9/1980  | UNAMUCSD Cerro Prieto          |
|                               | 78   | 310_vmcp_Oupa.dat | 6.3 | 34                      | 0.244 | -0.304 | 12.1  | -10.6 | 3.61     | -4.81  | 19.5    | 13.8 | 5.90      | 12.69 | 47         | 10                    | Rock(a)       | Mexico | V    | UP  | XX-XX-11          | Victoria, Mexico | 6/9/1980  | UNAMUCSD Cerro Prieto          |
| 28                            | 79   | 311_bbsv_090a.dat | 6.5 | 40                      | 0.059 | -0.056 | 1.9   | -1.9  | 0.23     | -0.34  | 12.9    | 13.2 | 3.56      | 5.25  | 5          | 0                     | Rock          | WUS    | H    | 90  | XX-RO-13          | Big Bear         | 6/28/1992 | Silent Valley - Poppet Flag    |
|                               | 80   | 312_bbsv_360a.dat | 6.5 | 40                      | 0.057 | -0.070 | 2.1   | -2.0  | 0.30     | -0.29  | 14.2    | 11.5 | 3.98      | 4.87  | 7          | 6                     | Rock          | WUS    | H2   | 360 | XX-RO-13          | Big Bear         | 6/28/1992 | Silent Valley - Poppet Flag    |
|                               | 81   | 313_bbsv_Oupa.dat | 6.5 | 40                      | 0.044 | -0.047 | 1.3   | -1.4  | 0.27     | -0.18  | 11.6    | 11.8 | 6.96      | 4.07  | 4          | 0                     | Rock          | WUS    | V    | UP  | XX-RO-13          | Big Bear         | 6/28/1992 | Silent Valley - Poppet Flag    |
| 29                            | 82   | 314_mhgg_067a.dat | 6.2 | 39                      | 0.114 | -0.089 | 3.1   | -3.6  | 0.83     | -0.88  | 10.7    | 15.9 | 9.57      | 6.01  | 5          | 3                     | Rock          | WUS    | H1   | 67  | XX-SS-09          | Morgan Hill      | 4/24/1984 | Gilroy, Gailan Coll            |
|                               | 83   | 315_mhgg_337a.dat | 6.2 | 39                      | 0.095 | -0.069 | 2.9   | -2.7  | 0.71     | -0.94  | 11.9    | 15.1 | 8.02      | 9.06  | 5          | 3                     | Rock          | WUS    | H2   | 337 | XX-SS-09          | Morgan Hill      | 4/24/1984 | Gilroy, Gailan Coll            |
|                               | 84   | 316_mhgg_Oupa.dat | 6.2 | 39                      | 0.115 | -0.082 | 2.2   | -1.9  | 0.25     | -0.26  | 7.6     | 9.3  | 5.69      | 5.44  | 2          | 0                     | Rock          | WUS    | V    | UP  | XX-SS-09          | Morgan Hill      | 4/24/1984 | Gilroy, Gailan Coll            |
| 30                            | 85   | 317_pspf_000a.dat | 6.1 | 28                      | 0.107 | -0.139 | 3.9   | -2.8  | 0.56     | -0.47  | 14.5    | 7.9  | 3.80      | 8.36  | 9          | 2                     | Rock          | WUS    | H1   | 0   | XX-SS-11          | N.Palm Springs   | 7/8/1986  | Silent Valley - Poppet Flat    |
|                               | 86   | 318_pspf_090a.dat | 6.1 | 28                      | 0.110 | -0.113 | 3.6   | -4.0  | 0.47     | -0.80  | 12.7    | 13.8 | 3.97      | 5.65  | 5          | 2                     | Rock          | WUS    | H2   | 90  | XX-SS-11          | N.Palm Springs   | 7/8/1986  | Silent Valley - Poppet Flat    |
|                               | 87   | 319_pspf_Oupa.dat | 6.1 | 28                      | 0.074 | -0.095 | 2.3   | -2.9  | 0.44     | -0.46  | 12.4    | 12.2 | 5.92      | 4.96  | 4          | 1                     | Rock          | WUS    | V    | UP  | XX-SS-11          | N.Palm Springs   | 7/8/1986  | Silent Valley - Poppet Flat    |
| 31                            | 88   | 320_sflh_111a.dat | 6.6 | 24                      | 0.161 | -0.192 | 5.6   | -5.4  | 0.88     | -0.90  | 13.6    | 11.1 | 4.46      | 5.81  | 22         | 8                     | Rock          | WUS    | H1   | 111 | XX-RO-13          | San Fernando     | 2/9/1971  | Lake Hughes                    |
|                               | 89   | 321_sflh_201a.dat | 6.6 | 24                      | 0.153 | -0.152 | 8.4   | -7.9  | 0.66     | -1.88  | 21.6    | 20.6 | 1.41      | 4.42  | 19         | 6                     | Rock          | WUS    | H2   | 201 | XX-RO-13          | San Fernando     | 2/9/1971  | Lake Hughes                    |
|                               | 90   | 322_sflh_dwna.dat | 6.6 | 24                      | 0.141 | -0.164 | 6.4   | -4.0  | 0.79     | -0.87  | 17.8    | 9.7  | 2.70      | 8.65  | 17         | 6                     | Rock          | WUS    | V    | DN  | XX-RO-13          | San Fernando     | 2/9/1971  | Lake Hughes                    |
| 32                            | 91   | 323_sfol_180a.dat | 6.6 | 39                      | 0.079 | -0.089 | 5.3   | -3.9  | 0.78     | -0.83  | 26.5    | 17.4 | 2.15      | 4.70  | 10         | 7                     | Rock          | WUS    | H1   | 180 | XX-RO-13          | San Fernando     | 2/9/1971  | Pasadena - Old Seismo Lab      |
|                               | 92   | 324_sfol_270a.dat | 6.6 | 39                      | 0.202 | -0.180 | 9.8   | -10.8 | 2.40     | -2.06  | 19.0    | 23.7 | 4.99      | 3.10  | 30         | 7                     | Rock          | WUS    | H2   | 270 | XX-RO-13          | San Fernando     | 2/9/1971  | Pasadena - Old Seismo Lab      |
|                               | 93   | 325_sfol_dwna.dat | 6.6 | 39                      | 0.076 | -0.091 | 4.3   | -3.9  | 1.36     | -1.01  | 22.3    | 16.9 | 5.46      | 5.92  | 6          | 2                     | Rock          | WUS    | V    | DN  | XX-RO-13          | San Fernando     | 2/9/1971  | Pasadena - Old Seismo Lab      |
| 33                            | 94   | 326_sfpd_164a.dat | 6.6 | 12                      | 1.229 | -0.788 | 38.8  | -49.1 | 12.08    | -2.71  | 12.4    | 24.5 | 9.68      | 0.87  | 391        | 10                    | Rock          | WUS    | H2   | 164 | XX-RO-13          | San Fernando     | 2/9/1971  | Pacoima Dam                    |
|                               | 95   | 327_sfpd_254a.dat | 6.6 | 12                      | 1.585 | -0.848 | 43.2  | -54.9 | 5.64     | -5.15  | 10.7    | 25.5 | 4.69      | 1.42  | 786        | 24                    | Rock          | WUS    | H1   | 254 | XX-RO-13          | San Fernando     | 2/9/1971  | Pacoima Dam                    |
|                               | 96   | 328_sfpd_dwna.dat | 6.6 | 12                      | 1.124 | -1.285 | 103.5 | -68.4 | 22.94    | -12.60 | 36.3    | 21.0 | 2.36      | 3.39  | 677        | 24                    | Rock          | WUS    | V    | DN  | XX-RO-13          | San Fernando     | 2/9/1971  | Pacoima Dam                    |
| 34                            | 97   | 329_nrgp_270a.dat | 6.7 | 25                      | 0.271 | -0.289 | 24.9  | -26.5 | 3.92     | -3.53  | 36.2    | 36.1 | 1.68      | 1.42  | 137        | 15                    | Rock          | WUS    | H1   | 270 | XX-XX-18          | Northridge       | 1/17/1994 | Griffith Park Observatory      |
|                               | 98   | 330_nrgp_360a.dat | 6.7 | 25                      | 0.129 | -0.164 | 13.5  | -10.4 | 2.39     | -1.82  | 41.3    | 25.1 | 1.65      | 2.68  | 37         | 11                    | Rock          | WUS    | H2   | 360 | XX-XX-18          | Northridge       | 1/17/1994 | Griffith Park Observatory      |
|                               | 99   | 331_nrgp_Oupa.dat | 6.7 | 25                      | 0.134 | -0.116 | 5.6   | -9.6  | 1.55     | -1.61  | 16.4    | 32.4 | 6.59      | 2.00  | 18         | 8                     | Rock          | WUS    | V    | UP  | XX-XX-18          | Northridge       | 1/17/1994 | Griffith Park Observatory      |
| 35                            | 100  | 332_nrbh_060a.dat | 6.7 | 23                      | 0.085 | -0.073 | 3.6   | -3.2  | 1.40     | -1.45  | 16.5    | 17.6 | 9.17      | 9.81  | 6          | 3                     | Rock          | WUS    | H1   | 60  | XX-XX-18          | Northridge       | 1/17/1994 | Burbank - Howard Rd            |
|                               | 101  | 333_nrbh_330a.dat | 6.7 | 23                      | 0.120 | -0.095 | 6.9   | -9.5  | 2.29     | -1.86  | 22.5    | 39.7 | 5.72      | 1.90  | 19         | 7                     | Rock          | WUS    | H2   | 330 | XX-XX-18          | Northridge       | 1/17/1994 | Burbank - Howard Rd            |
|                               | 102  | 334_nrbh_Oupa.dat | 6.7 | 23                      | 0.150 | -0.163 | 8.5   | -6.6  | 1.70     | -1.75  | 22.4    | 15.9 | 3.43      | 6.45  | 30         | 8                     | Rock          | WUS    | V    | UP  | XX-XX-18          | Northridge       | 1/17/1994 | Burbank - Howard Rd            |
| 36                            | 103  | 335_nrmw_000a.dat | 6.7 | 46                      | 0.085 | -0.087 | 3.4   | -2.7  | 0.52     | -0.57  | 15.9    | 12.1 | 3.67      | 6.88  | 9          | 7                     | Rock          | WUS    | H1   | 0   | XX-XX-18          | Northridge       | 1/17/1994 | Mt. Wilson - CIT Seismic Stn   |
|                               | 104  | 336_nrmw_090a.dat | 6.7 | 46                      | 0.234 | -0.169 | 6.5   | -7.3  | 0.54     | -0.70  | 11.0    | 16.9 | 2.90      | 2.19  | 27         | 7                     | Rock          | WUS    | H2   | 90  | XX-XX-18          | Northridge       | 1/17/1994 | Mt. Wilson - CIT Seismic Stn   |
|                               | 105  | 337_nrmw_Oupa.dat | 6.7 | 46                      | 0.119 | -0.135 | 5.7   | -3.4  | 0.45     | -0.42  | 18.9    | 9.9  | 1.62      | 4.87  | 20         | 9                     | Rock          | WUS    | V    | UP  | XX-XX-18          | Northridge       | 1/17/1994 | Mt. Wilson - CIT Seismic Stn   |
| 37                            | 106  | 338_nrpd_175a.dat | 6.7 | 20                      | 0.187 | -0.191 | 14.1  | -9.6  | 1.29     | -1.26  | 29.7    | 19.9 | 1.19      | 2.54  | 27         | 8                     | Rock          | WUS    | H1   | 175 | XX-XX-18          | Northridge       | 1/17/1994 | Pacoima Dam - Down Stream      |
|                               | 107  | 339_nrpd_265a.dat | 6.7 | 20                      | 0.353 | -0.415 | 45.1  | -17.6 | 4.98     | -4.92  | 50.2    | 16.7 | 0.85      | 6.46  | 84         | 7                     | Rock          | WUS    | H2   | 265 | XX-XX-18          | Northridge       | 1/17/1994 | Pacoima Dam - Down Stream      |
|                               | 108  | 340_nrpd_Oupa.dat | 6.7 | 20                      | 0.434 | -0.373 | 30.9  | -10.8 | 4.04     | -4.46  | 28.1    | 11.4 | 1.80      | 14.05 | 66         | 5                     | Rock          | WUS    | V    | UP  | XX-XX-18          | Northridge       | 1/17/1994 | Pacoima Dam - Down Stream      |

| M6 Master Accelerograph Table |      |                    |     |                         |       |        |       |       |          |        |          |      |           |       |            |                       |               |             |      |     |                   |                    |            |                          |   |
|-------------------------------|------|--------------------|-----|-------------------------|-------|--------|-------|-------|----------|--------|----------|------|-----------|-------|------------|-----------------------|---------------|-------------|------|-----|-------------------|--------------------|------------|--------------------------|---|
| Set                           | Rec# | Filename           | Mw  | Distance<br>(hyp)<br>km | PGA   |        | PGV   |       | PGD      |        | Ratio 1  |      | Ratio 2   |       | AI<br>0.95 | Duration<br>bracketed | Site<br>Class | Region      | Comp | deg | Setting &<br>Mech | Earthquake         | date       | Station                  |   |
|                               |      |                    |     |                         | +     | -      | +     | -     | Lin Disp |        | vm/km    |      | d*km/vm^2 |       |            |                       |               |             |      |     |                   |                    |            |                          |   |
|                               |      |                    |     |                         |       |        |       |       | g%       | cm     | in./s/%g | +    | -         | +     |            |                       |               |             |      |     |                   |                    |            |                          | - |
|                               |      |                    |     |                         |       |        |       |       |          |        |          |      |           |       |            |                       |               |             |      |     |                   |                    |            |                          |   |
|                               |      |                    |     |                         |       |        |       |       |          |        |          |      |           |       |            |                       |               |             |      |     |                   |                    |            |                          |   |
| 38                            | 109  | 341_nrp_x_104a.dat | 6.7 | 20                      | 1.226 | -0.977 | 112.6 | -55.2 | 31.74    | -35.01 | 36.1     | 22.3 | 3.01      | 11.00 | 800        | 34                    | Rock          | WUS         | H1   | 104 | XX-XX-18          | Northridge         | 1/17/1994  | Pacoima Dam - Upper Left |   |
|                               | 110  | 342_nrp_x_194a.dat | 6.7 | 20                      | 0.849 | -1.160 | 54.1  | -43.4 | 11.65    | -5.03  | 25.1     | 14.7 | 3.31      | 3.04  | 687        | 33                    | Rock          | WUS         | H2   | 194 | XX-XX-18          | Northridge         | 1/17/1994  | Pacoima Dam - Upper Left |   |
|                               | 111  | 343_nrp_x_0upa.dat | 6.7 | 20                      | 0.650 | -0.699 | 52.5  | -56.4 | 18.51    | -13.24 | 31.8     | 31.8 | 4.27      | 2.85  | 385        | 32                    | Rock          | WUS         | V    | UP  | XX-XX-18          | Northridge         | 1/17/1994  | Pacoima Dam - Upper Left |   |
| 39                            | 112  | 344_nrvr_000a.dat  | 6.7 | 38                      | 0.091 | -0.077 | 5.0   | -6.1  | 1.17     | -1.61  | 21.7     | 31.4 | 4.12      | 3.23  | 9          | 3                     | Rock          | WUS         | H1   | 0   | XX-XX-18          | Northridge         | 1/17/1994  | Vasquez Rocks Park       |   |
|                               | 113  | 345_nrvr_090a.dat  | 6.7 | 38                      | 0.140 | -0.151 | 18.4  | -9.3  | 1.46     | -2.88  | 51.9     | 24.3 | 0.59      | 4.90  | 34         | 8                     | Rock          | WUS         | H2   | 90  | XX-XX-18          | Northridge         | 1/17/1994  | Vasquez Rocks Park       |   |
|                               | 114  | 346_nrvr_0upa.dat  | 6.7 | 38                      | 0.139 | -0.128 | 11.1  | -10.8 | 2.88     | -2.86  | 31.3     | 33.4 | 3.21      | 3.06  | 29         | 8                     | Rock          | WUS         | V    | UP  | XX-XX-18          | Northridge         | 1/17/1994  | Vasquez Rocks Park       |   |
| 40                            | 115  | 347_nrwa_095a.dat  | 6.7 | 19                      | 0.069 | -0.106 | 3.1   | -3.6  | 1.11     | -0.71  | 17.7     | 13.5 | 7.82      | 5.59  | 8          | 6                     | Rock          | WUS         | H1   | 95  | XX-XX-18          | Northridge         | 1/17/1994  | LA - Wonderland Ave      |   |
|                               | 116  | 348_nrwa_185a.dat  | 6.7 | 19                      | 0.094 | -0.112 | 5.7   | -8.7  | 1.43     | -1.80  | 23.9     | 30.3 | 4.04      | 2.64  | 13         | 6                     | Rock          | WUS         | H2   | 185 | XX-XX-18          | Northridge         | 1/17/1994  | LA - Wonderland Ave      |   |
|                               | 117  | 349_nrwa_0upa.dat  | 6.7 | 19                      | 0.172 | -0.087 | 11.8  | -11.1 | 1.24     | -2.80  | 27.1     | 50.0 | 1.49      | 1.94  | 18         | 6                     | Rock          | WUS         | V    | UP  | XX-XX-18          | Northridge         | 1/17/1994  | LA - Wonderland Ave      |   |
| 41                            | 118  | 350_omnz_130a.dat  | 6.2 | 89                      | 0.065 | -0.080 | 4.0   | -4.0  | 0.30     | -0.38  | 24.5     | 19.5 | 1.17      | 1.88  | 8          | 4                     | Rock          | New Zealand | H1   | 130 | XX-XX-36          | Ormond             | 8/10/1993  | Maraenui, NZ             |   |
|                               | 119  | 351_omnz_040a.dat  | 6.2 | 89                      | 0.093 | -0.107 | 3.7   | -5.2  | 0.23     | -0.34  | 15.6     | 19.0 | 1.53      | 1.33  | 11         | 5                     | Rock          | New Zealand | H2   | 40  | XX-XX-36          | Ormond             | 8/10/1993  | Maraenui, NZ             |   |
|                               | 120  | 352_omnz_0upa.dat  | 6.2 | 89                      | 0.039 | -0.040 | 1.2   | -1.1  | 0.16     | -0.17  | 12.3     | 10.7 | 4.07      | 5.72  | 4          | 0                     | Rock          | New Zealand | V    | UP  | XX-XX-36          | Ormond             | 8/10/1993  | Maraenui, NZ             |   |
| 42                            | 121  | 353_vall_100a.dat  | 6.2 | 65                      | 0.147 | -0.191 | 12.0  | -13.4 | 1.27     | -1.36  | 32.1     | 27.7 | 1.27      | 1.41  | 61         | 17                    | Rock          | Chile       | H1   | 100 | XX-XX-50          | Valparaiso A Shock | 3/3/1985   | Llolleo, Chile           |   |
|                               | 122  | 354_vall_010a.dat  | 6.2 | 65                      | 0.163 | -0.186 | 10.9  | -10.8 | 1.50     | -1.07  | 26.4     | 22.8 | 2.02      | 1.68  | 65         | 24                    | Rock          | Chile       | H2   | 10  | XX-XX-50          | Valparaiso A Shock | 3/3/1985   | Llolleo, Chile           |   |
|                               | 123  | 355_vall_0upa.dat  | 6.2 | 65                      | 0.137 | -0.121 | 4.5   | -4.6  | 0.71     | -0.86  | 12.9     | 15.1 | 4.71      | 4.79  | 28         | 14                    | Rock          | Chile       | V    | UP  | XX-XX-50          | Valparaiso A Shock | 3/3/1985   | Llolleo, Chile           |   |
| 43                            | 124  | 356_cigo_290a.dat  | 6.6 | 17                      | 0.199 | -0.145 | 19.8  | -22.9 | 2.84     | -5.25  | 39.2     | 62.1 | 1.42      | 1.43  | 26         | 4                     | Rock          | India       | H1   | 290 | XX-XX-15          | Chamoli            | 3/28/1993  | Gopeshwar, India         |   |
|                               | 125  | 357_cigo_020a.dat  | 6.6 | 17                      | 0.205 | -0.360 | 44.9  | -28.5 | 12.39    | -4.16  | 86.1     | 31.2 | 1.24      | 1.80  | 72         | 10                    | Rock          | India       | H2   | 20  | XX-XX-15          | Chamoli            | 3/28/1993  | Gopeshwar, India         |   |
|                               | 126  | 358_cigo_0upa.dat  | 6.6 | 17                      | 0.157 | -0.151 | 6.9   | -7.6  | 1.65     | -3.25  | 17.5     | 19.7 | 5.26      | 8.44  | 22         | 6                     | Rock          | India       | V    | UP  | XX-XX-15          | Chamoli            | 3/28/1993  | Gopeshwar, India         |   |
| 44                            | 127  | 359_cigo_000a.dat  | 6.6 | 75                      | 0.064 | -0.073 | 3.2   | -3.5  | 0.86     | -0.74  | 19.7     | 18.8 | 5.24      | 4.36  | 10         | 6                     | Rock          | India       | H1   | 0   | XX-XX-15          | Chamoli            | 3/28/1993  | Ghansiali, India         |   |
|                               | 128  | 360_cigo_090a.dat  | 6.6 | 75                      | 0.081 | -0.084 | 3.7   | -4.2  | 1.25     | -0.84  | 17.9     | 19.8 | 7.32      | 3.87  | 13         | 7                     | Rock          | India       | H2   | 90  | XX-XX-15          | Chamoli            | 3/28/1993  | Ghansiali, India         |   |
|                               | 129  | 361_cigo_0upa.dat  | 6.6 | 75                      | 0.035 | -0.040 | 2.1   | -1.5  | 0.34     | -0.39  | 24.4     | 15.3 | 2.52      | 6.36  | 3          | 0                     | Rock          | India       | V    | UP  | XX-XX-15          | Chamoli            | 3/28/1993  | Ghansiali, India         |   |
| 45                            | 130  | 362_tknz_130a.dat  | 6.3 | 68                      | 0.066 | -0.084 | 2.3   | -3.4  | 0.22     | -0.21  | 13.6     | 15.8 | 2.73      | 1.50  | 6          | 2                     | Rock          | New Zealand | H1   | 130 | XX-XX-12          | Offshore Te Kuha   | 12/15/1994 | Maraenui, NZ             |   |
|                               | 131  | 363_tknz_040a.dat  | 6.3 | 68                      | 0.086 | -0.079 | 3.6   | -4.3  | 0.22     | -0.37  | 16.5     | 21.5 | 1.42      | 1.54  | 8          | 3                     | Rock          | New Zealand | H2   | 40  | XX-XX-12          | Offshore Te Kuha   | 12/15/1994 | Maraenui, NZ             |   |
|                               | 132  | 364_tknz_0upa.dat  | 6.3 | 68                      | 0.035 | -0.034 | 0.9   | -1.2  | 0.12     | -0.13  | 10.5     | 13.9 | 4.87      | 2.99  | 2          | 0                     | Rock          | New Zealand | V    | UP  | XX-XX-12          | Offshore Te Kuha   | 12/15/1994 | Maraenui, NZ             |   |
| 46                            | 133  | 365_nrmn_270a.dat  | 6.7 | 19                      | 0.162 | -0.147 | 7.3   | -7.3  | 1.73     | -2.04  | 17.7     | 19.6 | 5.17      | 5.49  | 28         | 9                     | Rock          | WUS         | H    | 270 | XX-XX-18          | Northridge         | 1/17/1994  | Monte Nido Fire Station  |   |
|                               | 134  | 366_nrmn_360a.dat  | 6.7 | 19                      | 0.178 | -0.179 | 6.8   | -8.4  | 3.17     | -2.54  | 15.0     | 18.5 | 12.01     | 6.30  | 31         | 9                     | Rock          | WUS         | H2   | 360 | XX-XX-18          | Northridge         | 1/17/1994  | Monte Nido Fire Station  |   |
|                               | 135  | 367_nrmn_0upa.dat  | 6.7 | 19                      | 0.125 | -0.118 | 3.4   | -3.8  | 1.56     | -0.96  | 10.8     | 12.8 | 16.25     | 7.50  | 17         | 10                    | Rock          | WUS         | V    | UP  | XX-XX-18          | Northridge         | 1/17/1994  | Monte Nido Fire Station  |   |
| 47                            | 136  | 368_iibi_000a.dat  | 6.2 | 22                      | 0.035 | -0.049 | 4.5   | -3.3  | 0.46     | -0.52  | 50.8     | 26.5 | 0.78      | 2.31  | 3          | 0                     | Rock          | Italy       | H1   | 0   | XX-XX-07          | Irpinia            | 11/23/1980 | Bagnoli Irpinio          |   |
|                               | 137  | 369_iibi_270a.dat  | 6.2 | 22                      | 0.031 | -0.058 | 3.1   | -3.5  | 0.67     | -0.56  | 39.8     | 23.8 | 2.08      | 2.57  | 2          | 0                     | Rock          | Italy       | H2   | 270 | XX-XX-07          | Irpinia            | 11/23/1980 | Bagnoli Irpinio          |   |
|                               | 138  | 370_iibi_0upa.dat  | 6.2 | 22                      | 0.032 | -0.024 | 2.2   | -2.9  | 0.73     | -0.70  | 27.6     | 46.5 | 4.59      | 2.01  | 1          | 0                     | Rock          | Italy       | V    | UP  | XX-XX-07          | Irpinia            | 11/23/1980 | Bagnoli Irpinio          |   |
| 48                            | 139  | 371_iist_000a.dat  | 6.2 | 27                      | 0.056 | -0.071 | 3.4   | -3.3  | 0.73     | -0.91  | 23.9     | 18.6 | 3.46      | 5.70  | 7          | 2                     | Rock          | Italy       | H1   | 0   | XX-XX-07          | Irpinia            | 11/23/1980 | Sturno                   |   |
|                               | 140  | 372_iist_270a.dat  | 6.2 | 27                      | 0.071 | -0.077 | 4.4   | -4.4  | 0.69     | -0.73  | 24.5     | 22.3 | 2.46      | 2.91  | 7          | 2                     | Rock          | Italy       | H2   | 270 | XX-XX-07          | Irpinia            | 11/23/1980 | Sturno                   |   |
|                               | 141  | 373_iist_0upa.dat  | 6.2 | 27                      | 0.032 | -0.037 | 2.2   | -2.4  | 0.40     | -0.39  | 26.7     | 25.8 | 2.66      | 2.45  | 1          | 0                     | Rock          | Italy       | V    | UP  | XX-XX-07          | Irpinia            | 11/23/1980 | Sturno                   |   |
| 49                            | 142  | 374_sffd_056a.dat  | 6.6 | 29                      | 0.071 | -0.060 | 4.7   | -3.8  | 0.41     | -0.68  | 25.8     | 25.1 | 1.31      | 2.71  | 4          | 1                     | Rock          | WUS         | H1   | 56  | XX-RO-13          | San Fernando       | 2/9/1971   | Fairmont Dam             |   |
|                               | 143  | 375_sffd_326a.dat  | 6.6 | 29                      | 0.109 | -0.092 | 6.4   | -5.1  | 0.98     | -1.08  | 23.3     | 22.0 | 2.53      | 3.68  | 5          | 2                     | Rock          | WUS         | H2   | 326 | XX-RO-13          | San Fernando       | 2/9/1971   | Fairmont Dam             |   |
|                               | 144  | 376_sffd_0upa.dat  | 6.6 | 29                      | 0.039 | -0.034 | 3.5   | -2.9  | 0.73     | -0.62  | 35.7     | 32.7 | 2.23      | 2.57  | 2          | 0                     | Rock          | WUS         | V    | UP  | XX-RO-13          | San Fernando       | 2/9/1971   | Fairmont Dam             |   |
| 50                            | 145  | 377_ivcp_147a.dat  | 6.5 | 25                      | 0.162 | -0.169 | 11.6  | -10.6 | 4.10     | -4.26  | 28.1     | 24.8 | 4.87      | 6.24  | 110        | 34                    | Rock          | WUS         | H1   | 147 | XX-RO-10          | Imperial Valley    | 10/15/1979 | Cerro Prieto             |   |
|                               | 146  | 378_ivcp_237a.dat  | 6.5 | 25                      | 0.148 | -0.157 | 15.6  | -18.6 | 8.04     | -7.36  | 41.7     | 46.7 | 4.77      | 3.27  | 120        | 41                    | Rock          | WUS         | H2   | 237 | XX-RO-10          | Imperial Valley    | 10/15/1979 | Cerro Prieto             |   |
|                               | 147  | 379_ivcp_0dna.dat  | 6.5 | 25                      | 0.175 | -0.212 | 6.7   | -6.7  | 2.12     | -3.26  | 15.0     | 12.5 | 8.20      | 14.92 | 68         | 24                    | Rock          | WUS         | V    | DN  | XX-RO-10          | Imperial Valley    | 10/15/1979 | Cerro Prieto             |   |
| 51                            | 148  | 380_kgkz_00la.dat  | 6.4 | 18                      | 0.215 | -0.147 | 9.2   | -9.3  | 1.66     | -1.47  | 16.8     | 25.0 | 4.16      | 2.44  | 25         | 5                     | Rock          | Greece      | H1   | L   | XX-RO-13          | Kozani, Greece     | 05/13/1995 | ITSAK Kozani             |   |

| M6 Master Accelerograph Table |      |                   |     |                         |       |        |      |       |          |       |         |          |           |       |            |                       |               |        |      |      |                   |                 |            |                                  |   |   |
|-------------------------------|------|-------------------|-----|-------------------------|-------|--------|------|-------|----------|-------|---------|----------|-----------|-------|------------|-----------------------|---------------|--------|------|------|-------------------|-----------------|------------|----------------------------------|---|---|
| Set                           | Rec# | Filename          | Mw  | Distance<br>(hyp)<br>km | PGA   |        | PGV  |       | PGD      |       | Ratio 1 |          | Ratio 2   |       | AI<br>0.95 | Duration<br>bracketed | Site<br>Class | Region | Comp | deg  | Setting &<br>Mech | Earthquake      | date       | Station                          |   |   |
|                               |      |                   |     |                         | +     | -      | +    | -     | Lin Disp |       | vm/km   |          | d*km/vm^2 |       |            |                       |               |        |      |      |                   |                 |            |                                  |   |   |
|                               |      |                   |     |                         |       |        |      |       | g%       | cm/s  | cm      | in./s/%g |           |       |            |                       |               |        |      |      |                   |                 |            |                                  | + | - |
|                               |      |                   |     |                         |       |        |      |       |          |       |         |          |           |       |            |                       |               |        |      |      |                   |                 |            |                                  |   |   |
|                               | 149  | 381_kgkz_00ta.dat | 6.4 | 18                      | 0.139 | -0.125 | 4.6  | -6.7  | 0.54     | -0.36 | 13.1    | 21.1     | 3.46      | 0.98  | 18         | 4                     | Rock          | Greece | H2   | T    | XX-RO-13          | Kozani, Greece  | 05/13/1995 | ITSAK Kozani                     |   |   |
| 52                            | 150  | 382_kgkz_Oupa.dat | 6.4 | 18                      | 0.092 | -0.072 | 4.3  | -3.6  | 0.53     | -0.58 | 18.2    | 19.6     | 2.63      | 3.19  | 6          | 4                     | Rock          | Greece | V    | UP   | XX-RO-13          | Kozani, Greece  | 05/13/1995 | ITSAK Kozani                     |   |   |
|                               | 151  | 383_sfsa_003a.dat | 6.6 | 46                      | 0.151 | -0.140 | 4.7  | -4.2  | 1.64     | -2.35 | 12.3    | 12.0     | 10.97     | 17.86 | 25         | 11                    | Rock          | WUS    | H1   | 3    | XX-RO-13          | San Fernando    | 2/9/1971   | Santa Anita Dam                  |   |   |
|                               | 152  | 384_sfsa_273a.dat | 6.6 | 46                      | 0.212 | -0.160 | 4.1  | -6.1  | 2.98     | -2.19 | 7.7     | 14.9     | 36.09     | 9.35  | 27         | 8                     | Rock          | WUS    | H2   | 273  | XX-RO-13          | San Fernando    | 2/9/1971   | Santa Anita Dam                  |   |   |
|                               | 153  | 385_sfsa_0dna.dat | 6.6 | 46                      | 0.063 | -0.056 | 2.6  | -3.9  | 1.79     | -1.64 | 16.4    | 27.7     | 16.25     | 5.80  | 5          | 3                     | Rock          | WUS    | V    | DN   | XX-RO-13          | San Fernando    | 2/9/1971   | Santa Anita Dam                  |   |   |
| 53                            | 153  | 386_cc71_71na.dat | 6.2 | 21                      | 0.195 | -0.191 | 13.2 | -11.8 | 0.90     | -1.54 | 26.8    | 24.3     | 0.98      | 2.07  | 32         | 64                    | Rock          | Taiwan | H1   | 71N  | XX-XX-08          | Chi-Chi         | 09/20/1999 | TCU071                           |   |   |
|                               | 154  | 387_cc71_71ea.dat | 6.2 | 21                      | 0.351 | -0.380 | 13.0 | -12.0 | 1.68     | -1.72 | 14.5    | 12.4     | 3.45      | 4.49  | 63         | 11                    | Rock          | Taiwan | H2   | 71E  | XX-XX-08          | Chi-Chi         | 09/20/1999 | TCU071                           |   |   |
|                               | 155  | 388_cc71_71va.dat | 6.2 | 21                      | 0.139 | -0.143 | 2.9  | -3.8  | 0.71     | -1.16 | 8.2     | 10.5     | 11.43     | 11.18 | 11         | 3                     | Rock          | Taiwan | V    | 71V  | XX-XX-08          | Chi-Chi         | 09/20/1999 | TCU071                           |   |   |
| 54                            | 156  | 389_cc12_02na.dat | 6.2 | 61                      | 0.064 | -0.040 | 3.7  | -2.7  | 0.71     | -0.76 | 22.5    | 26.5     | 3.35      | 4.07  | 3          | 0                     | Rock          | Taiwan | H1   | 102N | XX-XX-08          | Chi-Chi         | 09/20/1999 | TCU102                           |   |   |
|                               | 157  | 390_cc12_02ea.dat | 6.2 | 61                      | 0.042 | -0.030 | 4.2  | -4.3  | 1.29     | -1.64 | 39.4    | 56.3     | 2.98      | 2.61  | 3          | 0                     | Rock          | Taiwan | H2   | 102E | XX-XX-08          | Chi-Chi         | 09/20/1999 | TCU102                           |   |   |
|                               | 158  | 391_cc12_02va.dat | 6.2 | 61                      | 0.028 | -0.029 | 3.2  | -2.9  | 1.03     | -0.95 | 46.0    | 39.5     | 2.66      | 3.25  | 1          | 0                     | Rock          | Taiwan | V    | 102V | XX-XX-08          | Chi-Chi         | 09/20/1999 | TCU102                           |   |   |
| 55                            | 159  | 392_mhg6_000a.dat | 6.2 | 36                      | 0.201 | -0.222 | 8.7  | -11.4 | 2.48     | -2.18 | 17.1    | 20.2     | 6.42      | 3.66  | 34         | 8                     | Rock          | WUS    | H1   | 0    | XX-SS-09          | Morgan Hill     | 4/24/1984  | Gilroy Array # 6                 |   |   |
|                               | 160  | 393_mhg6_090a.dat | 6.2 | 36                      | 0.259 | -0.292 | 23.0 | -36.7 | 6.17     | -4.25 | 34.9    | 49.5     | 2.97      | 0.90  | 78         | 10                    | Rock          | WUS    | H2   | 90   | XX-SS-09          | Morgan Hill     | 4/24/1984  | Gilroy Array # 6                 |   |   |
|                               | 161  | 394_mhg6_Oupa.dat | 6.2 | 36                      | 0.405 | -0.302 | 9.0  | -14.0 | 1.89     | -1.26 | 8.7     | 18.3     | 9.28      | 1.90  | 30         | 5                     | Rock          | WUS    | V    | UP   | XX-SS-09          | Morgan Hill     | 4/24/1984  | Gilroy Array # 6                 |   |   |
| 56                            | 162  | 395_mhsj_270a.dat | 6.2 | 58                      | 0.070 | -0.081 | 6.5  | -6.1  | 2.52     | -2.59 | 36.8    | 29.7     | 4.06      | 5.52  | 17         | 9                     | Rock          | WUS    | H1   | 270  | XX-SS-09          | Morgan Hill     | 4/24/1984  | San Justo Dam                    |   |   |
|                               | 163  | 396_mhsj_360a.dat | 6.2 | 58                      | 0.070 | -0.061 | 4.7  | -5.1  | 1.86     | -1.28 | 26.6    | 33.2     | 5.72      | 2.92  | 9          | 5                     | Rock          | WUS    | H2   | 360  | XX-SS-09          | Morgan Hill     | 4/24/1984  | San Justo Dam                    |   |   |
|                               | 164  | 397_mhsj_Oupa.dat | 6.2 | 58                      | 0.030 | -0.033 | 2.2  | -1.7  | 0.50     | -0.41 | 28.6    | 19.9     | 3.14      | 4.71  | 2          | 0                     | Rock          | WUS    | V    | UP   | XX-SS-09          | Morgan Hill     | 4/24/1984  | San Justo Dam                    |   |   |
| 57                            | 165  | 398_bbsf_090a.dat | 6.5 | 71                      | 0.172 | -0.171 | 2.6  | -3.0  | 0.17     | -0.18 | 5.9     | 6.9      | 4.43      | 3.31  | 45         | 18                    | Rock          | WUS    | H1   | 90   | XX-RO-13          | Big Bear        | 6/28/1992  | Sage Fire Station                |   |   |
|                               | 166  | 399_bbsf_180a.dat | 6.5 | 71                      | 0.165 | -0.165 | 2.7  | -2.5  | 0.16     | -0.16 | 6.3     | 5.9      | 3.76      | 4.10  | 50         | 21                    | Rock          | WUS    | H2   | 360  | XX-RO-13          | Big Bear        | 6/28/1992  | Sage Fire Station                |   |   |
|                               | 167  | 400_bbsf_Oupa.dat | 6.5 | 71                      | 0.112 | -0.118 | 1.7  | -1.8  | 0.16     | -0.14 | 5.9     | 5.9      | 6.35      | 5.03  | 25         | 22                    | Rock          | WUS    | V    | UP   | XX-RO-13          | Big Bear        | 6/28/1992  | Sage Fire Station                |   |   |
| 58                            | 168  | 40a_nqhh_180a.dat | 6.8 | 56                      | 0.104 | -0.104 | 17.1 | -15.7 | 7.36     | -9.32 | 64.6    | 59.4     | 2.57      | 3.85  | 37         | 17                    | Rock          | WUS    | H1   | 180  | XX-XX-XX          | Nisqually       | 2/28/2001  | Howard Hanson Dam, L abut        |   |   |
|                               | 169  | 40b_nqhh_270a.dat | 6.8 | 56                      | 0.078 | -0.106 | 20.9 | -23.6 | 11.73    | -8.27 | 105.6   | 88.0     | 2.05      | 1.53  | 36         | 17                    | Rock          | WUS    | H2   | 270  | XX-XX-XX          | Nisqually       | 2/28/2001  | Howard Hanson Dam, L abut        |   |   |
|                               | 170  | 40c_nqhh_Oupa.dat | 6.8 | 56                      | 0.048 | -0.067 | 11.7 | -11.7 | 9.00     | -5.29 | 96.7    | 69.1     | 3.06      | 2.53  | 12         | 0                     | Rock          | WUS    | V    | UP   | XX-XX-XX          | Nisqually       | 2/28/2001  | Howard Hanson Dam, L abut        |   |   |
| 59                            | 171  | 40d_cvpl_070a.dat | 6.4 | 20                      | 0.168 | -0.100 | 5.0  | -4.2  | 1.42     | -1.40 | 11.6    | 16.3     | 9.56      | 7.94  | 12         | 6                     | Rock          | WUS    | H1   | 70   | XX-SS-10          | Chalfant Valley | 7/21/1986  | Bishop CA - Paradise Lodge       |   |   |
|                               | 172  | 40e_cvpl_160a.dat | 6.4 | 20                      | 0.117 | -0.147 | 7.9  | -11.1 | 3.01     | -2.32 | 26.5    | 29.6     | 5.56      | 2.73  | 18         | 9                     | Rock          | WUS    | H2   | 160  | XX-SS-10          | Chalfant Valley | 7/21/1986  | Bishop CA - Paradise Lodge       |   |   |
|                               | 173  | 40f_cvpl_Oupa.dat | 6.4 | 20                      | 0.091 | -0.087 | 5.5  | -4.8  | 1.13     | -1.06 | 24.0    | 21.8     | 3.29      | 3.90  | 11         | 7                     | Rock          | WUS    | V    | UP   | XX-SS-10          | Chalfant Valley | 7/21/1986  | Bishop CA - Paradise Lodge       |   |   |
| 60                            | 174  | 40g_cvlc_009a.dat | 6.4 | 29                      | 0.159 | -0.101 | 4.1  | -7.3  | 0.76     | -0.67 | 10.2    | 28.5     | 7.05      | 1.24  | 12         | 3                     | Rock          | WUS    | H1   | 9    | XX-SS-10          | Chalfant Valley | 7/21/1986  | Lake Crowley, Shelborn Residence |   |   |
|                               | 175  | 40h_cvlc_099a.dat | 6.4 | 29                      | 0.070 | -0.092 | 5.0  | -3.6  | 0.53     | -0.64 | 28.4    | 15.5     | 1.42      | 4.41  | 9          | 4                     | Rock          | WUS    | H2   | 99   | XX-SS-10          | Chalfant Valley | 7/21/1986  | Lake Crowley, Shelborn Residence |   |   |
|                               | 176  | 40i_cvlc_Oupa.dat | 6.4 | 29                      | 0.078 | -0.081 | 3.0  | -2.6  | 0.22     | -0.35 | 15.1    | 12.4     | 1.89      | 4.31  | 7          | 4                     | Rock          | WUS    | V    | UP   | XX-SS-10          | Chalfant Valley | 7/21/1986  | Lake Crowley, Shelborn Residence |   |   |
| 61                            | 177  | 40j_cvml_290a.dat | 6.4 | 43                      | 0.049 | -0.041 | 2.1  | -2.9  | 0.33     | -0.33 | 17.0    | 27.3     | 3.54      | 1.65  | 3          | 0                     | Rock          | WUS    | H1   | 290  | XX-SS-10          | Chalfant Valley | 7/21/1986  | Mamoth Lakes Sheriff Sta         |   |   |
|                               | 178  | 40k_cvml_020a.dat | 6.4 | 43                      | 0.031 | -0.042 | 2.3  | -1.7  | 0.31     | -0.35 | 29.1    | 16.5     | 1.79      | 4.67  | 2          | 0                     | Rock          | WUS    | H2   | 20   | XX-SS-10          | Chalfant Valley | 7/21/1986  | Mamoth Lakes Sheriff Sta         |   |   |
|                               | 179  | 40m_cvml_Oupa.dat | 6.4 | 43                      | 0.020 | -0.025 | 1.4  | -1.6  | 0.22     | -0.25 | 26.3    | 25.3     | 2.35      | 2.31  | 1          | 0                     | Rock          | WUS    | V    | UP   | XX-SS-10          | Chalfant Valley | 7/21/1986  | Mamoth Lakes Sheriff Sta         |   |   |

Table 4.3. Master accelerograph table of magnitude 4.9 – 6.1 earthquakes.

| M6 Master Accelerograph Table |      |                   |     |                         |        |        |       |        |                 |         |                  |        |                      |        |            |                       |               |        |      |     |                   |                     |            |                          |
|-------------------------------|------|-------------------|-----|-------------------------|--------|--------|-------|--------|-----------------|---------|------------------|--------|----------------------|--------|------------|-----------------------|---------------|--------|------|-----|-------------------|---------------------|------------|--------------------------|
| Set                           | Rec# | Filename          | Mw  | Distance<br>(hyp)<br>km | PGA    |        | PGV   |        | PGD<br>Lin Disp |         | Ratio 1<br>vm/km |        | Ratio 2<br>d*km/vm^2 |        | AI<br>0.95 | Duration<br>bracketed | Site<br>Class | Region | Comp | deg | Setting &<br>Mech | Earthquake          | date       | Station                  |
|                               |      |                   |     |                         | +      | -      | +     | -      | +               | -       | +                | -      | +                    | -      |            |                       |               |        |      |     |                   |                     |            |                          |
|                               |      |                   |     |                         | g%     |        | cm/s  |        | cm              |         | in./s/%g         |        | +                    | -      |            |                       |               |        |      |     |                   |                     |            |                          |
|                               |      |                   |     |                         |        |        |       |        |                 |         |                  |        |                      |        |            |                       |               |        |      |     |                   |                     |            |                          |
| 48                            | 167  | 401_wnmc_000a.dat | 6.0 | 41                      | 0.0832 | -0.089 | 3.91  | -3.94  | 0.518           | -0.388  | 18.506           | 17.381 | 2.764                | 2.186  | 9.470      | 4.260                 | Rock(a)       | WUS    | H1   | 0   | XX-XX-15          | Whittier Narrows    | 10/1/1987  | Mill Creek               |
|                               | 168  | 402_wnmc_090a.dat | 6.0 | 41                      | 0.0706 | -0.065 | 3.02  | -3.24  | 0.315           | -0.244  | 16.828           | 19.508 | 2.394                | 1.491  | 6.680      | 4.240                 | Rock(a)       | WUS    | H2   | 90  | XX-XX-15          | Whittier Narrows    | 10/1/1987  | Mill Creek               |
|                               | 169  | 403_wnmc_Oupa.dat | 6.0 | 41                      | 0.0397 | -0.036 | 1.16  | -1.51  | 0.100           | -0.083  | 11.548           | 16.504 | 2.881                | 1.275  | 2.183      | 0.000                 | Rock(a)       | WUS    | V    | UP  | XX-XX-15          | Whittier Narrows    | 10/1/1987  | Mill Creek               |
| 49                            | 170  | 404_wnkr_090a.dat | 6.0 | 20                      | 0.106  | -0.112 | 6.81  | -8.01  | 0.895           | -0.992  | 25.314           | 28.060 | 2.004                | 1.703  | 7.862      | 3.206                 | Rock(a)       | WUS    | H1   | 90  | XX-XX-15          | Whittier Narrows    | 10/1/1987  | Pasadena - Kresge Lab    |
|                               | 171  | 405_wnkr_360a.dat | 6.0 | 20                      | 0.0892 | -0.079 | 3.76  | -3.60  | 0.275           | -0.216  | 16.578           | 17.943 | 1.706                | 1.292  | 4.411      | 1.806                 | Rock(a)       | WUS    | H2   | 360 | XX-XX-15          | Whittier Narrows    | 10/1/1987  | Pasadena - Kresge Lab    |
|                               | 172  | 406_wnkr_Oupa.dat | 6.0 | 20                      | 0.0536 | -0.081 | 3.34  | -2.21  | 0.372           | -0.297  | 24.525           | 10.802 | 1.755                | 4.795  | 2.921      | 2.116                 | Rock(a)       | WUS    | V    | UP  | XX-XX-15          | Whittier Narrows    | 10/1/1987  | Pasadena - Kresge Lab    |
| 50                            | 173  | 407_wnmw_000a.dat | 6.0 | 24                      | 0.1047 | -0.123 | 3.32  | -3.25  | 0.372           | -0.311  | 12.507           | 10.380 | 3.457                | 3.559  | 13.176     | 6.761                 | Rock(a)       | WUS    | H1   | 0   | XX-XX-15          | Whittier Narrows    | 10/1/1987  | Mt. Wilson               |
|                               | 174  | 408_wnmw_090a.dat | 6.0 | 24                      | 0.1429 | -0.186 | 4.22  | -4.61  | 0.206           | -0.186  | 11.618           | 9.759  | 1.620                | 1.592  | 23.500     | 6.911                 | Rock(a)       | WUS    | H2   | 90  | XX-XX-15          | Whittier Narrows    | 10/1/1987  | Mt. Wilson               |
|                               | 175  | 409_wnmw_Oupa.dat | 6.0 | 24                      | 0.097  | -0.119 | 3.25  | -2.30  | 0.195           | -0.254  | 13.201           | 7.617  | 1.753                | 5.586  | 10.204     | 7.286                 | Rock(a)       | WUS    | V    | UP  | XX-XX-15          | Whittier Narrows    | 10/1/1987  | Mt. Wilson               |
| 51                            | 176  | 410_wnvr_000a.dat | 6.0 | 56                      | 0.0461 | -0.06  | 2.11  | -1.89  | 0.116           | -0.072  | 18.068           | 12.375 | 1.168                | 1.198  | 2.436      | 0.566                 | Rock(a)       | WUS    | H1   | 0   | XX-XX-15          | Whittier Narrows    | 10/1/1987  | Vasquez Rock Park        |
|                               | 177  | 411_wnvr_090a.dat | 6.0 | 56                      | 0.0582 | -0.06  | 1.52  | -2.34  | 0.110           | -0.088  | 10.250           | 15.381 | 2.731                | 0.945  | 2.506      | 0.876                 | Rock(a)       | WUS    | H2   | 90  | XX-XX-15          | Whittier Narrows    | 10/1/1987  | Vasquez Rock Park        |
|                               | 178  | 412_wnvr_Oupa.dat | 6.0 | 56                      | 0.0394 | -0.034 | 0.90  | -1.07  | 0.069           | -0.089  | 8.960            | 12.339 | 3.330                | 2.603  | 1.059      | 0.000                 | Rock(a)       | WUS    | V    | UP  | XX-XX-15          | Whittier Narrows    | 10/1/1987  | Vasquez Rock Park        |
| 52                            | 179  | 413_w2mw_000a.dat | 5.3 | 23                      | 0.1576 | -0.097 | 5.72  | -3.63  | 0.212           | -0.245  | 14.286           | 14.788 | 1.002                | 1.763  | 6.153      | 0.886                 | Rock(a)       | WUS    | H1   | 0   | XX-XX-13          | Whittier Narrows II | 10/4/1987  | Mt. Wilson               |
|                               | 180  | 414_w2mw_090a.dat | 5.3 | 23                      | 0.1424 | -0.115 | 4.57  | -4.54  | 0.197           | -0.126  | 12.634           | 15.556 | 1.317                | 0.687  | 7.216      | 0.716                 | Rock(a)       | WUS    | H2   | 90  | XX-XX-13          | Whittier Narrows II | 10/4/1987  | Mt. Wilson               |
|                               | 181  | 415_w2mw_Oupa.dat | 5.3 | 23                      | 0.0863 | -0.072 | 2.20  | -1.76  | 0.138           | -0.156  | 10.028           | 9.615  | 2.419                | 3.579  | 2.393      | 0.596                 | Rock(a)       | WUS    | V    | UP  | XX-XX-13          | Whittier Narrows II | 10/4/1987  | Mt. Wilson               |
| 53                            | 182  | 416_psar_270a.dat | 6.1 | 47                      | 0.1017 | -0.104 | 5.18  | -4.69  | 0.299           | -0.635  | 20.044           | 17.831 | 1.111                | 2.933  | 7.603      | 2.950                 | Rock          | WUS    | H1   | 270 | XX-XX-11          | N. Palm Springs     | 7/8/1986   | Red Mountain             |
|                               | 183  | 417_psar_360a.dat | 6.1 | 47                      | 0.1292 | -0.107 | 3.17  | -3.43  | 0.266           | -0.458  | 9.676            | 12.666 | 3.347                | 4.064  | 6.634      | 4.370                 | Rock          | WUS    | H2   | 360 | XX-XX-11          | N. Palm Springs     | 7/8/1986   | Red Mountain             |
|                               | 184  | 418_psar_Oupa.dat | 6.1 | 47                      | 0.06   | -0.072 | 2.22  | -1.64  | 0.166           | -0.215  | 14.571           | 9.026  | 1.980                | 5.598  | 2.009      | 0.215                 | Rock          | WUS    | V    | UP  | XX-XX-11          | N. Palm Springs     | 7/8/1986   | Red Mountain             |
| 54                            | 185  | 419_pssr_270a.dat | 6.1 | 50                      | 0.0966 | -0.106 | 2.56  | -2.02  | 0.109           | -0.102  | 10.431           | 7.510  | 1.578                | 2.590  | 5.593      | 3.105                 | Rock          | WUS    | H1   | 270 | XX-XX-11          | N. Palm Springs     | 7/8/1986   | Santa Rosa Mountain      |
|                               | 186  | 420_pssr_360a.dat | 6.1 | 50                      | 0.1026 | -0.08  | 1.32  | -2.23  | 0.051           | -0.103  | 5.079            | 10.963 | 2.946                | 1.633  | 4.114      | 1.730                 | Rock          | WUS    | H2   | 360 | XX-XX-11          | N. Palm Springs     | 7/8/1986   | Santa Rosa Mountain      |
|                               | 187  | 421_pssr_Oupa.dat | 6.1 | 50                      | 0.0464 | -0.051 | 1.21  | -1.45  | 0.087           | -0.097  | 10.248           | 11.183 | 2.723                | 2.300  | 2.036      | 0.000                 | Rock          | WUS    | V    | UP  | XX-XX-11          | N. Palm Springs     | 7/8/1986   | Santa Rosa Mountain      |
| 55                            | 188  | 422_psat_270a.dat | 6.1 | 61                      | 0.0679 | -0.11  | 6.21  | -6.54  | 0.710           | -0.634  | 36.009           | 23.482 | 1.226                | 1.595  | 5.371      | 1.431                 | Rock          | WUS    | H1   | 270 | XX-XX-11          | N. Palm Springs     | 7/8/1986   | Anza - Tule Canyon       |
|                               | 189  | 423_psat_360a.dat | 6.1 | 61                      | 0.0952 | -0.07  | 7.51  | -5.10  | 0.559           | -0.707  | 31.039           | 28.784 | 0.926                | 1.860  | 5.256      | 0.845                 | Rock          | WUS    | H2   | 360 | XX-XX-11          | N. Palm Springs     | 7/8/1986   | Anza - Tule Canyon       |
|                               | 190  | 424_psat_Oupa.dat | 6.1 | 61                      | 0.0309 | -0.049 | 2.62  | -2.26  | 0.295           | -0.238  | 33.355           | 18.251 | 1.304                | 2.224  | 1.476      | 0.000                 | Rock          | WUS    | V    | UP  | XX-XX-11          | N. Palm Springs     | 7/8/1986   | Anza - Tule Canyon       |
| 56                            | 191  | 425_pswb_000a.dat | 6.1 | 61                      | 0.0702 | -0.055 | 1.59  | -1.94  | 0.196           | -0.176  | 8.923            | 14.002 | 5.327                | 2.498  | 2.906      | 1.826                 | Rock          | WUS    | H1   | 0   | XX-XX-11          | N. Palm Springs     | 7/8/1986   | Winchester Bergman Ranch |
|                               | 192  | 426_pswb_090a.dat | 6.1 | 61                      | 0.0844 | -0.093 | 1.76  | -1.61  | 0.287           | -0.290  | 8.216            | 6.847  | 7.657                | 10.139 | 4.089      | 2.501                 | Rock          | WUS    | H2   | 90  | XX-XX-11          | N. Palm Springs     | 7/8/1986   | Winchester Bergman Ranch |
|                               | 193  | 427_pswb_Oupa.dat | 6.1 | 61                      | 0.062  | -0.072 | 1.55  | -1.51  | 0.221           | -0.244  | 9.846            | 8.270  | 5.599                | 7.539  | 2.583      | 1.286                 | Rock          | WUS    | V    | UP  | XX-XX-11          | N. Palm Springs     | 7/8/1986   | Winchester Bergman Ranch |
| 57                            | 194  | 428_pslm_162a.dat | 6.1 | 80                      | 0.0517 | -0.062 | 1.43  | -1.51  | 0.074           | -0.082  | 10.901           | 9.652  | 1.837                | 2.166  | 2.606      | 1.195                 | Rock          | WUS    | H2   | 162 | XX-XX-11          | N. Palm Springs     | 7/8/1986   | Lake Mathews Dike Toe    |
|                               | 195  | 429_pslm_252a.dat | 6.1 | 80                      | 0.0404 | -0.046 | 0.74  | -0.74  | 0.021           | -0.033  | 7.264            | 6.343  | 1.475                | 2.662  | 1.777      | 0.000                 | Rock          | WUS    | H1   | 252 | XX-XX-11          | N. Palm Springs     | 7/8/1986   | Lake Mathews Dike Toe    |
|                               | 196  | 430_pslm_Oupa.dat | 6.1 | 80                      | 0.0305 | -0.039 | 0.52  | -0.47  | 0.014           | -0.016  | 6.706            | 4.725  | 1.509                | 2.745  | 0.979      | 0.000                 | Rock          | WUS    | V    | UP  | XX-XX-11          | N. Palm Springs     | 7/8/1986   | Lake Mathews Dike Toe    |
| 58                            | 197  | 431_bccp_161a.dat | 5.5 | 7                       | 1.3882 | -1.144 | 47.20 | -43.19 | 10.083          | -11.280 | 13.386           | 14.868 | 6.162                | 6.783  | 334.327    | 8.345                 | Rock          | WUS    | H1   | 161 | XX-XX-06          | Baja California     | 2/7/1987   | Cerro Prieto             |
|                               | 198  | 432_bccp_251a.dat | 5.5 | 7                       | 0.6687 | -0.891 | 52.21 | -65.76 | 7.844           | -5.713  | 30.740           | 29.076 | 1.887                | 1.154  | 295.650    | 10.340                | Rock          | WUS    | H2   | 251 | XX-XX-06          | Baja California     | 2/7/1987   | Cerro Prieto             |
|                               | 199  | 433_bccp_Oupa.dat | 5.5 | 7                       | 0.5402 | -0.59  | 18.03 | -28.85 | 2.520           | -1.185  | 13.139           | 19.263 | 4.108                | 0.824  | 172.894    | 6.735                 | Rock          | WUS    | V    | UP  | XX-XX-06          | Baja California     | 2/7/1987   | Cerro Prieto             |
| 59                            | 200  | 434_hmfb_000a.dat | 6.0 | 6                       | 0.0323 | -0.047 | 0.67  | -0.47  | 0.018           | -0.023  | 8.217            | 3.995  | 1.268                | 4.619  | 0.179      | 0.000                 | Rock          | WUS    | H1   | 0   | XX-XX-XX          | Helena, Montana     | 10/31/1935 | Helena Federal Bldg.     |
|                               | 201  | 435_hmfb_090a.dat | 6.0 | 6                       | 0.0414 | -0.027 | 0.65  | -0.18  | 0.044           | -0.038  | 6.177            | 2.640  | 4.274                | 31.520 | 0.118      | 0.000                 | Rock          | WUS    | H2   | 90  | XX-XX-XX          | Helena, Montana     | 10/31/1935 | Helena Federal Bldg.     |
|                               | 202  | 436_hmfb_Oupa.dat | 6.0 | 6                       | 0.0117 | -0.01  | 0.21  | -0.30  | 0.055           | -0.038  | 6.983            | 12.018 | 14.508               | 4.079  | 0.038      | 0.000                 | Rock          | WUS    | V    | UP  | XX-XX-XX          | Helena, Montana     | 10/31/1935 | Helena Federal Bldg.     |

| M6 Master Accelerograph Table |      |                   |     |                         |        |        |       |        |          |        |         |        |           |       |            |                       |               |        |      |     |                   |                     |            |                               |          |  |   |   |
|-------------------------------|------|-------------------|-----|-------------------------|--------|--------|-------|--------|----------|--------|---------|--------|-----------|-------|------------|-----------------------|---------------|--------|------|-----|-------------------|---------------------|------------|-------------------------------|----------|--|---|---|
| Set                           | Rec# | Filename          | Mw  | Distance<br>(hyp)<br>km | PGA    |        | PGV   |        | PGD      |        | Ratio 1 |        | Ratio 2   |       | AI<br>0.95 | Duration<br>bracketed | Site<br>Class | Region | Comp | deg | Setting &<br>Mech | Earthquake          | date       | Station                       |          |  |   |   |
|                               |      |                   |     |                         | +      | -      | +     | -      | Lin Disp |        | vm/km   |        | d*km/vm^2 |       |            |                       |               |        |      |     |                   |                     |            |                               |          |  |   |   |
|                               |      |                   |     |                         |        |        |       |        | g%       |        | cm/s    |        | cm        |       |            |                       |               |        |      |     |                   |                     |            |                               | in./s/%g |  | + | - |
|                               |      |                   |     |                         |        |        |       |        |          |        |         |        |           |       |            |                       |               |        |      |     |                   |                     |            |                               |          |  |   |   |
| 60                            | 203  | 437_s7gg_010a.dat | 5.3 | 14                      | 0.0934 | -0.095 | 3.91  | -2.16  | 0.187    | -0.181 | 16.468  | 8.936  | 1.124     | 3.620 | 2.704      | 0.426                 | Rock          | WUS    | H1   | 10  | XX-XX-08          | San Francisco       | 3/22/1957  | Golden Gate Park              |          |  |   |   |
|                               | 204  | 438_s7gg_100a.dat | 5.3 | 14                      | 0.1118 | -0.101 | 4.14  | -4.58  | 0.432    | -0.310 | 14.569  | 17.864 | 2.766     | 1.464 | 4.978      | 1.611                 | Rock          | WUS    | H2   | 100 | XX-XX-08          | San Francisco       | 3/22/1957  | Golden Gate Park              |          |  |   |   |
|                               | 205  | 439_s7gg_Oupa.dat | 5.3 | 14                      | 0.0305 | -0.047 | 1.09  | -1.08  | 0.181    | -0.134 | 14.118  | 9.020  | 4.525     | 5.334 | 0.667      | 0.000                 | Rock          | WUS    | V    | UP  | XX-XX-08          | San Francisco       | 3/22/1957  | Golden Gate Park              |          |  |   |   |
| 61                            | 206  | 440_smcd_155a.dat | 5.6 | 22                      | 0.2963 | -0.302 | 13.00 | -14.87 | 1.604    | -2.004 | 17.267  | 19.388 | 2.760     | 2.684 | 39.092     | 4.139                 | Rock          | WUS    | H1   | 155 | XX-XX-12          | Sierra Madre        | 6/28/1991  | Cogswell Dam - Right Abutment |          |  |   |   |
|                               | 207  | 441_smcd_065a.dat | 5.6 | 22                      | 0.2641 | -0.212 | 9.55  | -7.99  | 0.579    | -0.940 | 14.244  | 14.827 | 1.642     | 3.063 | 27.867     | 3.039                 | Rock          | WUS    | H2   | 65  | XX-XX-12          | Sierra Madre        | 6/28/1991  | Cogswell Dam - Right Abutment |          |  |   |   |
|                               | 208  | 442_smcd_Oupa.dat | 5.6 | 22                      | 0.1665 | -0.228 | 6.09  | -6.56  | 0.772    | -0.445 | 14.394  | 11.347 | 3.400     | 2.311 | 19.435     | 3.379                 | Rock          | WUS    | V    | UP  | XX-XX-12          | Sierra Madre        | 6/28/1991  | Cogswell Dam - Right Abutment |          |  |   |   |
| 62                            | 209  | 443_hhg1_157a.dat | 5.1 | 13                      | 0.1054 | -0.061 | 2.55  | -2.71  | 0.089    | -0.128 | 9.533   | 17.556 | 1.405     | 1.042 | 3.065      | 1.235                 | Rock          | WUS    | H1   | 157 | XX-XX-06          | Hollister           | 11/28/1974 | Gillroy Array # 1             |          |  |   |   |
|                               | 210  | 444_hhg1_247a.dat | 5.1 | 13                      | 0.1325 | -0.084 | 3.99  | -2.71  | 0.128    | -0.168 | 11.859  | 12.673 | 1.045     | 1.886 | 4.168      | 1.100                 | Rock          | WUS    | H2   | 247 | XX-XX-06          | Hollister           | 11/28/1974 | Gillroy Array # 1             |          |  |   |   |
| 63                            | 211  | 445_oror_037a.dat | 5.9 | 14                      | 0.0775 | -0.092 | 2.03  | -3.70  | 0.169    | -0.168 | 10.302  | 15.854 | 3.121     | 1.104 | 3.230      | 0.600                 | Rock          | WUS    | H1   | 37  | XX-XX-06          | Orville             | 8/1/1975   | Oroville Seismograph          |          |  |   |   |
|                               | 212  | 446_oror_307a.dat | 5.9 | 14                      | 0.0684 | -0.072 | 2.84  | -2.49  | 0.223    | -0.214 | 16.364  | 13.548 | 1.853     | 2.446 | 3.581      | 1.425                 | Rock          | WUS    | H2   | 307 | XX-XX-06          | Orville             | 8/1/1975   | Oroville Seismograph          |          |  |   |   |
| 64                            | 213  | 447_clcd_160a.dat | 5.7 | 11                      | 0.1402 | -0.157 | 10.80 | -8.20  | 0.809    | -1.306 | 30.332  | 20.505 | 0.953     | 2.999 | 17.005     | 3.162                 | Rock          | WUS    | H1   | 160 | XX-XX-10          | Coyote Lake         | 8/6/1979   | Coyote Lake Dam(SW ABut)      |          |  |   |   |
|                               | 214  | 448_clcd_250a.dat | 5.7 | 11                      | 0.2791 | -0.259 | 14.18 | -20.29 | 2.331    | -1.896 | 20.002  | 30.839 | 3.173     | 1.170 | 32.313     | 3.992                 | Rock          | WUS    | H2   | 250 | XX-XX-10          | Coyote Lake         | 8/6/1979   | Coyote Lake Dam(SW ABut)      |          |  |   |   |
|                               | 215  | 449_clcd_Oupa.dat | 5.7 | 11                      | 0.1212 | -0.071 | 6.44  | -4.16  | 0.384    | -0.674 | 20.896  | 23.117 | 1.103     | 2.704 | 5.218      | 2.612                 | Rock          | WUS    | V    | UP  | XX-XX-10          | Coyote Lake         | 8/6/1979   | Coyote Lake Dam(SW ABut)      |          |  |   |   |
| 65                            | 216  | 450_c7cm_030a.dat | 5.2 | 37                      | 0.085  | -0.115 | 2.29  | -3.10  | 0.092    | -0.096 | 10.589  | 10.622 | 1.460     | 1.119 | 7.892      | 2.660                 | Rock          | WUS    | H1   | 30  | XX-XX-21          | Northern California | 8/6/1979   | Cape Mendocino                |          |  |   |   |
|                               | 217  | 451_c7cm_120a.dat | 5.2 | 37                      | 0.1473 | -0.179 | 4.90  | -4.60  | 0.158    | -0.121 | 13.097  | 10.121 | 0.950     | 1.006 | 10.688     | 2.645                 | Rock          | WUS    | H2   | 120 | XX-XX-21          | Northern California | 8/6/1979   | Cape Mendocino                |          |  |   |   |
|                               | 218  | 452_c7cm_Odna.dat | 5.2 | 37                      | 0.0265 | -0.024 | 0.76  | -0.82  | 0.035    | -0.039 | 11.274  | 13.652 | 1.568     | 1.331 | 0.702      | 0.000                 | Rock          | WUS    | V    | DN  | XX-XX-21          | Northern California | 8/6/1979   | Cape Mendocino                |          |  |   |   |
| 66                            | 219  | 453_lccs_095a.dat | 5.3 | 21                      | 0.0708 | -0.059 | 1.80  | -1.62  | 0.098    | -0.115 | 9.993   | 10.914 | 2.114     | 2.503 | 1.638      | 0.686                 | Rock          | WUS    | H1   | 95  | XX-XX-08          | Lytle Creek         | 9/12/1970  | Cedar Springs - Allen Ranch   |          |  |   |   |
|                               | 220  | 454_lccs_185a.dat | 5.3 | 21                      | 0.0503 | -0.046 | 1.14  | -1.20  | 0.048    | -0.058 | 8.935   | 10.228 | 1.825     | 1.804 | 1.065      | 0.001                 | Rock          | WUS    | H2   | 185 | XX-XX-08          | Lytle Creek         | 9/12/1970  | Cedar Springs - Allen Ranch   |          |  |   |   |
| 67                            | 221  | 455_lcdc_090a.dat | 5.3 | 22                      | 0.1321 | -0.146 | 3.19  | -3.33  | 0.153    | -0.181 | 9.504   | 8.981  | 1.946     | 2.333 | 8.230      | 1.630                 | Rock          | WUS    | H1   | 90  | XX-XX-08          | Lytle Creek         | 9/12/1970  | Devils Canyon                 |          |  |   |   |
|                               | 222  | 456_lcdc_180a.dat | 5.3 | 22                      | 0.1213 | -0.151 | 4.54  | -5.60  | 0.172    | -0.228 | 14.754  | 14.598 | 0.988     | 1.077 | 9.388      | 2.030                 | Rock          | WUS    | H2   | 180 | XX-XX-08          | Lytle Creek         | 9/12/1970  | Devils Canyon                 |          |  |   |   |
|                               | 223  | 457_lcdc_Odna.dat | 5.3 | 22                      | 0.0837 | -0.08  | 1.64  | -1.73  | 0.074    | -0.101 | 7.702   | 8.534  | 2.258     | 2.636 | 1.945      | 0.260                 | Rock          | WUS    | V    | DN  | XX-XX-08          | Lytle Creek         | 9/12/1970  | Devils Canyon                 |          |  |   |   |
| 68                            | 224  | 458_lcsa_003a.dat | 5.3 | 46                      | 0.03   | -0.042 | 0.94  | -1.64  | 0.047    | -0.095 | 12.362  | 15.260 | 1.566     | 1.461 | 0.642      | 0.000                 | Rock          | WUS    | H1   | 3   | XX-XX-08          | Lytle Creek         | 9/12/1970  | Santa Anita Dam               |          |  |   |   |
|                               | 225  | 459_lcsa_273a.dat | 5.3 | 46                      | 0.0178 | -0.018 | 0.40  | -0.50  | 0.040    | -0.035 | 8.868   | 10.817 | 4.360     | 2.514 | 0.288      | 0.000                 | Rock          | WUS    | H2   | 273 | XX-XX-08          | Lytle Creek         | 9/12/1970  | Santa Anita Dam               |          |  |   |   |
|                               | 226  | 460_lcsa_Odna.dat | 5.3 | 46                      | 0.013  | -0.013 | 0.20  | -0.27  | 0.011    | -0.011 | 6.204   | 8.307  | 3.358     | 1.788 | 0.073      | 0.000                 | Rock          | WUS    | V    | DN  | XX-XX-08          | Lytle Creek         | 9/12/1970  | Santa Anita Dam               |          |  |   |   |
| 69                            | 227  | 461_dtdt_00la.dat | 5.3 | 9                       | 0.2234 | -0.199 | 7.88  | -6.72  | 0.537    | -0.459 | 13.891  | 13.297 | 1.894     | 1.983 | 16.996     | 2.630                 | Rock          | Turkey | H1   | L   | XX-XX-07          | Dursunbery, Turkey  | 7/18/1979  | Dursunbery                    |          |  |   |   |
|                               | 228  | 462_dtdt_00ta.dat | 5.3 | 9                       | 0.3662 | -0.168 | 8.11  | -10.18 | 0.577    | -0.743 | 8.714   | 23.858 | 3.151     | 1.181 | 20.120     | 2.360                 | Rock          | Turkey | H2   | T   | XX-XX-07          | Dursunbery, Turkey  | 7/18/1979  | Dursunbery                    |          |  |   |   |
|                               | 229  | 463_dtdt_00va.dat | 5.3 | 9                       | 0.127  | -0.102 | 5.72  | -4.01  | 0.309    | -0.308 | 17.733  | 15.411 | 1.177     | 1.928 | 7.085      | 2.010                 | Rock          | Turkey | V    | V   | XX-XX-07          | Dursunbery, Turkey  | 7/18/1979  | Dursunbery                    |          |  |   |   |
| 70                            | 230  | 464_itiz_00la.dat | 5.3 | 6                       | 0.3297 | -0.41  | 12.46 | -10.34 | 0.452    | -0.388 | 14.877  | 9.931  | 0.942     | 1.460 | 31.661     | 1.160                 | Rock          | Turkey | H    | L   | XX-XX-05          | Izmir, Turkey       | 12/16/1977 | Izmir                         |          |  |   |   |
|                               | 231  | 465_itiz_00ta.dat | 5.3 | 6                       | 0.1345 | -0.146 | 3.75  | -5.33  | 0.291    | -0.203 | 10.967  | 14.369 | 2.737     | 1.025 | 5.812      | 0.720                 | Rock          | Turkey | H2   | T   | XX-XX-05          | Izmir, Turkey       | 12/16/1977 | Izmir                         |          |  |   |   |
|                               | 232  | 466_itiz_00va.dat | 5.3 | 6                       | 0.0707 | -0.075 | 1.61  | -2.38  | 0.065    | -0.061 | 8.967   | 12.507 | 1.743     | 0.796 | 2.028      | 1.540                 | Rock          | Turkey | V    | V   | XX-XX-05          | Izmir, Turkey       | 12/16/1977 | Izmir                         |          |  |   |   |
| 71                            | 233  | 467_fisr_000a.dat | 5.9 | 18                      | 0.0554 | -0.06  | 4.82  | -4.41  | 1.130    | -0.918 | 34.222  | 29.082 | 2.646     | 2.762 | 2.958      | 1.885                 | Rock          | Italy  | H1   | 0   | XX-XX-04          | Friuli, Italy       | 9/15/1976  | San Rocco                     |          |  |   |   |
|                               | 234  | 468_fisr_270a.dat | 5.9 | 18                      | 0.1244 | -0.134 | 7.62  | -6.27  | 1.242    | -1.994 | 24.107  | 18.378 | 2.610     | 6.678 | 7.940      | 3.175                 | Rock          | Italy  | H2   | 270 | XX-XX-04          | Friuli, Italy       | 9/15/1976  | San Rocco                     |          |  |   |   |
|                               | 235  | 469_fisr_Oupa.dat | 5.9 | 18                      | 0.0585 | -0.05  | 3.99  | -6.23  | 1.987    | -1.309 | 26.835  | 49.207 | 7.171     | 1.650 | 2.087      | 0.020                 | Rock          | Italy  | V    | UP  | XX-XX-04          | Friuli, Italy       | 9/15/1976  | San Rocco                     |          |  |   |   |
| 72                            | 236  | 470_f2sr_0nsa.dat | 5.5 | 21                      | 0.0282 | -0.029 | 1.41  | -2.33  | 0.478    | -0.431 | 19.750  | 31.576 | 6.610     | 2.257 | 0.502      | 0.000                 | Rock          | Italy  | H1   | NS  | XX-XX-06          | Friuli, Italy       | 9/11/1976  | San Rocco                     |          |  |   |   |
|                               | 237  | 471_f2sr_0wea.dat | 5.5 | 21                      | 0.0718 | -0.045 | 3.59  | -4.31  | 0.812    | -0.543 | 19.704  | 38.087 | 4.426     | 1.279 | 1.863      | 0.091                 | Rock          | Italy  | H2   | WE  | XX-XX-06          | Friuli, Italy       | 9/11/1976  | San Rocco                     |          |  |   |   |
|                               | 238  | 472_f2sr_Oupa.dat | 5.5 | 21                      | 0.0102 | -0.013 | 1.36  | -1.82  | 0.295    | -0.336 | 52.679  | 54.365 | 1.584     | 1.311 | 0.227      | 0.000                 | Rock          | Italy  | V    | UP  | XX-XX-06          | Friuli, Italy       | 9/11/1976  | San Rocco                     |          |  |   |   |

| M6 Master Accelerograph Table |      |                   |     |                         |        |        |       |        |          |        |                  |        |                      |        |            |                       |               |        |      |     |                   |                 |            |                      |   |   |
|-------------------------------|------|-------------------|-----|-------------------------|--------|--------|-------|--------|----------|--------|------------------|--------|----------------------|--------|------------|-----------------------|---------------|--------|------|-----|-------------------|-----------------|------------|----------------------|---|---|
| Set                           | Rec# | Filename          | Mw  | Distance<br>(hyp)<br>km | PGA    |        | PGV   |        | PGD      |        | Ratio 1<br>vm/km |        | Ratio 2<br>d*km/vm^2 |        | AI<br>0.95 | Duration<br>bracketed | Site<br>Class | Region | Comp | deg | Setting &<br>Mech | Earthquake      | date       | Station              |   |   |
|                               |      |                   |     |                         | +      | -      | +     | -      | Lin Disp |        | +                | -      | +                    | -      |            |                       |               |        |      |     |                   |                 |            |                      | + | - |
|                               |      |                   |     |                         | g%     |        | cm/s  |        | cm       |        | in./s/%g         |        |                      |        |            |                       |               |        |      |     |                   |                 |            |                      |   |   |
|                               |      |                   |     |                         |        |        |       |        |          |        |                  |        |                      |        |            |                       |               |        |      |     |                   |                 |            |                      |   |   |
| 73                            | 239  | 473_hmcc_180a.dat | 6.0 | 6                       | 0.1498 | -0.116 | 4.58  | -5.77  | 1.040    | -0.770 | 12.030           | 19.557 | 7.295                | 2.635  | 6.430      | 1.740                 | Rock(a)       | WUS    | H1   | 180 | XX-SS-06          | Helena, Montana | 10/31/1935 | USGS Carroll College |   |   |
|                               | 240  | 474_hmcc_270a.dat | 6.0 | 6                       | 0.1731 | -0.107 | 9.98  | -16.43 | 2.335    | -2.184 | 22.690           | 60.571 | 3.982                | 0.847  | 9.300      | 1.560                 | Rock(a)       | WUS    | H2   | 270 | XX-SS-06          | Helena, Montana | 10/31/1935 | USGS Carroll College |   |   |
|                               | 241  | 475_hmcc_0dna.dat | 6.0 | 6                       | 0.1024 | -0.098 | 5.54  | -7.24  | 2.247    | -1.428 | 21.312           | 28.984 | 7.343                | 2.629  | 3.020      | 1.520                 | Rock(a)       | WUS    | V    | DN  | XX-SS-06          | Helena, Montana | 10/31/1935 | USGS Carroll College |   |   |
| 74                            | 242  | 476_cosb_000a.dat | 5.4 | 16                      | 0.0437 | -0.028 | 4.49  | -5.12  | 2.285    | -1.683 | 40.532           | 71.523 | 4.843                | 1.773  | 1.698      | 0.000                 | Rock          | WUS    | H1   | 0   | XX-RX-02          | Coalinga 03     | 6/11/1983  | CDMG Sulphur Baths   |   |   |
|                               | 243  | 477_cosb_090a.dat | 5.4 | 16                      | 0.0335 | -0.037 | 4.40  | -4.48  | 1.641    | -1.278 | 51.737           | 47.793 | 2.785                | 2.308  | 1.542      | 0.000                 | Rock          | WUS    | H2   | 90  | XX-RX-02          | Coalinga 03     | 6/11/1983  | CDMG Sulphur Baths   |   |   |
|                               | 244  | 478_cosb_0upa.dat | 5.4 | 16                      | 0.0273 | -0.034 | 2.90  | -3.51  | 1.197    | -1.472 | 41.850           | 41.243 | 3.805                | 3.921  | 1.260      | 0.000                 | Rock          | WUS    | V    | UP  | XX-RX-02          | Coalinga 03     | 6/11/1983  | CDMG Sulphur Baths   |   |   |
| 75                            | 245  | 479_lvmt_265a.dat | 5.4 | 18                      | 0.198  | -0.149 | 6.11  | -11.69 | 0.677    | -1.017 | 12.159           | 30.928 | 3.516                | 1.086  | 16.978     | 2.761                 | Rock          | WUS    | H1   | 265 | XX-SS-15          | Livermore 02    | 1/27/1980  | Morgan Terr Park     |   |   |
|                               | 246  | 480_lvmt_355a.dat | 5.4 | 18                      | 0.2511 | -0.252 | 9.77  | -9.18  | 1.299    | -1.105 | 15.328           | 14.321 | 3.349                | 3.244  | 33.727     | 2.256                 | Rock          | WUS    | H2   | 355 | XX-SS-15          | Livermore 02    | 1/27/1980  | Morgan Terr Park     |   |   |
|                               | 247  | 481_lvmt_0upa.dat | 5.4 | 18                      | 0.0778 | -0.066 | 4.08  | -2.85  | 0.390    | -0.288 | 20.636           | 17.055 | 1.791                | 2.285  | 3.173      | 0.506                 | Rock          | WUS    | V    | UP  | XX-SS-15          | Livermore 02    | 1/27/1980  | Morgan Terr Park     |   |   |
| 76                            | 248  | 482_c2sb_000a.dat | 5.2 | 17                      | 0.0441 | -0.055 | 2.17  | -1.83  | 0.214    | -0.192 | 19.348           | 13.058 | 1.972                | 3.092  | 1.698      | 0.016                 | Rock          | WUS    | H1   | 0   | XX-RX-09          | Coalinga 04     | 7/9/1983   | CDMG Sulphur Baths   |   |   |
|                               | 249  | 483_c2sb_090a.dat | 5.2 | 17                      | 0.0376 | -0.075 | 1.45  | -1.26  | 0.120    | -0.153 | 15.157           | 6.642  | 2.113                | 7.099  | 1.668      | 0.026                 | Rock          | WUS    | H2   | 90  | XX-RX-09          | Coalinga 04     | 7/9/1983   | CDMG Sulphur Baths   |   |   |
|                               | 250  | 484_c2sb_0upa.dat | 5.2 | 17                      | 0.0316 | -0.042 | 0.99  | -0.97  | 0.091    | -0.088 | 12.299           | 9.242  | 2.893                | 3.768  | 0.874      | 0.000                 | Rock          | WUS    | V    | UP  | XX-RX-09          | Coalinga 04     | 7/9/1983   | CDMG Sulphur Baths   |   |   |
| 77                            | 251  | 485_c3sb_000a.dat | 5.8 | 15                      | 0.1412 | -0.101 | 5.47  | -4.29  | 0.693    | -0.791 | 15.252           | 16.707 | 3.207                | 4.258  | 9.477      | 2.846                 | Rock          | WUS    | H1   | 0   | XX-RX-07          | Coalinga 05     | 7/22/1983  | CDMG Sulphur Baths   |   |   |
|                               | 252  | 486_c3sb_090a.dat | 5.8 | 15                      | 0.1034 | -0.127 | 6.24  | -3.58  | 0.543    | -0.656 | 23.764           | 11.074 | 1.414                | 6.388  | 9.621      | 3.816                 | Rock          | WUS    | H2   | 90  | XX-RX-07          | Coalinga 05     | 7/22/1983  | CDMG Sulphur Baths   |   |   |
|                               | 253  | 487_c3sb_0upa.dat | 5.8 | 15                      | 0.0823 | -0.082 | 3.03  | -4.07  | 0.608    | -0.687 | 14.481           | 19.629 | 5.352                | 3.323  | 5.169      | 2.031                 | Rock          | WUS    | V    | UP  | XX-RX-07          | Coalinga 05     | 7/22/1983  | CDMG Sulphur Baths   |   |   |
| 78                            | 254  | 488_c4sb_000a.dat | 4.9 | 14                      | 0.039  | -0.034 | 1.42  | -1.56  | 0.139    | -0.205 | 14.349           | 18.171 | 2.634                | 2.798  | 0.561      | 0.000                 | Rock          | WUS    | H1   | 0   | XX-RX-08          | Coalinga 06     | 7/22/1983  | CDMG Sulphur Baths   |   |   |
|                               | 255  | 489_c4sb_090a.dat | 4.9 | 14                      | 0.0212 | -0.03  | 0.75  | -0.96  | 0.108    | -0.158 | 13.913           | 12.537 | 4.000                | 5.056  | 0.403      | 0.000                 | Rock          | WUS    | H2   | 90  | XX-RX-08          | Coalinga 06     | 7/22/1983  | CDMG Sulphur Baths   |   |   |
|                               | 256  | 490_c4sb_0upa.dat | 4.9 | 14                      | 0.0284 | -0.029 | 0.89  | -1.12  | 0.116    | -0.170 | 12.386           | 14.996 | 4.026                | 3.919  | 0.481      | 0.000                 | Rock          | WUS    | V    | UP  | XX-RX-08          | Coalinga 06     | 7/22/1983  | CDMG Sulphur Baths   |   |   |
| 79                            | 257  | 491_nibv_0ewa.dat | 5.9 | 36                      | 0.0194 | -0.023 | 1.03  | -1.02  | 0.092    | -0.085 | 20.989           | 17.363 | 1.632                | 1.862  | 0.876      | 0.000                 | Rock          | Italy  | H1   | EW  | XX-NX-06          | Norcia, Italy   | 9/19/1979  | Bevagna, Italy       |   |   |
|                               | 258  | 492_nibv_0nsa.dat | 5.9 | 36                      | 0.0381 | -0.04  | 2.18  | -2.06  | 0.294    | -0.412 | 22.569           | 20.420 | 2.303                | 3.785  | 1.372      | 0.000                 | Rock          | Italy  | H2   | NS  | XX-NX-06          | Norcia, Italy   | 9/19/1979  | Bevagna, Italy       |   |   |
|                               | 259  | 493_nibv_0upa.dat | 5.9 | 36                      | 0.0203 | -0.025 | 0.67  | -0.90  | 0.064    | -0.064 | 13.007           | 14.381 | 2.809                | 1.909  | 0.707      | 0.000                 | Rock          | Italy  | V    | UP  | XX-NX-06          | Norcia, Italy   | 9/19/1979  | Bevagna, Italy       |   |   |
| 80                            | 260  | 494_nics_0ewa.dat | 5.9 | 7                       | 0.1996 | -0.169 | 11.50 | -8.40  | 1.679    | -1.455 | 22.689           | 19.559 | 2.485                | 3.417  | 17.033     | 3.720                 | Rock          | Italy  | H1   | EW  | XX-NX-06          | Norcia, Italy   | 9/19/1979  | Cascia, Italy        |   |   |
|                               | 261  | 495_nics_0nsa.dat | 5.9 | 7                       | 0.1327 | -0.161 | 8.47  | -6.17  | 0.621    | -0.614 | 25.131           | 15.054 | 1.127                | 2.553  | 23.091     | 4.180                 | Rock          | Italy  | H2   | NS  | XX-NX-06          | Norcia, Italy   | 9/19/1979  | Cascia, Italy        |   |   |
|                               | 262  | 496_nics_0upa.dat | 5.9 | 7                       | 0.1457 | -0.135 | 3.78  | -4.09  | 0.428    | -0.256 | 10.217           | 11.964 | 4.279                | 2.018  | 11.543     | 4.390                 | Rock          | Italy  | V    | UP  | XX-NX-06          | Norcia, Italy   | 9/19/1979  | Cascia, Italy        |   |   |
| 81                            | 263  | 497_c5sb_000a.dat | 5.2 | 15                      | 0.1518 | -0.143 | 8.49  | -7.01  | 1.267    | -0.911 | 22.019           | 19.274 | 2.617                | 2.601  | 6.723      | 1.711                 | Rock          | WUS    | H1   | 0   | XX-RX-08          | Coalinga 07     | 7/25/1983  | CDMG Sulphur Baths   |   |   |
|                               | 264  | 498_c5sb_090a.dat | 5.2 | 15                      | 0.1662 | -0.23  | 8.17  | -10.89 | 0.762    | -0.699 | 19.355           | 18.671 | 1.860                | 1.327  | 11.531     | 1.256                 | Rock          | WUS    | H2   | 90  | XX-RX-08          | Coalinga 07     | 7/25/1983  | CDMG Sulphur Baths   |   |   |
|                               | 265  | 499_c5sb_0upa.dat | 5.2 | 15                      | 0.1191 | -0.139 | 2.95  | -6.45  | 0.325    | -0.314 | 9.759            | 18.234 | 4.357                | 1.030  | 7.169      | 1.411                 | Rock          | WUS    | V    | UP  | XX-RX-08          | Coalinga 07     | 7/25/1983  | CDMG Sulphur Baths   |   |   |
| 82                            | 266  | 500_c6sb_000a.dat | 5.2 | 20                      | 0.0139 | -0.013 | 0.64  | -0.54  | 0.064    | -0.061 | 18.135           | 16.464 | 2.121                | 2.630  | 0.207      | 0.000                 | Rock          | WUS    | H    | 0   | XX-SS-07          | Coalinga 08     | 9/9/1983   | CDMG Sulphur Baths   |   |   |
|                               | 267  | 501_c6sb_090a.dat | 5.2 | 20                      | 0.0165 | -0.011 | 0.54  | -0.63  | 0.041    | -0.059 | 12.800           | 21.985 | 2.272                | 1.631  | 0.193      | 0.000                 | Rock          | WUS    | H2   | 90  | XX-SS-07          | Coalinga 08     | 9/9/1983   | CDMG Sulphur Baths   |   |   |
|                               | 268  | 502_c6sb_0upa.dat | 5.2 | 20                      | 0.0157 | -0.011 | 0.53  | -0.61  | 0.039    | -0.036 | 13.267           | 21.787 | 2.151                | 1.039  | 0.241      | 0.000                 | Rock          | WUS    | V    | UP  | XX-SS-07          | Coalinga 08     | 9/9/1983   | CDMG Sulphur Baths   |   |   |
| 83                            | 269  | 503_clga_230a.dat | 5.7 | 15                      | 0.1026 | -0.08  | 2.63  | -3.37  | 0.353    | -0.484 | 10.076           | 16.609 | 5.150                | 3.331  | 5.761      | 1.837                 | Rock          | WUS    | H1   | 230 | XX-SS-10          | Coyote          | 8/6/1979   | Gilroy Array # 1     |   |   |
|                               | 270  | 504_clga_320a.dat | 5.7 | 15                      | 0.1163 | -0.132 | 6.52  | -8.25  | 0.888    | -1.523 | 22.092           | 24.517 | 2.378                | 2.908  | 7.186      | 1.767                 | Rock          | WUS    | H2   | 320 | XX-SS-10          | Coyote          | 8/6/1979   | Gilroy Array # 1     |   |   |
|                               | 271  | 505_clga_0upa.dat | 5.7 | 15                      | 0.061  | -0.072 | 2.04  | -2.53  | 0.407    | -0.337 | 13.173           | 13.860 | 5.840                | 3.707  | 3.208      | 2.567                 | Rock          | WUS    | V    | UP  | XX-SS-10          | Coyote          | 8/6/1979   | Gilroy Array # 1     |   |   |
| 84                            | 272  | 506_clg6_230a.dat | 5.7 | 9                       | 0.3334 | -0.434 | 49.21 | -17.74 | 6.519    | -7.697 | 58.100           | 16.098 | 0.880                | 10.403 | 69.690     | 3.957                 | Rock          | WUS    | H1   | 230 | XX-SS-10          | Coyote          | 8/6/1979   | Gilroy Array # 6     |   |   |
|                               | 273  | 507_clg6_320a.dat | 5.7 | 9                       | 0.2617 | -0.316 | 24.47 | -21.13 | 3.849    | -2.058 | 36.818           | 26.316 | 1.649                | 1.429  | 61.161     | 5.562                 | Rock          | WUS    | H2   | 320 | XX-SS-10          | Coyote          | 8/6/1979   | Gilroy Array # 6     |   |   |
|                               | 274  | 508_clg6_0upa.dat | 5.7 | 9                       | 0.1359 | -0.146 | 11.91 | -12.80 | 3.959    | -2.913 | 34.480           | 34.533 | 3.724                | 2.544  | 14.119     | 3.467                 | Rock          | WUS    | V    | UP  | XX-SS-10          | Coyote          | 8/6/1979   | Gilroy Array # 6     |   |   |

| M6 Master Accelerograph Table |      |                   |     |                         |        |        |      |       |          |        |          |        |           |       |            |                       |               |        |      |     |                   |                  |            |                           |
|-------------------------------|------|-------------------|-----|-------------------------|--------|--------|------|-------|----------|--------|----------|--------|-----------|-------|------------|-----------------------|---------------|--------|------|-----|-------------------|------------------|------------|---------------------------|
| Set                           | Rec# | Filename          | Mw  | Distance<br>(hyp)<br>km | PGA    |        | PGV  |       | PGD      |        | Ratio 1  |        | Ratio 2   |       | AI<br>0.95 | Duration<br>bracketed | Site<br>Class | Region | Comp | deg | Setting &<br>Mech | Earthquake       | date       | Station                   |
|                               |      |                   |     |                         | +      | -      | +    | -     | Lin Disp |        | vm/km    |        | d*km/vm^2 |       |            |                       |               |        |      |     |                   |                  |            |                           |
|                               |      |                   |     |                         |        |        |      |       | +        | -      | in./s/%g | cm/s   | +         | -     |            |                       |               |        |      |     |                   |                  |            |                           |
|                               |      |                   |     |                         |        |        |      |       |          |        |          |        |           |       |            |                       |               |        |      |     |                   |                  |            |                           |
| 85                            | 275  | 509_mlmc_117a.dat | 4.9 | 11                      | 0.0784 | -0.075 | 1.46 | -1.62 | 0.102    | -0.087 | 7.340    | 8.515  | 3.683     | 2.426 | 2.700      | 1.326                 | Rock          | WUS    | H    | 117 | XX-XX-08          | Mammoth Lakes 09 | 6/11/1980  | USC McGee Creek           |
|                               | 276  | 510_mlmc_207a.dat | 4.9 | 11                      | 0.1936 | -0.211 | 2.97 | -2.21 | 0.077    | -0.085 | 6.046    | 4.121  | 1.659     | 3.614 | 9.212      | 0.701                 | Rock          | WUS    | H2   | 207 | XX-XX-08          | Mammoth Lakes 09 | 6/11/1980  | USC McGee Creek           |
|                               | 277  | 511_mlmc_Oupa.dat | 4.9 | 11                      | 0.0904 | -0.066 | 0.74 | -0.76 | 0.035    | -0.024 | 3.234    | 4.509  | 5.599     | 2.758 | 1.847      | 0.946                 | Rock          | WUS    | V    | UP  | XX-XX-08          | Mammoth Lakes 09 | 6/11/1980  | USC McGee Creek           |
| 86                            | 278  | 512_azpf_045a.dat | 5.2 | 19                      | 0.1099 | -0.086 | 1.71 | -2.49 | 0.105    | -0.110 | 6.141    | 11.419 | 3.844     | 1.492 | 2.417      | 1.000                 | Rock          | WUS    | H    | 45  | XX-SS-14          | Anza             | 2/25/1980  | Pinyon Flat               |
|                               | 279  | 513_azpf_135a.dat | 5.2 | 19                      | 0.107  | -0.131 | 3.22 | -5.11 | 0.492    | -0.368 | 11.834   | 15.331 | 4.988     | 1.814 | 3.095      | 0.835                 | Rock          | WUS    | H2   | 135 | XX-SS-14          | Anza             | 2/25/1980  | Pinyon Flat               |
|                               | 280  | 514_azpf_Oupa.dat | 5.2 | 19                      | 0.0459 | -0.042 | 0.81 | -1.11 | 0.064    | -0.085 | 6.905    | 10.318 | 4.458     | 2.864 | 1.206      | 0.000                 | Rock          | WUS    | V    | UP  | XX-SS-14          | Anza             | 2/25/1980  | Pinyon Flat               |
| 87                            | 281  | 515_scsl_234a.dat | 6.0 | 76                      | 0.036  | -0.035 | 2.68 | -2.94 | 0.655    | -0.973 | 29.232   | 33.030 | 3.233     | 3.866 | 1.646      | 0.000                 | Rock          | WUS    | H    | 234 | XX-XX-XX          | Southern Cal     | 11/22/1952 | San Luis Obispo           |
|                               | 282  | 516_scsl_324a.dat | 6.0 | 76                      | 0.0441 | -0.054 | 2.57 | -3.33 | 0.531    | -0.470 | 22.951   | 24.490 | 3.469     | 2.227 | 2.083      | 0.021                 | Rock          | WUS    | H2   | 324 | XX-XX-XX          | Southern Cal     | 11/22/1952 | San Luis Obispo           |
|                               | 283  | 517_scsl_Oupa.dat | 6.0 | 76                      | 0.0275 | -0.021 | 2.37 | -1.60 | 0.671    | -0.411 | 33.814   | 30.543 | 3.236     | 3.247 | 0.574      | 0.000                 | Rock          | WUS    | V    | UP  | XX-XX-XX          | Southern Cal     | 11/22/1952 | San Luis Obispo           |
| 88                            | 284  | 518_aztv_045a.dat | 5.2 | 16                      | 0.1283 | -0.131 | 3.92 | -2.80 | 0.166    | -0.123 | 12.015   | 8.396  | 1.360     | 2.030 | 3.993      | 0.625                 | Rock          | WUS    | H    | 45  | XX-SS-14          | Anza             | 2/25/1980  | Terwilliger Valley        |
|                               | 285  | 519_aztv_135a.dat | 5.2 | 16                      | 0.0805 | -0.079 | 1.67 | -1.64 | 0.064    | -0.064 | 8.181    | 8.223  | 1.803     | 1.824 | 1.980      | 0.705                 | Rock          | WUS    | H2   | 135 | XX-SS-14          | Anza             | 2/25/1980  | Terwilliger Valley        |
|                               | 286  | 520_aztv_Oupa.dat | 5.2 | 16                      | 0.0678 | -0.066 | 1.66 | -1.29 | 0.057    | -0.057 | 9.656    | 7.662  | 1.367     | 2.226 | 1.479      | 0.640                 | Rock          | WUS    | V    | UP  | XX-SS-14          | Anza             | 2/25/1980  | Terwilliger Valley        |
| 89                            | 287  | 521_bb7r_090a.dat | 4.9 | 33                      | 0.0113 | -0.011 | 0.31 | -0.31 | 0.063    | -0.067 | 10.699   | 11.048 | 7.399     | 7.667 | 0.094      | 0.000                 | Rock          | WUS    | H    | 90  | XX-SS-06          | Big Bear City    | 2/22/2003  | Seven Oaks Dam Right Abut |
|                               | 288  | 522_bb7r_360a.dat | 4.9 | 33                      | 0.013  | -0.012 | 0.45 | -0.43 | 0.089    | -0.091 | 13.686   | 14.132 | 5.553     | 5.789 | 0.115      | 0.000                 | Rock          | WUS    | H2   | 360 | XX-SS-06          | Big Bear City    | 2/22/2003  | Seven Oaks Dam Right Abut |
|                               | 289  | 523_bb7r_Oupa.dat | 4.9 | 33                      | 0.0081 | -0.008 | 0.27 | -0.23 | 0.020    | -0.029 | 13.357   | 11.073 | 2.138     | 4.442 | 0.065      | 0.000                 | Rock          | WUS    | V    | UP  | XX-SS-06          | Big Bear City    | 2/22/2003  | Seven Oaks Dam Right Abut |
| 90                            | 290  | 524_bb7d_090a.dat | 4.9 | 33                      | 0.027  | -0.031 | 0.77 | -0.66 | 0.073    | -0.081 | 11.251   | 8.462  | 3.260     | 5.558 | 0.633      | 0.000                 | Rock          | WUS    | H    | 90  | XX-SS-06          | Big Bear City    | 2/22/2003  | Seven Oaks Dam Downstream |
|                               | 291  | 525_bb7d_360a.dat | 4.9 | 33                      | 0.0419 | -0.03  | 0.77 | -0.86 | 0.072    | -0.081 | 7.268    | 11.231 | 4.958     | 3.228 | 0.648      | 0.000                 | Rock          | WUS    | H2   | 360 | XX-SS-06          | Big Bear City    | 2/22/2003  | Seven Oaks Dam Downstream |
|                               | 292  | 526_bb7d_Oupa.dat | 4.9 | 33                      | 0.0125 | -0.012 | 0.22 | -0.25 | 0.021    | -0.024 | 6.875    | 8.123  | 5.488     | 4.613 | 0.143      | 0.000                 | Rock          | WUS    | V    | UP  | XX-SS-06          | Big Bear City    | 2/22/2003  | Seven Oaks Dam Downstream |
| 91                            | 293  | 527_bbsb_111a.dat | 4.9 | 41                      | 0.0064 | -0.007 | 0.41 | -0.33 | 0.055    | -0.083 | 25.002   | 18.420 | 2.081     | 5.211 | 0.078      | 0.000                 | Rock          | WUS    | H    | 111 | XX-SS-06          | Big Bear City    | 2/22/2003  | San Bernardino - Del Rosa |
|                               | 294  | 528_bbsb_021a.dat | 4.9 | 41                      | 0.0082 | -0.008 | 0.38 | -0.36 | 0.093    | -0.123 | 18.173   | 19.237 | 5.234     | 6.740 | 0.087      | 0.000                 | Rock          | WUS    | H2   | 21  | XX-SS-06          | Big Bear City    | 2/22/2003  | San Bernardino - Del Rosa |
|                               | 295  | 529_bbsb_Oupa.dat | 4.9 | 41                      | 0.0062 | -0.007 | 0.19 | -0.24 | 0.036    | -0.045 | 11.835   | 14.053 | 6.198     | 5.280 | 0.047      | 0.000                 | Rock          | WUS    | V    | UP  | XX-SS-06          | Big Bear City    | 2/22/2003  | San Bernardino - Del Rosa |
| 92                            | 296  | 530_lzat_Onsa.dat | 5.8 | 19                      | 0.0933 | -0.061 | 3.33 | -3.29 | 0.417    | -0.437 | 14.059   | 21.150 | 3.437     | 2.425 | 5.515      | 2.111                 | Rock          | Italy  | H    | NS  | XX-XX-14          | Lazio-Abruzzo    | 5/7/1984   | ENEL 99999 Atina, Italy   |
|                               | 297  | 531_lzat_Owea.dat | 5.8 | 19                      | 0.1135 | -0.07  | 3.77 | -4.00 | 0.345    | -0.337 | 13.084   | 22.446 | 2.700     | 1.450 | 4.677      | 1.252                 | Rock          | Italy  | H2   | WE  | XX-XX-14          | Lazio-Abruzzo    | 5/7/1984   | ENEL 99999 Atina, Italy   |
|                               | 298  | 532_lzat_Oupa.dat | 5.8 | 19                      | 0.0757 | -0.046 | 1.75 | -2.03 | 0.234    | -0.263 | 9.105    | 17.227 | 5.656     | 2.910 | 3.096      | 0.035                 | Rock          | Italy  | V    | UP  | XX-XX-14          | Lazio-Abruzzo    | 5/7/1984   | ENEL 99999 Atina, Italy   |
| 93                            | 299  | 533_h4ss_205a.dat | 5.5 | 14                      | 0.0439 | -0.044 | 5.32 | -5.03 | 1.266    | -0.847 | 47.688   | 45.232 | 1.925     | 1.437 | 2.270      | 0.000                 | Rock          | WUS    | H    | 205 | XX-SS-09          | Hollister-04     | 1/26/1980  | SAGO South - Surface      |
|                               | 300  | 534_h4ss_295a.dat | 5.5 | 14                      | 0.0615 | -0.09  | 4.96 | -9.26 | 1.500    | -1.698 | 31.735   | 40.546 | 3.683     | 1.745 | 4.619      | 1.276                 | Rock          | WUS    | H2   | 295 | XX-SS-09          | Hollister-04     | 1/26/1980  | SAGO South - Surface      |
|                               | 301  | 535_h4ss_Oupa.dat | 5.5 | 14                      | 0.0305 | -0.053 | 3.27 | -3.38 | 0.529    | -0.388 | 42.260   | 25.143 | 1.477     | 1.764 | 1.692      | 0.026                 | Rock          | WUS    | V    | UP  | XX-SS-09          | Hollister-04     | 1/26/1980  | SAGO South - Surface      |
| 94                            | 302  | 536_pgpk_Onsa.dat | 5.0 | 176                     | 0.1499 | -0.157 | 8.04 | -8.03 | 0.541    | -0.496 | 21.116   | 20.171 | 1.230     | 1.183 | 19.937     | 4.311                 | Rock          | Greece | H    | NS  | XX-XX-81          | Pelekanada       | 10/10/1984 | ITSAK Pelekanada, Greece  |
|                               | 303  | 537_pgpk_Owea.dat | 5.0 | 176                     | 0.1489 | -0.168 | 7.80 | -6.29 | 0.532    | -0.481 | 20.638   | 14.750 | 1.274     | 2.001 | 20.317     | 3.814                 | Rock          | Greece | H2   | WE  | XX-XX-81          | Pelekanada       | 10/10/1984 | ITSAK Pelekanada, Greece  |
|                               | 304  | 538_pgpk_Oupa.dat | 5.0 | 176                     | 0.0834 | -0.102 | 2.87 | -2.93 | 0.175    | -0.159 | 13.553   | 11.377 | 1.734     | 1.840 | 9.199      | 4.755                 | Rock          | Greece | V    | UP  | XX-XX-81          | Pelekanada       | 10/10/1984 | ITSAK Pelekanada, Greece  |
| 95                            | 305  | 539_dgkv_Onsa.dat | 5.2 | 48                      | 0.0398 | -0.049 | 2.25 | -1.83 | 0.105    | -0.106 | 22.230   | 14.849 | 0.807     | 1.504 | 1.836      | 0.000                 | Rock          | Greece | H    | NS  | XX-SS-14          | Drama            | 11/9/1985  | ITSAK Kavala              |
|                               | 306  | 540_dgkv_Owea.dat | 5.2 | 48                      | 0.0387 | -0.036 | 1.37 | -1.20 | 0.082    | -0.065 | 13.958   | 13.145 | 1.648     | 1.605 | 1.374      | 0.000                 | Rock          | Greece | H2   | WE  | XX-SS-14          | Drama            | 11/9/1985  | ITSAK Kavala              |
|                               | 307  | 541_dgkv_Oupa.dat | 5.2 | 48                      | 0.0491 | -0.031 | 1.51 | -1.11 | 0.090    | -0.071 | 12.093   | 14.185 | 1.899     | 1.757 | 0.791      | 0.000                 | Rock          | Greece | V    | UP  | XX-SS-14          | Drama            | 11/9/1985  | ITSAK Kavala              |
| 96                            | 308  | 542_cc38_00ea.dat | 5.9 | 64                      | 0.009  | -0.007 | 0.60 | -0.75 | 0.131    | -0.140 | 26.097   | 43.212 | 3.239     | 1.664 | 0.111      | 0.000                 | Rock          | Taiwan | H    | E   | XX-XX-08          | Chi-Chi          | 9/20/1999  | CWB HWA 038, Taiwan       |
|                               | 309  | 543_cc38_00na.dat | 5.9 | 64                      | 0.0125 | -0.01  | 1.03 | -0.73 | 0.192    | -0.164 | 32.429   | 27.915 | 2.223     | 3.128 | 0.154      | 0.000                 | Rock          | Taiwan | H2   | N   | XX-XX-08          | Chi-Chi          | 9/20/1999  | CWB HWA 038, Taiwan       |
|                               | 310  | 544_cc38_00va.dat | 5.9 | 64                      | 0.0085 | -0.007 | 0.68 | -0.42 | 0.115    | -0.104 | 31.511   | 24.380 | 2.060     | 3.918 | 0.106      | 0.000                 | Rock          | Taiwan | V    | V   | XX-XX-08          | Chi-Chi          | 9/20/1999  | CWB HWA 038, Taiwan       |

| M6 Master Accelerograph Table |      |                   |     |                         |        |        |       |       |          |        |          |        |           |        |            |                       |               |        |      |     |                   |                      |            |                                    |
|-------------------------------|------|-------------------|-----|-------------------------|--------|--------|-------|-------|----------|--------|----------|--------|-----------|--------|------------|-----------------------|---------------|--------|------|-----|-------------------|----------------------|------------|------------------------------------|
| Set                           | Rec# | Filename          | Mw  | Distance<br>(hyp)<br>km | PGA    |        | PGV   |       | PGD      |        | Ratio 1  |        | Ratio 2   |        | AI<br>0.95 | Duration<br>bracketed | Site<br>Class | Region | Comp | deg | Setting &<br>Mech | Earthquake           | date       | Station                            |
|                               |      |                   |     |                         | +      | -      | +     | -     | Lin Disp |        | vm/km    |        | d*km/vm^2 |        |            |                       |               |        |      |     |                   |                      |            |                                    |
|                               |      |                   |     |                         | +      | -      | +     | -     | +        | -      | +        | -      |           |        |            |                       |               |        |      |     |                   |                      |            |                                    |
|                               |      |                   |     |                         | g%     |        | cm/s  |       | cm       |        | in./s/%g |        | +         | -      |            |                       |               |        |      |     |                   |                      |            |                                    |
| 97                            | 311  | 545_cc46_00na.dat | 5.9 | 67                      | 0.0253 | -0.03  | 2.47  | -2.40 | 0.275    | -0.298 | 38.468   | 31.308 | 1.116     | 1.531  | 0.817      | 0.000                 | Rock          | Taiwan | H    | N   | XX-XX-08          | Chi-Chi              | 9/20/1999  | CWB HWA 046, Taiwan                |
|                               | 312  | 546_cc46_00wa.dat | 5.9 | 67                      | 0.0263 | -0.027 | 1.92  | -1.82 | 0.231    | -0.260 | 28.684   | 26.315 | 1.624     | 2.095  | 0.856      | 0.000                 | Rock          | Taiwan | H2   | W   | XX-XX-08          | Chi-Chi              | 9/20/1999  | CWB HWA 046, Taiwan                |
|                               | 313  | 547_cc46_00va.dat | 5.9 | 67                      | 0.0149 | -0.015 | 1.37  | -1.18 | 0.197    | -0.217 | 36.216   | 30.836 | 1.532     | 2.304  | 0.265      | 0.000                 | Rock          | Taiwan | V    | V   | XX-XX-08          | Chi-Chi              | 9/20/1999  | CWB HWA 046, Taiwan                |
| 98                            | 314  | 548_cc31_00ea.dat | 5.9 | 112                     | 0.0159 | -0.016 | 0.85  | -0.71 | 0.095    | -0.082 | 21.048   | 17.572 | 2.064     | 2.527  | 0.343      | 0.000                 | Rock          | Taiwan | H    | E   | XX-XX-08          | Chi-Chi              | 9/20/1999  | CWB ILA 031, Taiwan                |
|                               | 315  | 549_cc31_00na.dat | 5.9 | 112                     | 0.0194 | -0.017 | 2.02  | -1.68 | 0.235    | -0.241 | 40.997   | 39.993 | 1.099     | 1.385  | 0.539      | 0.000                 | Rock          | Taiwan | H2   | N   | XX-XX-08          | Chi-Chi              | 9/20/1999  | CWB ILA 031, Taiwan                |
|                               | 316  | 550_cc31_00va.dat | 5.9 | 112                     | 0.0087 | -0.01  | 0.79  | -0.94 | 0.131    | -0.150 | 35.684   | 37.050 | 1.790     | 1.658  | 0.114      | 0.000                 | Rock          | Taiwan | V    | V   | XX-XX-08          | Chi-Chi              | 9/20/1999  | CWB ILA 031, Taiwan                |
| 99                            | 317  | 551_cc45_00ea.dat | 5.9 | 68                      | 0.0236 | -0.024 | 1.32  | -2.85 | 0.475    | -0.366 | 22.027   | 47.419 | 6.308     | 1.047  | 0.472      | 0.000                 | Rock          | Taiwan | H    | E   | XX-XX-08          | Chi-Chi              | 9/20/1999  | CWB TCU 045, Taiwan                |
|                               | 318  | 552_cc45_00na.dat | 5.9 | 68                      | 0.022  | -0.019 | 1.41  | -1.30 | 0.163    | -0.200 | 25.179   | 27.417 | 1.770     | 2.165  | 0.549      | 0.000                 | Rock          | Taiwan | H2   | N   | XX-XX-08          | Chi-Chi              | 9/20/1999  | CWB TCU 045, Taiwan                |
|                               | 319  | 553_cc45_00va.dat | 5.9 | 68                      | 0.0116 | -0.01  | 0.68  | -0.90 | 0.125    | -0.181 | 23.052   | 36.107 | 3.066     | 2.145  | 0.151      | 0.000                 | Rock          | Taiwan | V    | V   | XX-XX-08          | Chi-Chi              | 9/20/1999  | CWB TCU 045, Taiwan                |
| 100                           | 320  | 554_cc71_00ea.dat | 5.9 | 24                      | 0.1011 | -0.099 | 6.29  | -4.74 | 0.722    | -0.788 | 24.482   | 18.891 | 1.809     | 3.400  | 10.902     | 4.978                 | Rock          | Taiwan | H    | E   | XX-XX-08          | Chi-Chi              | 9/20/1999  | CWB TCU 071, Taiwan                |
|                               | 321  | 555_cc71_00na.dat | 5.9 | 24                      | 0.0551 | -0.058 | 2.78  | -2.92 | 0.323    | -0.250 | 19.868   | 19.695 | 2.255     | 1.683  | 4.779      | 2.753                 | Rock          | Taiwan | H2   | N   | XX-XX-08          | Chi-Chi              | 9/20/1999  | CWB TCU 071, Taiwan                |
|                               | 322  | 556_cc71_00va.dat | 5.9 | 24                      | 0.0267 | -0.026 | 1.40  | -1.29 | 0.212    | -0.257 | 20.648   | 19.466 | 2.838     | 3.947  | 1.163      | 0.000                 | Rock          | Taiwan | V    | V   | XX-XX-08          | Chi-Chi              | 9/20/1999  | CWB TCU 071, Taiwan                |
| 101                           | 323  | 557_smmw_000a.dat | 0.0 | 0                       | 0.276  | -0.187 | 13.54 | -9.93 | 0.714    | -1.777 | 19.314   | 20.949 | 1.054     | 3.300  | 37.110     | 3.879                 | Rock          | WUS    | H    | 0   | XX-XX-12          | Sierra Madre         | 6/28/1991  | CDMG Mt. Wilson                    |
|                               | 324  | 558_smmw_090a.dat | 0.0 | 0                       | 0.2001 | -0.198 | 7.79  | -6.25 | 0.756    | -1.067 | 15.319   | 12.428 | 2.449     | 5.300  | 29.797     | 3.659                 | Rock          | WUS    | H2   | 90  | XX-XX-12          | Sierra Madre         | 6/28/1991  | CDMG Mt. Wilson                    |
|                               | 325  | 559_smmw_0upa.dat | 0.0 | 0                       | 0.2372 | -0.194 | 4.34  | -5.74 | 0.731    | -0.646 | 7.199    | 11.627 | 9.039     | 3.738  | 24.572     | 3.699                 | Rock          | WUS    | V    | UP  | XX-XX-12          | Sierra Madre         | 6/28/1991  | CDMG Mt. Wilson                    |
| 102                           | 326  | 560_n6gp_00Ea.dat | 5.3 | 24                      | 0.0286 | -0.032 | 2.31  | -2.01 | 0.213    | -0.253 | 31.735   | 24.868 | 1.123     | 1.950  | 1.017      | 0.000                 | Rock          | WUS    | H    | 0   | XX-XX-13          | Northridge           | 3/20/1994  | Griffith Park Observatory          |
|                               | 327  | 561_n6gp_90Wa.dat | 5.3 | 24                      | 0.0529 | -0.056 | 2.39  | -2.19 | 0.169    | -0.235 | 17.762   | 15.400 | 1.536     | 2.694  | 2.416      | 1.680                 | Rock          | WUS    | H2   | 90  | XX-XX-13          | Northridge           | 3/20/1994  | Griffith Park Observatory          |
|                               | 328  | 562_n6gp_0upa.dat | 5.3 | 24                      | 0.021  | -0.027 | 1.14  | -1.33 | 0.056    | -0.109 | 21.394   | 19.442 | 0.883     | 1.622  | 0.543      | 0.000                 | Rock          | WUS    | V    | UP  | XX-XX-13          | Northridge           | 3/20/1994  | Griffith Park Observatory          |
| 103                           | 329  | 563_sms2_000a.dat | 5.7 | 32                      | 0.0885 | -0.119 | 5.04  | -3.29 | 0.339    | -0.504 | 22.448   | 10.887 | 1.155     | 5.433  | 4.170      | 0.462                 | Rock          | WUS    | H    | 0   | XX-XX-12          | Little Skull Mtn, NV | 6/29/1992  | USGS Station # 2 NTS Control Point |
|                               | 330  | 564_sms2_270a.dat | 5.7 | 32                      | 0.0906 | -0.057 | 3.24  | -4.66 | 0.475    | -0.636 | 14.080   | 32.013 | 4.023     | 1.647  | 2.564      | 0.552                 | Rock          | WUS    | H2   | 270 | XX-XX-12          | Little Skull Mtn, NV | 6/29/1992  | USGS Station # 2 NTS Control Point |
|                               | 331  | 565_sms2_0upa.dat | 5.7 | 32                      | 0.0502 | -0.07  | 2.61  | -2.31 | 0.237    | -0.253 | 20.507   | 13.061 | 1.705     | 3.245  | 1.543      | 0.447                 | Rock          | WUS    | V    | UP  | XX-XX-12          | Little Skull Mtn, NV | 6/29/1992  | USGS Station # 2 NTS Control Point |
| 104                           | 332  | 566_sms8_000a.dat | 5.7 | 100                     | 0.0123 | -0.011 | 0.51  | -0.52 | 0.095    | -0.099 | 16.116   | 18.179 | 4.499     | 4.033  | 0.190      | 0.000                 | Rock          | WUS    | H    | 0   | XX-XX-12          | Little Skull Mtn, NV | 6/29/1992  | USGS Station # 8 Death Valley      |
|                               | 333  | 567_sms8_270a.dat | 5.7 | 100                     | 0.0129 | -0.009 | 0.43  | -0.40 | 0.094    | -0.097 | 13.067   | 17.535 | 6.513     | 5.288  | 0.157      | 0.000                 | Rock          | WUS    | H2   | 270 | XX-XX-12          | Little Skull Mtn, NV | 6/29/1992  | USGS Station # 8 Death Valley      |
|                               | 334  | 568_sms8_0upa.dat | 5.7 | 100                     | 0.0088 | -0.007 | 0.26  | -0.30 | 0.098    | -0.086 | 11.735   | 16.740 | 12.281    | 6.506  | 0.103      | 0.000                 | Rock          | WUS    | V    | UP  | XX-XX-12          | Little Skull Mtn, NV | 6/29/1992  | USGS Station # 8 Death Valley      |
| 105                           | 335  | 569_cagi_020a.dat | 5.4 | 15                      | 0.0006 | -6E-04 | 0.03  | -0.02 | 0.003    | -0.003 | 17.675   | 15.114 | 2.456     | 3.445  | 0.000      | 0.000                 | Rock          | India  | H    | 20  | XX-XX-10          | Chamoli Aftershock   | 3/28/1996  | Gopershwar, India                  |
|                               | 336  | 570_cagi_290a.dat | 5.4 | 15                      | 0.0004 | -2E-04 | 0.02  | -0.03 | 0.004    | -0.003 | 15.900   | 46.943 | 5.777     | 0.977  | 0.000      | 0.000                 | Rock          | India  | H2   | 290 | XX-XX-10          | Chamoli Aftershock   | 3/28/1996  | Gopershwar, India                  |
|                               | 337  | 571_cagi_00va.dat | 5.4 | 15                      | 0.0004 | -5E-04 | 0.01  | -0.01 | 0.004    | -0.002 | 10.493   | 10.374 | 11.461    | 6.518  | 0.000      | 0.000                 | Rock          | India  | V    | V   | XX-XX-10          | Chamoli Aftershock   | 3/28/1996  | Gopershwar, India                  |
| 106                           | 338  | 572_ibui_087a.dat | 6.0 | 78                      | 0.0015 | -0.002 | 0.04  | -0.03 | 0.005    | -0.008 | 9.196    | 6.430  | 5.396     | 17.757 | 0.001      | 0.000                 | Rock          | India  | H    | 87  | XX-XX-XX          | India-Burma Border   | 5/8/1997   | Ummulong, India                    |
|                               | 339  | 573_ibui_357a.dat | 6.0 | 78                      | 0.0009 | -0.001 | 0.02  | -0.02 | 0.006    | -0.010 | 7.784    | 9.480  | 16.465    | 16.220 | 0.001      | 0.000                 | Rock          | India  | H2   | 357 | XX-XX-XX          | India-Burma Border   | 5/8/1997   | Ummulong, India                    |
|                               | 340  | 574_ibui_00va.dat | 6.0 | 78                      | 0.0002 | -3E-04 | 0.01  | -0.01 | 0.003    | -0.003 | 13.468   | 10.216 | 11.339    | 14.892 | 0.000      | 0.000                 | Rock          | India  | V    | V   | XX-XX-XX          | India-Burma Border   | 5/8/1997   | Ummulong, India                    |
| 107                           | 341  | 575_n2s1_010a.dat | 5.4 | Unknown                 | 0.2286 | -0.138 | 6.73  | -4.04 | 0.412    | -0.325 | 11.600   | 11.545 | 2.037     | 2.691  | 7.098      | 3.910                 | Rock          | Canada | H    | 10  | XX-XX-10          | Nahanni              | 12/23/1985 | Nahanni, NWT - Station #1          |
|                               | 342  | 576_n2s1_280a.dat | 5.4 | Unknown                 | 0.0894 | -0.058 | 3.12  | -3.14 | 0.397    | -0.360 | 13.757   | 21.221 | 3.564     | 2.087  | 3.140      | 1.260                 | Rock          | Canada | H2   | 280 | XX-XX-10          | Nahanni              | 12/23/1985 | Nahanni, NWT - Station #1          |
|                               | 343  | 577_n2s1_0upa.dat | 5.4 | Unknown                 | 0.1122 | -0.082 | 4.60  | -1.84 | 0.369    | -0.328 | 16.138   | 8.832  | 1.922     | 7.808  | 2.959      | 0.445                 | Rock          | Canada | V    | UP  | XX-XX-10          | Nahanni              | 12/23/1985 | Nahanni, NWT - Station #1          |
| 108                           | 344  | 578_n1s3_270a.dat | 5.7 | Unknown                 | 0.0876 | -0.09  | 2.08  | -1.19 | 0.395    | -0.370 | 9.351    | 5.212  | 7.845     | 23.053 | 2.120      | 0.835                 | Rock          | Canada | H    | 270 | XX-XX-10          | Nahanni              | 12/25/1985 | Nahanni, NWT - Station #3          |
|                               | 345  | 579_n1s3_360a.dat | 5.7 | Unknown                 | 0.0942 | -0.105 | 1.11  | -1.17 | 0.140    | -0.143 | 4.625    | 4.396  | 10.583    | 10.693 | 2.550      | 1.180                 | Rock          | Canada | H2   | 360 | XX-XX-10          | Nahanni              | 12/25/1985 | Nahanni, NWT - Station #3          |
|                               | 346  | 580_n1s3_0upa.dat | 5.7 | Unknown                 | 0.0631 | -0.074 | 1.19  | -1.55 | 0.283    | -0.380 | 7.441    | 8.232  | 12.295    | 11.503 | 1.684      | 0.910                 | Rock          | Canada | V    | UP  | XX-XX-10          | Nahanni              | 12/25/1985 | Nahanni, NWT - Station #3          |

Table 4.4. Sets of earthquake time-history data classified by moment magnitude ranges.

| Earthquake Magnitude          | Magnitude 7 | Magnitude 6 | Magnitude 5 |
|-------------------------------|-------------|-------------|-------------|
| Moment Magnitude range (Mw)   | 6.90 – 8.10 | 6.90 – 8.10 | 4.85 – 6.06 |
| Average Moment Magnitude (Mw) | 7.25        | 7.25        | 5.57        |
| No. sets (set id range)       | 23 (1-23)   | 23 (1-23)   | 61 (48-108) |
| H or H1                       | 23          | 23          | 61          |
| H2                            | 22          | 22          | 61          |
| V                             | 23          | 23          | 58          |
| TOTAL TH's                    | 68          | 68          | 180         |

Table 4.5. Comparison between the Richter and Moment Magnitude Scales.

| Earthquake               | Richter Scale | Moment Magnitude |
|--------------------------|---------------|------------------|
| New Madrid, MO, 1812     | 8.7           | 8.1              |
| San Francisco, CA, 1906  | 8.3           | 7.7              |
| Prince William, AK, 1964 | 8.4           | 9.2              |
| Northridge, CA, 1994     | 6.4           | 6.7              |

The criteria for selection of “rock” data were records that were assigned a rock site classification, and where more site information was available, the site’s  $V_{s30}$  (average shear wave velocity ( $V_s$ ) in the upper 30 m). Records were accepted if  $V_{s30}$  exceeded 600 meters per second (m/s) to insure “rock” records using an upper bound site class C to avoid stiff soil sites. A  $V_{s30}$  of 760 m/s is an unweathered rock and including only down to 600 m/s allows weathered rock, but voids highly weathered rock or stiff soil sites which start at 360 m/s. Also, records were selected based on instrument housing as free-field, or less preferred, but acceptable, one-story structures.

The records selected were all instrument corrected records. The further processing included a baseline correction based on the procedure, “baseline,” a PC-based algorithm developed by Norm Abrahamson that uses a polynomial fit to remove any baseline shift from the earthquake acceleration time-history. The baseline shift is usually an artifact introduced by the data collection process. Since the application of this data is to estimate permanent displacements, it was important that this artifact be removed so that the data doesn’t include an initial undesirable permanent

component of displacement. The specifics of the parameters used in the processing were use of 5th order polynomial, 50 zeros padded at the end of each record, and a 10 second taper. All records received identical processing. Visual data quality checks involved reviewing time-histories and response spectra to be sure that all data appeared free-field and rock-like in nature. All response spectra were plotted together to identify any large deviations from the full population data set. The sources of these data were predominately from the Pacific Earthquake Engineering Research Center (PEER) database and Consortium of Strong-ground motion Observations Systems (COSMOS) virtual data center. 4.2 Regression results of earthquakes covering the Moment Magnitude ( $M_w$ ) range of 6.9 – 8.1 (Magnitude 7)

This section will discuss the results from regression analyses of the non-dimensionalized displacement relationships described by Equations 3.20, 3.39, and 3.58 previously derived in Chapter 3. The values for the coefficients summarized by the above mentioned equations and the standard error terms, as well as the probabilistic measures of Equation Forms One, Two and Three as shown in Table 4.6, will be discussed in Sections 4.2.1, 4.2.2, and 4.2.3. These regression analyses were performed for baseline corrected acceleration time histories recorded on rock with a  $M_w$  range of 6.9 to 8.1 and an average  $M_w$  of 7.3.

Table 4.6. Values for the regression equations constants for Moment Magnitude ( $M_w$ ) range of 6.9 – 8.1 (Magnitude 7).

| Coefficients and <i>Std. Error</i> | Equation Form One | Equation Form Two | Equation Form Three |
|------------------------------------|-------------------|-------------------|---------------------|
| $\beta_1$                          |                   | 70.146            | 66.727              |
| $\beta_2$                          |                   | -9.200            | -9.134              |
| $\beta_3$                          |                   |                   | -0.018              |
| $\beta_4$                          | -0.124            |                   |                     |
| $\beta_5$                          | -2.076            |                   |                     |
| <i>Std. Error</i>                  | 1.428             | 0.932             | 0.932               |

#### 4.2.1 Three-term regression results

The standard error term (*Std. error*) for this regression analysis was determined to be 0.93 for both the non-dimensionalized displacement as well as the standardized displacement for earthquakes of Magnitude 7. This non-dimensionalized three-term displacement equation is identified as

Equation Form Three with the coefficients and *Std. error* terms summarized in column four of Table 4.6.

#### 4.2.1.1 Mean relationships

The regression analysis of the 23 sets of Magnitude 7 acceleration time histories resulted in the mean non-dimensionalized displacement relationship of

$$\frac{d_m \bullet k_m g}{v_m^2} = 66.7 \bullet \exp \left( -9.13 \bullet \frac{k_c}{k_m} \right) \bullet \left( \frac{k_c}{k_m} \right)^{-0.018} \quad (4.1)$$

where:

- $d_m$  = permanent displacement
- $k_m g$  = peak (positive) rock acceleration expressed in units of length per sec<sup>2</sup>, consistent with units of  $d_m$  (length) and  $v_m$  (length per sec)
- $v_m$  = peak (positive) ground velocity of the earthquake
- $k_c$  = critical acceleration expressed as a fraction of  $g$
- $k_m$  = peak (positive) rock acceleration expressed as a fraction of  $g$ .

This mean relationship is shown in yellow in Figure 4.1.

By a second independent regression analysis, the mean standardized maximum displacement ( $d_s$ ) in units of inches was derived for the standardized velocity,  $v_s = 29.92$  in./sec (0.76 m/sec) and the standardized acceleration  $k_s = 0.5 g$  (193.04 in./sec<sup>2</sup> : 4.90 m/sec<sup>2</sup>)

$$d_s = 309.5 \bullet \exp \left( -9.13 \bullet \frac{k_c}{k_m} \right) \bullet \left( \frac{k_c}{k_m} \right)^{-0.018} \quad (4.2)$$

The standardized maximum displacement ( $d_s$ ) can be converted to the permanent displacement ( $d_m$ ) by the following transformation (Franklin and Chang 1977),

$$d_m = d_s \bullet \left[ \left( \frac{k_s}{v_s^2} \right) \bullet \left( \frac{v_m^2}{k_m} \right) \right] \quad (4.3)$$

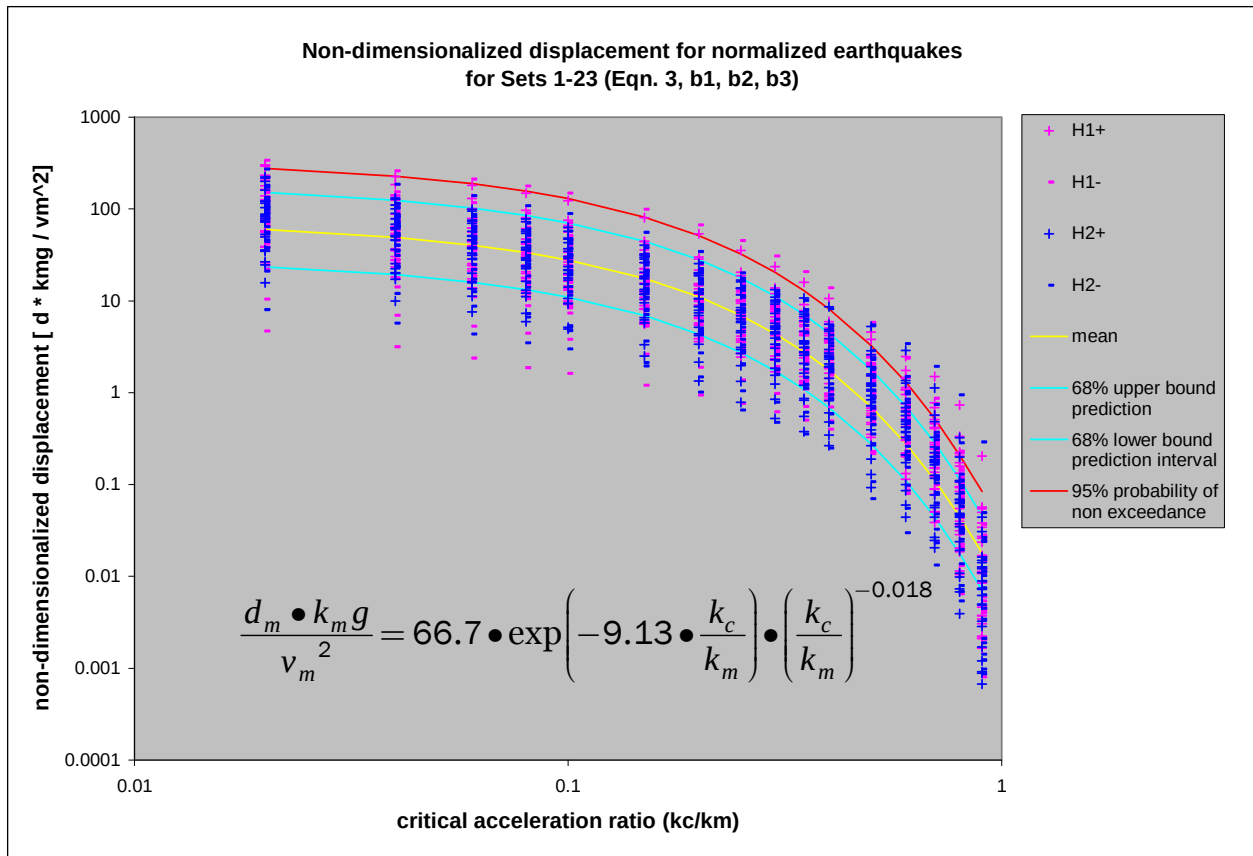


Figure 4.1. Non-dimensionalized displacements with the mean, 68 percent prediction intervals and 95 percent probability of non-exceedance curves.

where:

$k_s$  = standardized acceleration expressed as a fraction of  $g$  (0.5)

$v_s$  = standardized velocity (29.92 in./sec).

The mean permanent displacement is derived by introducing Equation 4.2 into Equation 4.3.

$$d_m = 309.5 \bullet \exp\left(-9.13 \bullet \frac{k_c}{k_m}\right) \bullet \left(\frac{k_c}{k_m}\right)^{-0.018} \bullet \left[0.216 \bullet \left(\frac{v_m^2}{k_m \bullet g}\right)\right] \quad (4.4)$$

where the right-hand-side term  $k_m g$  is the peak (positive) rock acceleration expressed in units of length per sec<sup>2</sup>.

Note that Equation 4.4 is the same as Equation 4.1, indicating consistent results from both regression analyses.

#### 4.2.1.2 Ninety-five percent probability of non-exceedance

The regression analysis of the 23 sets of Magnitude 7 rock acceleration time histories resulted in the non-dimensionalized displacement for 95 percent probability of non-exceedance of

$$\frac{d_m \bullet k_m g}{v_m^2} = 66.7 \bullet \exp \left( -9.13 \bullet \frac{k_c}{k_m} \right) \bullet \left( \frac{k_c}{k_m} \right)^{-0.018} \bullet 4.64 \quad (4.5)$$

The 95 percent probability of non-exceedance is shown in red in Figure 4.1.

By the second independent regression analysis, the standardized maximum displacement ( $d_s$ ) in units of inches, derived using  $v_s = 29.92$  in./sec and  $k_s = 0.5$  g, is

$$d_s = 309.5 \bullet \exp \left( -9.13 \bullet \frac{k_c}{k_m} \right) \bullet \left( \frac{k_c}{k_m} \right)^{-0.018} \bullet 4.64 \quad (4.6)$$

The corresponding permanent displacement is

$$d_m = 309.5 \bullet \exp \left( -9.13 \bullet \frac{k_c}{k_m} \right) \bullet \left( \frac{k_c}{k_m} \right)^{-0.018} \bullet 4.64 \bullet \left[ 0.216 \bullet \left( \frac{v_m^2}{k_m \bullet g} \right) \right] \quad (4.7)$$

Note that Equation 4.7 is the same as Equation 4.5, indicating consistent results from both regression analyses,

#### 4.2.1.3 Sixty-eight percent prediction intervals

The regression analysis of the 23 sets of Magnitude 7 rock acceleration time histories resulted in the non-dimensionalized displacement relationships for the 68 percent prediction intervals of

$$\frac{d_m \bullet k_m g}{v_m^2} = 66.7 \bullet \exp \left( -9.13 \bullet \frac{k_c}{k_m} \right) \bullet \left( \frac{k_c}{k_m} \right)^{-0.018} \bullet 2.53 \quad (4.8a)$$

$$\frac{d_m \bullet k_m g}{v_m^2} = 66.7 \bullet \exp \left( -9.13 \bullet \frac{k_c}{k_m} \right) \bullet \left( \frac{k_c}{k_m} \right)^{-0.018} \bullet 0.39 \quad (4.8b)$$

The 68 percent prediction intervals are shown in blue in Figure 4.1.

By the second independent regression analysis, the standardized maximum displacements ( $d_s$ ) in units of inches, derived using  $v_s = 29.92$  in./sec and  $k_s = 0.5 g$ , are

$$d_s = 309.5 \bullet \exp\left(-9.13 \bullet \frac{k_c}{k_m}\right) \bullet \left(\frac{k_c}{k_m}\right)^{-0.018} \bullet 2.53 \quad (4.9a)$$

$$d_s = 309.5 \bullet \exp\left(-9.13 \bullet \frac{k_c}{k_m}\right) \bullet \left(\frac{k_c}{k_m}\right)^{-0.018} \bullet 0.39 \quad (4.9b)$$

Introducing Equation 4.3, the corresponding permanent displacements are

$$d_m = 309.5 \bullet \exp\left(-9.13 \bullet \frac{k_c}{k_m}\right) \bullet \left(\frac{k_c}{k_m}\right)^{-0.018} \bullet 2.53 \bullet \left[0.216 \bullet \left(\frac{v_m^2}{k_m \bullet g}\right)\right] \quad (4.10a)$$

$$d_m = 309.5 \bullet \exp\left(-9.13 \bullet \frac{k_c}{k_m}\right) \bullet \left(\frac{k_c}{k_m}\right)^{-0.018} \bullet 0.39 \bullet \left[0.216 \bullet \left(\frac{v_m^2}{k_m \bullet g}\right)\right] \quad (4.10b)$$

where the right-hand-side term  $k_m g$  is the peak (positive) rock acceleration expressed in units of length per sec<sup>2</sup>.

Note that Equations 4.10a and 4.10b are the same as Equations 4.8a and 4.8b, indicating consistent results from both regression analyses.

#### 4.2.2 Two-term regression results, linear in natural logarithm transformation

The standard error term (*Std. error*) for this regression analysis was determined to be 0.93 for both the non-dimensionalized displacement as well as the standardized displacement for earthquakes of Magnitude 7. This non-dimensionalized two-term displacement equation is identified as Equation Form Two with the coefficients and *Std. error* terms summarized in column three of Table 4.6.

#### 4.2.2.1 Mean relationships

The regression analysis of the 23 sets of Magnitude 7 rock acceleration time histories resulted in the mean non-dimensionalized displacement relationship of

$$\frac{d_m \bullet k_m g}{v_m^2} = 70.1 \bullet \exp \left( -9.2 \bullet \frac{k_c}{k_m} \right) \quad (4.11)$$

where the left-hand-side term  $k_m g$  is the peak (positive) rock acceleration expressed in units of length per sec<sup>2</sup>, consistent with units of  $d_m$  (length) and  $v_m$  (length per sec) in which  $d_m$  is the permanent displacement,  $v_m$  is the peak (positive) ground velocity of the earthquake and  $k_c$  is the critical acceleration expressed as a fraction of  $g$ . The right hand side term  $k_m$  is the peak (positive) rock acceleration expressed as a fraction of  $g$ .

This mean relationship is shown in yellow in Figure 4.2.

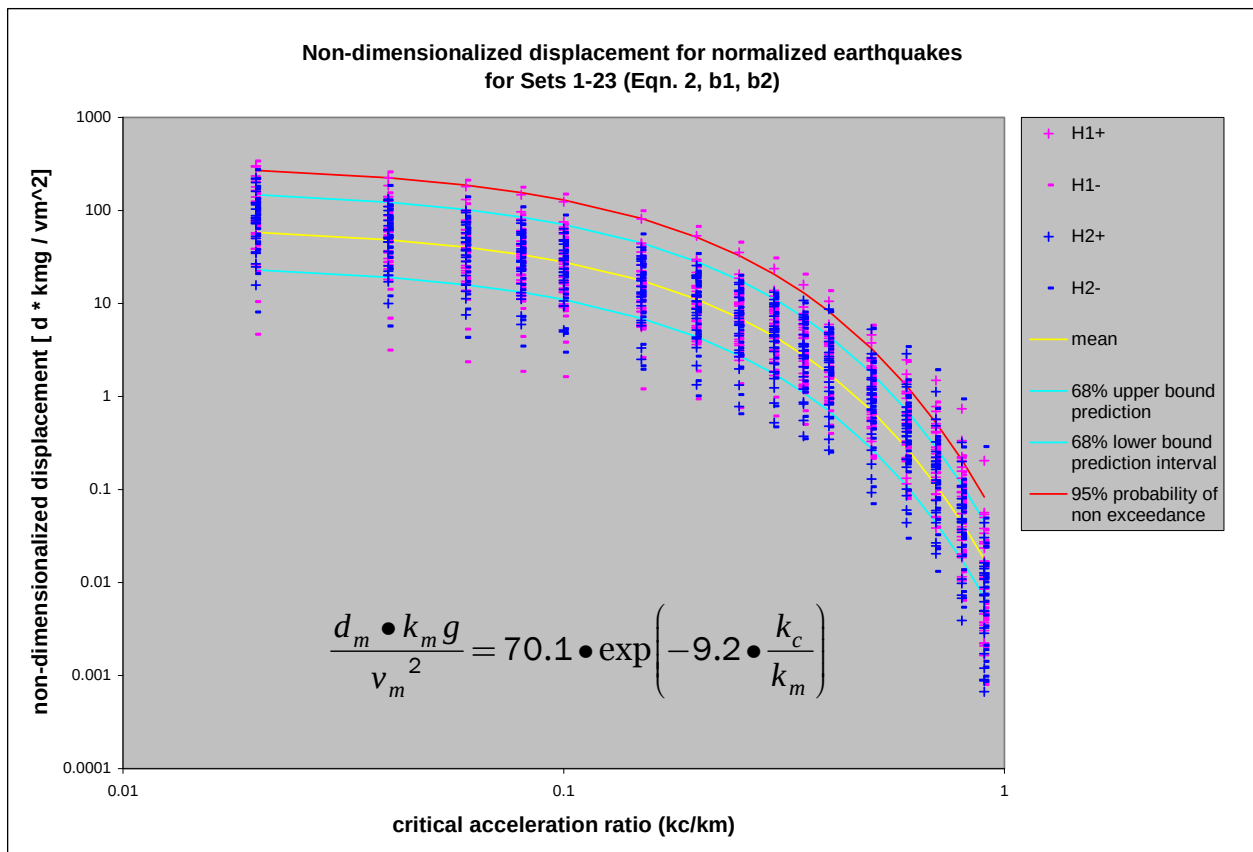


Figure 4.2. Non-dimensionalized displacements with the mean, 68 percent prediction intervals and 95 percent probability of non-exceedance curves.

By a second independent regression analysis, the mean standardized maximum displacement ( $d_s$ ) in units of inches was derived for the standardized velocity,  $v_s = 29.92$  in./sec (0.76 m/sec) and the standardized acceleration  $k_s = 0.5$  g (193.04 in./sec<sup>2</sup> : 4.90 m/sec<sup>2</sup>)

$$d_s = 325.3 \bullet \exp \left( -9.2 \bullet \frac{k_c}{k_m} \right) \quad (4.12)$$

The standardized maximum displacement ( $d_s$ ) can be converted to the permanent displacement ( $d_m$ ) by the following transformation,

$$d_m = d_s \bullet \left[ \left( \frac{k_s}{v_s^2} \right) \bullet \left( \frac{v_m^2}{k_m} \right) \right] \quad (\text{bis 4.3})$$

where:

$k_s$  = standardized acceleration expressed as a fraction of  $g$  (0.5)

$v_s$  = standardized velocity (29.92 in./sec).

The mean permanent displacement is derived by introducing Equation 4.12 into Equation 4.3.

$$d_m = 325.3 \bullet \exp \left( -9.2 \bullet \frac{k_c}{k_m} \right) \bullet \left[ 0.216 \bullet \left( \frac{v_m^2}{k_m \bullet g} \right) \right] \quad (4.13)$$

where the right-hand-side term  $k_m g$  is the peak (positive) rock acceleration expressed in units of length per sec<sup>2</sup>.

Note that Equation 4.13 is the same as Equation 4.11, indicating consistent results from both regression analyses.

#### 4.2.2.2 Ninety-five percent probability of non-exceedance

The regression analysis of the 23 sets of Magnitude 7 rock acceleration time histories resulted in the non-dimensionalized displacement for 95 percent probability of non-exceedance of

$$\frac{d_m \bullet k_m g}{v_m^2} = 70.1 \bullet \exp \left( -9.2 \bullet \frac{k_c}{k_m} \right) \bullet 4.64 \quad (4.14)$$

The 95 percent probability of non-exceedance is shown in red in Figure 4.2.

By the second, independent regression analysis, the standardized maximum displacement ( $d_s$ ) in units of inches, derived using  $v_s = 29.92$  in./sec and  $k_s = 0.5 g$ , is

$$d_s = 325.3 \bullet \exp\left(-9.2 \bullet \frac{k_c}{k_m}\right) \bullet 4.64 \quad (4.15)$$

The corresponding permanent displacement is

$$d_m = 325.3 \bullet \exp\left(-9.2 \bullet \frac{k_c}{k_m}\right) \bullet 4.64 \bullet \left[0.216 \bullet \left(\frac{v_m^2}{k_m \bullet g}\right)\right] \quad (4.16)$$

where the right-hand-side term  $k_m g$  is the peak (positive) rock acceleration expressed in units of length per sec<sup>2</sup>.

Note that Equation 4.16 is the same as Equation 4.14, indicating consistent results from both regression analyses.

#### 4.2.2.3 Sixty-eight percent prediction intervals

The regression analysis of the 23 sets of Magnitude 7 rock acceleration time histories resulted in the non-dimensionalized displacement relationships for the 68 percent prediction intervals of

$$\frac{d_m \bullet k_m g}{v_m^2} = 70.1 \bullet \exp\left(-9.2 \bullet \frac{k_c}{k_m}\right) \bullet 2.53 \quad (4.17a)$$

$$\frac{d_m \bullet k_m g}{v_m^2} = 70.1 \bullet \exp\left(-9.2 \bullet \frac{k_c}{k_m}\right) \bullet 0.39 \quad (4.17b)$$

The 68 percent prediction intervals are shown in blue in Figure 4.2.

By the second independent regression analysis, the standardized maximum displacements ( $d_s$ ) in units of inches, derived using  $v_s = 29.92$  in./sec and  $k_s = 0.5 g$ , are

$$d_s = 325.3 \bullet \exp\left(-9.2 \bullet \frac{k_c}{k_m}\right) \bullet 2.53 \quad (4.18a)$$

$$d_s = 325.3 \bullet \exp\left(-9.2 \bullet \frac{k_c}{k_m}\right) \bullet 0.39 \quad (4.18b)$$

Introducing Equation 4.3, the corresponding permanent displacements are

$$d_m = 325.3 \bullet \exp\left(-9.2 \bullet \frac{k_c}{k_m}\right) \bullet 2.53 \bullet \left[0.216 \bullet \left(\frac{v_m^2}{k_m \bullet g}\right)\right] \quad (4.19a)$$

$$d_m = 325.3 \bullet \exp\left(-9.2 \bullet \frac{k_c}{k_m}\right) \bullet 0.39 \bullet \left[0.216 \bullet \left(\frac{v_m^2}{k_m \bullet g}\right)\right] \quad (4.19b)$$

where the right-hand-side term  $k_m g$  is the peak (positive) rock acceleration expressed in units of length per sec<sup>2</sup>.

Note that Equations 4.19a and 4.19b are the same as Equations 4.17a and 4.17b, indicating consistent results from both regression analyses.

### 4.2.3 Two-term regression results, linear in common logarithm transformation

The standard error term (*Std. error*) for this regression analysis was determined to be 1.43 for both the non-dimensionalized displacement as well as the standardized displacement for earthquakes of Magnitude 7. This non-dimensionalized two-term displacement equation is identified as Equation Form One with the coefficients and *Std. error* terms summarized in column two of Table 4.6.

#### 4.2.3.1 Mean relationships

The regression analysis of the 23 sets of Magnitude 7 rock acceleration time histories resulted in the mean non-dimensionalized displacement relationship of

$$\frac{d_m \bullet k_m g}{v_m^2} = 0.124 \bullet \left( \frac{k_c}{k_m} \right)^{-2.08} \quad (4.20)$$

where:

- $d_m$  = permanent displacement
- $k_m g$  = peak (positive) rock acceleration expressed in units of length per sec<sup>2</sup>, consistent with units of  $d_m$  (length) and  $v_m$  (length per sec)
- $v_m$  = peak (positive) ground velocity of the earthquake
- $k_c$  = critical acceleration expressed as a fraction of  $g$
- $k_m$  = peak (positive) rock acceleration expressed as a fraction of  $g$ .

This mean relationship is shown in yellow in Figure 4.3.

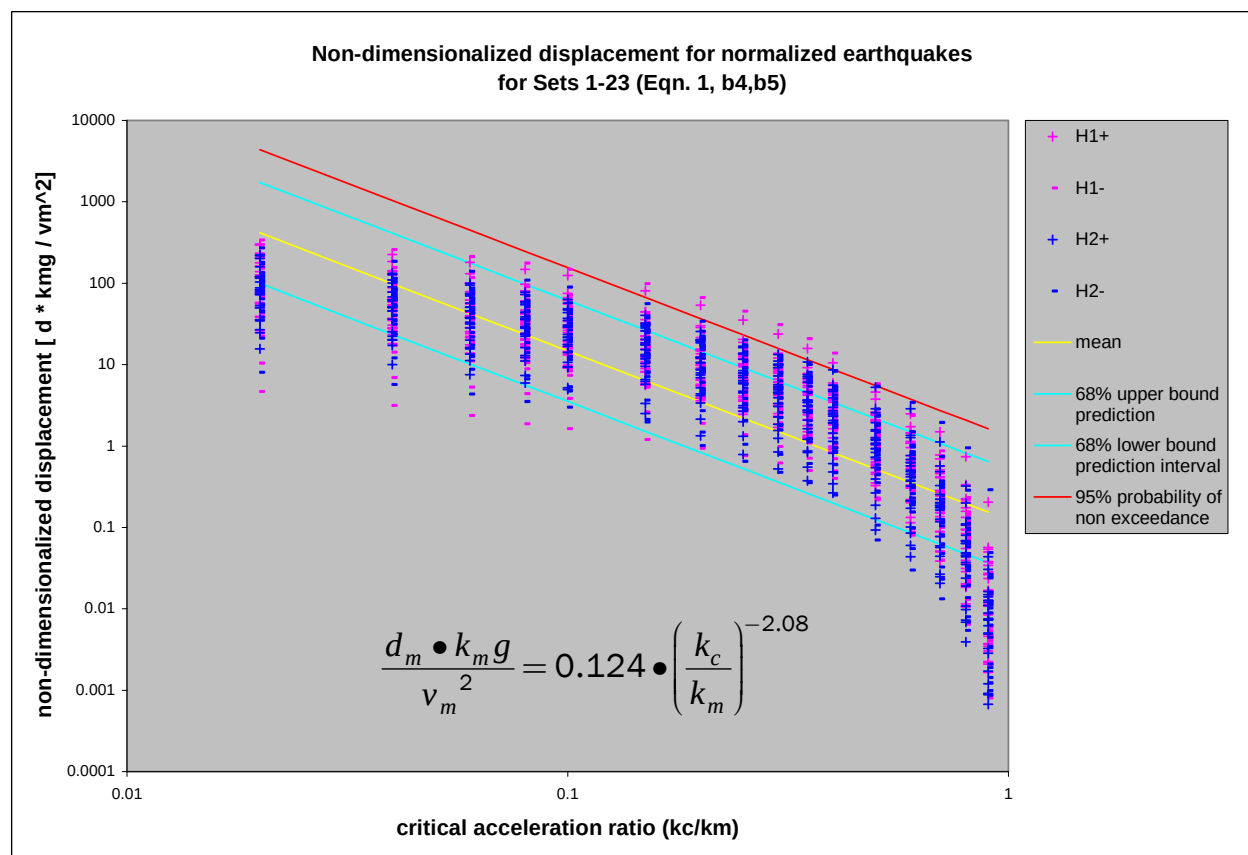


Figure 4.3. Non-dimensionalized displacements with the mean, 68 percent prediction intervals and 95 percent probability of non-exceedance curves.

By a second independent regression analysis, the mean standardized maximum displacement ( $d_s$ ) in units of inches was derived for the standardized velocity,  $v_s = 29.92$  in./sec (0.76 m/sec) and the standardized acceleration  $k_s = 0.5 g$  (193.04 in./sec<sup>2</sup> : 4.90 m/sec<sup>2</sup>)

$$d_s = 0.573 \cdot \left( \frac{k_c}{k_m} \right)^{-2.08} \quad (4.21)$$

The standardized maximum displacement ( $d_s$ ) can be converted to the permanent displacement ( $d_m$ ) by the following transformation,

$$d_m = d_s \cdot \left[ \left( \frac{k_s}{v_s^2} \right) \cdot \left( \frac{v_m^2}{k_m} \right) \right] \quad (\text{bis 4.3})$$

where:

$k_s$  = standardized acceleration expressed as a fraction of  $g$  (0.5)

$v_s$  = standardized velocity (29.92 in./sec).

The mean permanent displacement is derived by introducing Equation 4.21 into Equation 4.3.

$$d_m = 0.573 \cdot \left( \frac{k_c}{k_m} \right)^{-2.08} \cdot \left[ 0.216 \cdot \left( \frac{v_m^2}{k_m \cdot g} \right) \right] \quad (4.22)$$

where the right-hand-side term  $k_m g$  is the peak (positive) rock acceleration expressed in units of length per sec<sup>2</sup>.

Note that Equation 4.22 is the same as Equation 4.20, indicating consistent results from both regression analyses.

#### 4.2.3.2 Ninety-five percent probability of non-exceedance

The regression analysis of the 23 sets of Magnitude 7 rock acceleration time histories resulted in the non-dimensionalized displacement for 95 percent probability of non-exceedance of

$$\frac{d_m \bullet k_m g}{v_m^2} = 0.124 \bullet \left( \frac{k_c}{k_m} \right)^{-2.08} \bullet 2.78 \quad (4.23)$$

The 95 percent probability of non-exceedance is shown in red in Figure 4.3.

By the second independent regression analysis, the standardized maximum displacement ( $d_s$ ) in units of inches, derived using  $v_s = 29.92$  in./sec and  $k_s = 0.5$  g, is

$$d_s = 0.573 \bullet \left( \frac{k_c}{k_m} \right)^{-2.08} \bullet 2.78 \quad (4.24)$$

Introducing Equation 4.3, the corresponding permanent displacement is

$$d_m = 0.573 \bullet \left( \frac{k_c}{k_m} \right)^{-2.08} \bullet 2.78 \bullet \left[ 0.216 \bullet \left( \frac{v_m^2}{k_m \bullet g} \right) \right] \quad (4.25)$$

where the right-hand-side term  $k_m g$  is the peak (positive) rock acceleration expressed in units of length per sec<sup>2</sup>.

Note that Equation 4.25 is the same as Equation 4.23, indicating consistent results from both regression analyses.

#### 4.2.3.3 Sixty-eight percent prediction intervals

The regression analysis of the 23 sets of Magnitude 7 rock acceleration time histories resulted in the non-dimensionalized displacement relationships for the 68 percent prediction intervals of

$$\frac{d_m \bullet k_m g}{v_m^2} = 0.124 \bullet \left( \frac{k_c}{k_m} \right)^{-2.08} \bullet 1.86 \quad (4.26a)$$

$$\frac{d_m \bullet k_m g}{v_m^2} = 0.124 \bullet \left( \frac{k_c}{k_m} \right)^{-2.08} \bullet 0.538 \quad (4.26b)$$

The 68 percent prediction intervals are shown in blue in Figure 4.3.

By the second independent regression analysis, the standardized maximum displacements ( $d_s$ ) in units of inches, derived using  $v_s = 29.92$  in./sec and  $k_s = 0.5$  g, are

$$d_s = 325.3 \bullet \exp\left(-9.2 \bullet \frac{k_c}{k_m}\right) \bullet 1.86 \quad (4.27a)$$

$$d_s = 325.3 \bullet \exp\left(-9.2 \bullet \frac{k_c}{k_m}\right) \bullet 0.538 \quad (4.27b)$$

Introducing Equation 4.3, the corresponding permanent displacements are,

$$d_m = 325.3 \bullet \exp\left(-9.2 \bullet \frac{k_c}{k_m}\right) \bullet 1.86 \bullet \left[0.216 \bullet \left(\frac{v_m^2}{k_m \bullet g}\right)\right] \quad (4.28a)$$

$$d_m = 325.3 \bullet \exp\left(-9.2 \bullet \frac{k_c}{k_m}\right) \bullet 0.538 \bullet \left[0.216 \bullet \left(\frac{v_m^2}{k_m \bullet g}\right)\right] \quad (4.28b)$$

where the right-hand-side term  $k_m g$  is the peak (positive) rock acceleration expressed in units of length per sec<sup>2</sup>.

Note that Equations 4.28a and 4.28b are the same as Equations 4.26a and 4.26b, indicating consistent results from both regression analyses.

#### **4.2.4 Comparison of regression results of all three forms of the simplified non-dimensionalized displacement relationships**

The three forms of regression analysis (discussed in Sections 4.2.1, 4.2.2, and 4.2.3), namely, the three-term regression analysis (identified as eqn3 in Figure 4.4), the two-term, linear in Natural Logarithm Transformation (eqn2 in Figure 4.4) and the two-term, linear in common logarithm transformation (eqn1 in Figure 4.4) will have their results compared and evaluated.

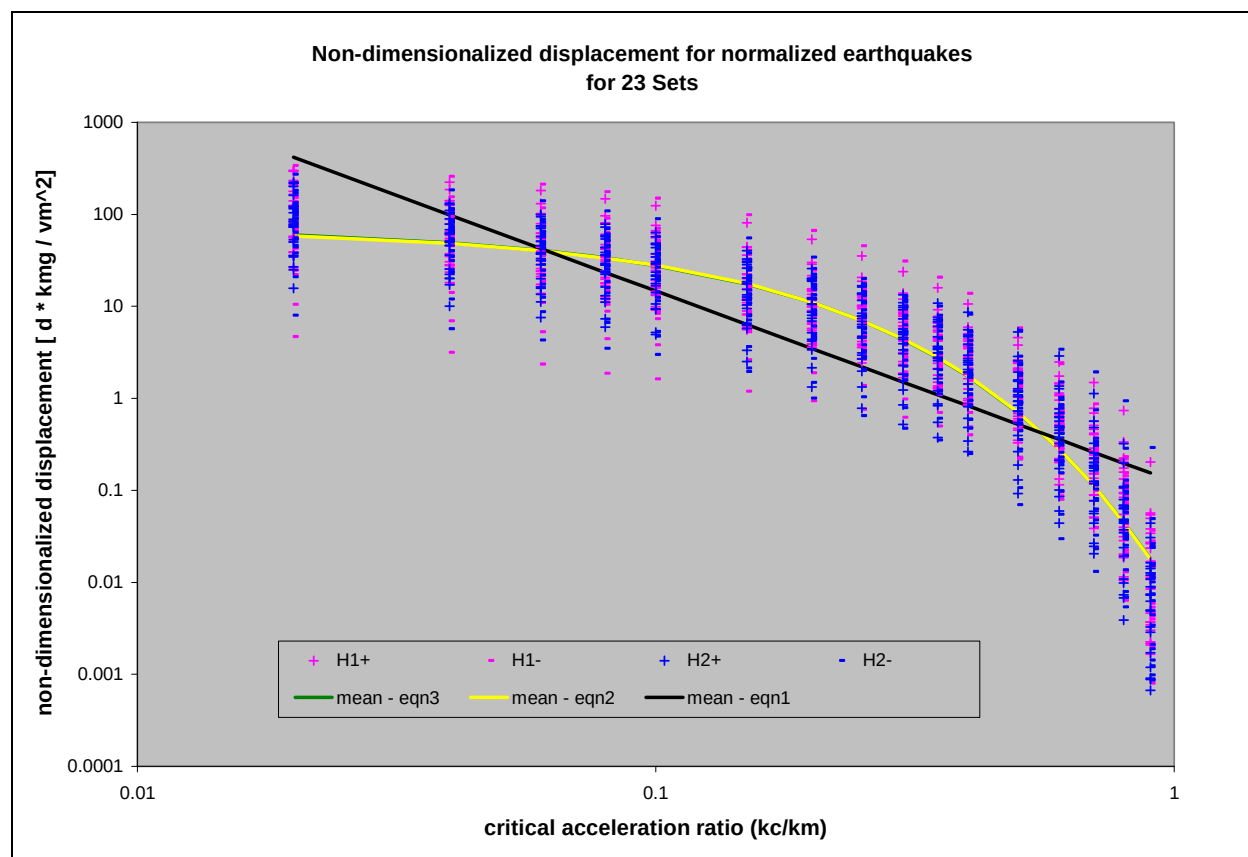


Figure 4.4. Non-dimensionalized displacements and comparisons of the means of the three regression analysis equations for Magnitude 7 earthquakes.

One method of comparison will be the *Std. error* term determined from the error in the estimates. The *Std. error* for eqn3 is 0.93, for eqn2, 0.93 and for eqn1, equal to 1.43 when transformed to a natural logarithm from a common logarithm standard error value of 0.62. These results show that eqn3 and eqn2 have a more accurate estimate as compared to eqn1, and that eqn3 and eqn2 have practically equal values.

Another comparison is the mean relationships as illustrated in Figure 4.4. As can be seen, eqn2 and eqn3 follow the shape of the data and are positioned at the center of the data points while eqn1 does not. Note also that the mean curves of eqn2 and eqn3 are almost superimposing each other, which show the similarity of the results.

Lastly, given the small value of the exponent for the  $(k_c/k_m)$  term of eqn3 (-0.018), this explains the comparable results of eqn2 and eqn3.

### 4.3 Regression results of earthquakes covering the Moment Magnitude ( $M_w$ ) range of 6.1 – 6.8 (Magnitude 6)

This subsequent section will discuss the results from regression analyses of the non-dimensionalized displacement relationships described by Equations 3.20, 3.39, and 3.58 previously derived in chapter three. The values for the coefficients summarized by the above mentioned equations and the standard error terms, as well as the probabilistic measures of Equation Forms One, Two and Three, as documented in Table 4.7, will be discussed in Sections 4.2.1, 4.2.2, and 4.2.3. These regression analyses were performed for baseline corrected acceleration time histories recorded on rock with a  $M_w$  range of 6.1 to 6.8 and an average  $M_w$  of 6.5.

Table 4.7. Values for the regression equations constants for Moment Magnitude ( $M_w$ ) range of 6.1 – 6.8 (Magnitude 6).

| Coefficients and <i>Std. Error</i> | Equation Form One | Equation Form Two | Equation Form Three |
|------------------------------------|-------------------|-------------------|---------------------|
| $\beta_1$                          |                   | 78.618            | 71.851              |
| $\beta_2$                          |                   | -9.121            | -9.003              |
| $\beta_3$                          |                   |                   | -0.032              |
| $\beta_4$                          | -0.146            |                   |                     |
| $\beta_5$                          | -2.060            |                   |                     |
| <i>Std. Error</i>                  | 1.328             | 0.792             | 0.792               |

#### 4.3.1 Three-term regression results

The standard error term (*Std. error*) for this regression analysis was determined to be 0.79 for both the non-dimensionalized displacement as well as the standardized displacement for earthquakes of Magnitude 6. This non-dimensionalized three-term displacement equation is identified as Equation Form Three with the coefficients and *Std. error* terms summarized in column four of Table 4.7.

##### 4.3.1.1 Mean relationships

The regression analysis of the 38 sets of Magnitude 6 rock acceleration time histories resulted in the mean non-dimensionalized displacement relationship of

$$\frac{d_m \bullet k_m g}{v_m^2} = 71.9 \bullet \exp \left( -9.00 \bullet \frac{k_c}{k_m} \right) \bullet \left( \frac{k_c}{k_m} \right)^{-0.032} \quad (4.29)$$

where:

- $d_m$  = permanent displacement
- $k_m g$  = peak (positive) rock acceleration expressed in units of length per sec<sup>2</sup>, consistent with units of  $d_m$  (length) and  $v_m$  (length per sec)
- $v_m$  = peak (positive) ground velocity of the earthquake
- $k_c$  = critical acceleration expressed as a fraction of  $g$
- $k_m$  = peak (positive) rock acceleration expressed as a fraction of  $g$ .

This mean relationship is shown in yellow in Figure 4.5.

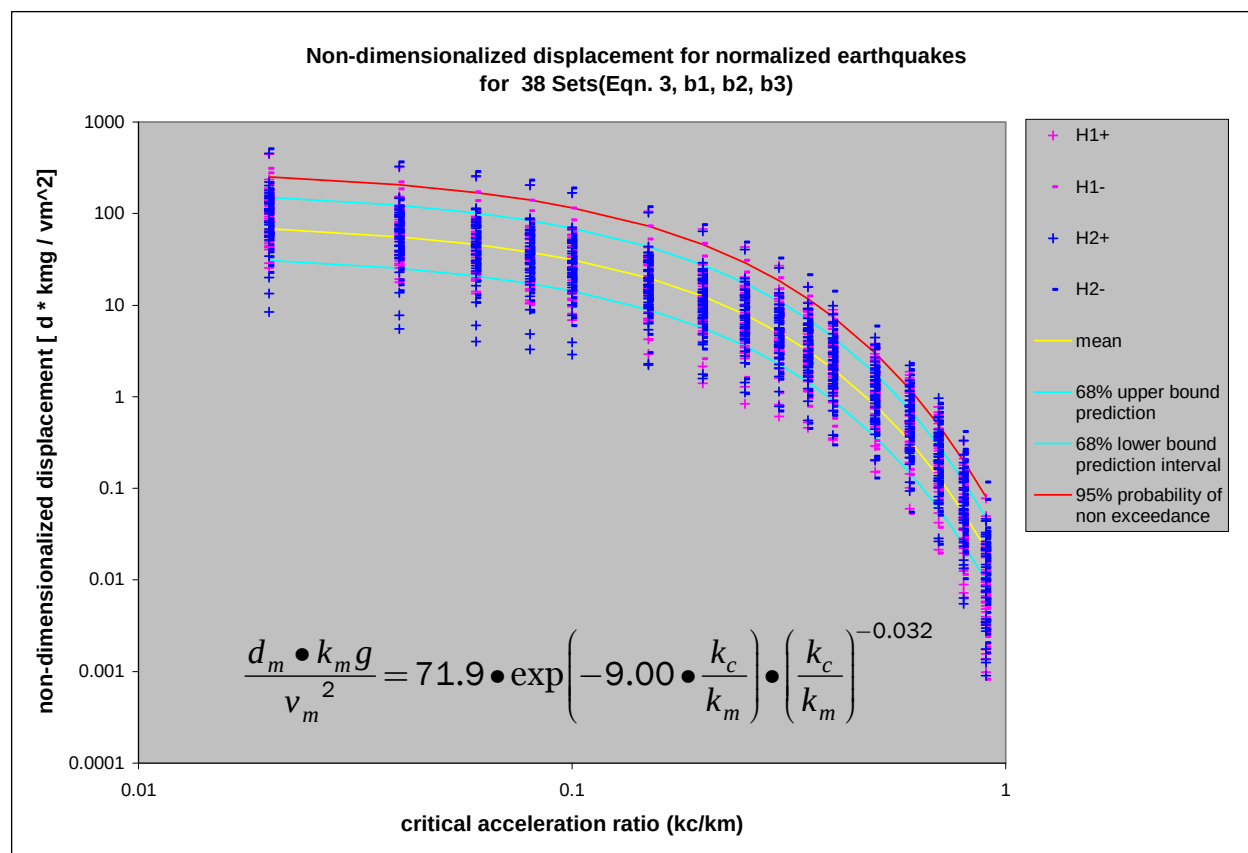


Figure 4.5. Non-dimensionalized displacements with the mean, 68 percent prediction intervals and 95 percent probability of non-exceedance curves.

By a second independent regression analysis, the mean standardized maximum displacement ( $d_s$ ) in units of inches was derived for the standardized velocity,  $v_s = 29.92$  in./sec (0.76 m/sec) and the standardized acceleration  $k_s = 0.5$  g (193.04 in./sec<sup>2</sup> : 4.90 m/sec<sup>2</sup>)

$$d_s = 333.22 \bullet \exp \left( -9.00 \bullet \frac{k_c}{k_m} \right) \bullet \left( \frac{k_c}{k_m} \right)^{-0.032} \quad (4.30)$$

The standardized maximum displacement ( $d_s$ ) can be converted to the permanent displacement ( $d_m$ ) by the following transformation,

$$d_m = d_s \bullet \left[ \left( \frac{k_s}{v_s^2} \right) \bullet \left( \frac{v_m^2}{k_m} \right) \right] \quad (\text{bis. 4.3})$$

where:

$k_s$  = standardized acceleration expressed as a fraction of  $g$  (0.5)

$v_s$  = standardized velocity (29.92 in./sec).

The mean permanent displacement is derived by introducing Equation 4.30 into Equation 4.3.

$$d_m = 333.22 \bullet \exp \left( -9.00 \bullet \frac{k_c}{k_m} \right) \bullet \left( \frac{k_c}{k_m} \right)^{-0.032} \bullet \left[ 0.216 \bullet \left( \frac{v_m^2}{k_m \bullet g} \right) \right] \quad (4.31)$$

where the right-hand-side term  $k_m g$  is the peak (positive) rock acceleration expressed in units of length per sec<sup>2</sup>.

Note that Equation 4.31 is the same as Equation 4.29, indicating consistent results from both regression analyses.

#### 4.3.1.2 Ninety-five percent probability of non-exceedance

The regression analysis of the 38 sets of Magnitude 6 rock acceleration time histories resulted in the non-dimensionalized displacement for 95 percent probability of non-exceedance of

$$\frac{d_m \bullet k_m g}{v_m^2} = 71.9 \bullet \exp\left(-9.00 \bullet \frac{k_c}{k_m}\right) \bullet \left(\frac{k_c}{k_m}\right)^{-0.032} \bullet 3.68 \quad (4.32)$$

The 95 percent probability of non-exceedance is shown in red in Figure 4.5.

By the second, independent regression analysis, the standardized maximum displacement ( $d_s$ ) in units of inches, derived using  $v_s = 29.92$  in./sec and  $k_s = 0.5$  g, is

$$d_s = 333.2 \bullet \exp\left(-9.00 \bullet \frac{k_c}{k_m}\right) \bullet \left(\frac{k_c}{k_m}\right)^{-0.032} \bullet 3.68 \quad (4.33)$$

Introducing Equation 4.3, the corresponding permanent displacement is

$$d_m = 333.2 \bullet \exp\left(-9.00 \bullet \frac{k_c}{k_m}\right) \bullet \left(\frac{k_c}{k_m}\right)^{-0.032} \bullet 3.68 \bullet \left[0.216 \bullet \left(\frac{v_m^2}{k_m \bullet g}\right)\right] \quad (4.34)$$

where the right-hand-side term  $k_m g$  is the peak (positive) rock acceleration expressed in units of length per sec<sup>2</sup>.

Note that Equation 4.34 is the same as Equation 4.32, indicating consistent results from both regression analyses,

#### 4.3.1.3 Sixty-eight percent prediction intervals

The regression analysis of the 38 sets of Magnitude 6 rock acceleration time histories resulted in the non-dimensionalized displacement relationships for the 68 percent prediction intervals of

$$\frac{d_m \bullet k_m g}{v_m^2} = 71.9 \bullet \exp\left(-9.00 \bullet \frac{k_c}{k_m}\right) \bullet \left(\frac{k_c}{k_m}\right)^{-0.032} \bullet 2.20 \quad (4.35a)$$

$$\frac{d_m \bullet k_m g}{v_m^2} = 71.9 \bullet \exp\left(-9.00 \bullet \frac{k_c}{k_m}\right) \bullet \left(\frac{k_c}{k_m}\right)^{-0.032} \bullet 0.45 \quad (4.35b)$$

The 68 percent prediction intervals are shown in blue in Figure 4.5.

By the second independent regression analysis, the standardized maximum displacements ( $d_s$ ) in units of inches, derived using  $v_s = 29.92$  in./sec and  $k_s = 0.5$  g, are

$$d_s = 333.2 \bullet \exp\left(-9.00 \bullet \frac{k_c}{k_m}\right) \bullet \left(\frac{k_c}{k_m}\right)^{-0.032} \bullet 2.20 \quad (4.36a)$$

$$d_s = 333.2 \bullet \exp\left(-9.00 \bullet \frac{k_c}{k_m}\right) \bullet \left(\frac{k_c}{k_m}\right)^{-0.032} \bullet 0.454 \quad (4.36b)$$

Introducing Equation 4.3, the corresponding permanent displacements are

$$d_m = 333.2 \bullet \exp\left(-9.00 \bullet \frac{k_c}{k_m}\right) \bullet \left(\frac{k_c}{k_m}\right)^{-0.032} \bullet 2.20 \bullet \left[0.216 \bullet \left(\frac{v_m^2}{k_m \bullet g}\right)\right] \quad (4.37a)$$

$$d_m = 333.2 \bullet \exp\left(-9.00 \bullet \frac{k_c}{k_m}\right) \bullet \left(\frac{k_c}{k_m}\right)^{-0.032} \bullet 0.454 \bullet \left[0.216 \bullet \left(\frac{v_m^2}{k_m \bullet g}\right)\right] \quad (4.37b)$$

where the right-hand-side term  $k_m g$  is the peak (positive) rock acceleration expressed in units of length per sec<sup>2</sup>.

Note that Equations 4.37a and 4.37b are the same as Equations 4.35a and 4.35b, indicating consistent results from both regression analyses.

#### 4.3.2 Two-term regression results, linear in natural logarithm transformation

The standard error term (*Std. error*) for this regression analysis was determined to be 0.79 for both the non-dimensionalized displacement as well as the standardized displacement for earthquakes of Magnitude 6. This non-dimensionalized two-term displacement equation is identified as Equation Form Two with the coefficients and *Std. error* terms summarized in column three of Table 4.7.

#### 4.3.2.1 Mean relationships

The regression analysis of the 38 sets of Magnitude 6 rock acceleration time histories resulted in the mean non-dimensionalized displacement relationship of

$$\frac{d_m \bullet k_m g}{v_m^2} = 78.6 \bullet \exp \left( -9.12 \bullet \frac{k_c}{k_m} \right) \quad (4.38)$$

where:

$d_m$  = permanent displacement

$k_m g$  = peak (positive) rock acceleration expressed in units of length per sec<sup>2</sup>, consistent with units of  $d_m$  (length) and  $v_m$  (length per sec)

$v_m$  = peak (positive) ground velocity of the earthquake

$k_c$  = critical acceleration expressed as a fraction of  $g$

$k_m$  = peak (positive) rock acceleration expressed as a fraction of  $g$ .

This mean relationship is shown in yellow in Figure 4.6.

By a second independent regression analysis, the mean standardized maximum displacement ( $d_s$ ) in units of inches was derived for the standardized velocity,  $v_s = 29.92$  in./sec (0.76 m/sec) and the standardized acceleration  $k_s = 0.5 g$  (193.04 in./sec<sup>2</sup> : 4.90 m/sec<sup>2</sup>)

$$d_s = 364.6 \bullet \exp \left( -9.12 \bullet \frac{k_c}{k_m} \right) \quad (4.39)$$

The standardized maximum displacement ( $d_s$ ) can be converted to the permanent displacement ( $d_m$ ) by the following transformation,

$$d_m = d_s \bullet \left[ \left( \frac{k_s}{v_s^2} \right) \bullet \left( \frac{v_m^2}{k_m} \right) \right] \quad (\text{bis 4.3})$$

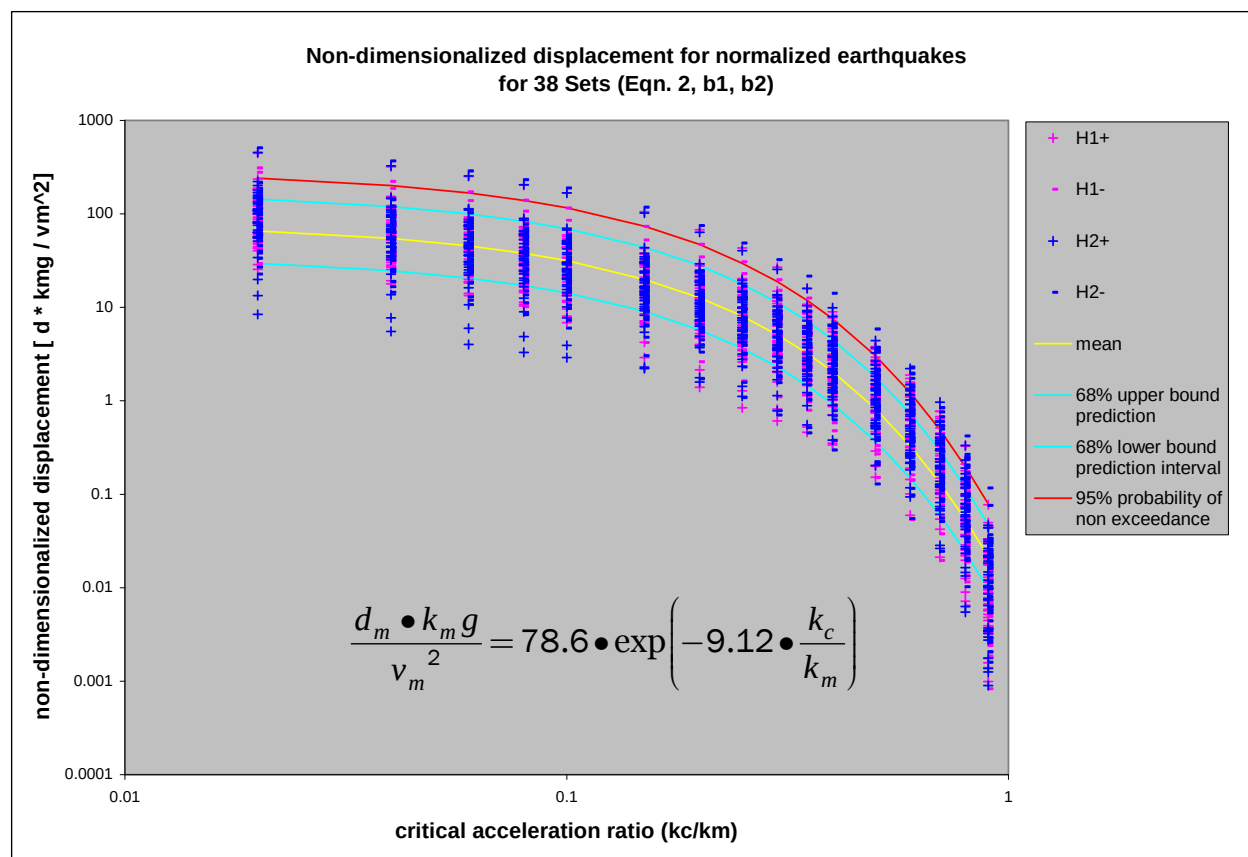


Figure 4.6. Non-dimensionalized displacements with the mean, 68 percent prediction intervals and 95 percent probability of non-exceedance curves.

where:

$k_s$  = standardized acceleration expressed as a fraction of  $g$  (0.5)

$v_s$  = standardized velocity (29.92 in./sec).

The mean permanent displacement is derived by introducing Equation 4.39 into Equation 4.3.

$$d_m = 364.6 \bullet \exp\left(-9.12 \bullet \frac{k_c}{k_m}\right) \bullet \left[0.216 \bullet \left(\frac{v_m^2}{k_m \bullet g}\right)\right] \quad (4.40)$$

where the right-hand-side term  $k_m g$  is the peak (positive) rock acceleration expressed in units of length per sec<sup>2</sup>.

Note that Equation 4.40 is the same as Equation 4.38, indicating consistent results from both regression analyses.

#### 4.3.2.2 Ninety-five percent probability of non-exceedance

The regression analysis of the 38 sets of Magnitude 6 rock acceleration time histories resulted in the non-dimensionalized displacement for 95 percent probability of non-exceedance of

$$\frac{d_m \bullet k_m g}{v_m^2} = 78.6 \bullet \exp\left(-9.12 \bullet \frac{k_c}{k_m}\right) \bullet 3.68 \quad (4.41)$$

The 95 percent probability of non-exceedance is shown in red in Figure 4.6.

By the second, independent regression analysis, the standardized maximum displacement ( $d_s$ ) in units of inches, derived using  $v_s = 29.92$  in./sec and  $k_s = 0.5 g$ , is

$$d_s = 364.6 \bullet \exp\left(-9.12 \bullet \frac{k_c}{k_m}\right) \bullet 3.68 \quad (4.42)$$

Introducing Equation 4.3, the corresponding permanent displacement is

$$d_m = 364.6 \bullet \exp\left(-9.12 \bullet \frac{k_c}{k_m}\right) \bullet 3.68 \bullet \left[0.216 \bullet \left(\frac{v_m^2}{k_m \bullet g}\right)\right] \quad (4.43)$$

where the right-hand-side term  $k_m g$  is the peak (positive) rock acceleration expressed in units of length per sec<sup>2</sup>.

Note that Equation 4.43 is the same as Equation 4.41, indicating consistent results from both regression analyses.

#### 4.3.2.3 Sixty-eight percent prediction intervals

The regression analysis of the 38 sets of Magnitude 6 rock acceleration time histories resulted in the non-dimensionalized displacement relationships for the 68 percent prediction intervals of

$$\frac{d_m \bullet k_m g}{v_m^2} = 78.6 \bullet \exp\left(-9.12 \bullet \frac{k_c}{k_m}\right) \bullet 2.20 \quad (4.44a)$$

$$\frac{d_m \bullet k_m g}{v_m^2} = 78.6 \bullet \exp\left(-9.12 \bullet \frac{k_c}{k_m}\right) \bullet 0.454 \quad (4.44b)$$

The 68 percent prediction intervals are shown in blue in Figure 4.6.

By the second independent regression analysis, the standardized maximum displacements ( $d_s$ ) in units of inches, derived using  $v_s = 29.92$  in./sec and  $k_s = 0.5$  g, are

$$d_s = 364.6 \bullet \exp\left(-9.12 \bullet \frac{k_c}{k_m}\right) 2.20 \quad (4.45a)$$

$$d_s = 325.3 \bullet \exp\left(-9.2 \bullet \frac{k_c}{k_m}\right) \bullet 0.454 \quad (4.45b)$$

Introducing Equation 4.3, the corresponding permanent displacements are

$$d_m = 364.6 \bullet \exp\left(-9.12 \bullet \frac{k_c}{k_m}\right) \bullet 2.20 \bullet \left[0.216 \bullet \left(\frac{v_m^2}{k_m \bullet g}\right)\right] \quad (4.46a)$$

$$d_m = 364.6 \bullet \exp\left(-9.12 \bullet \frac{k_c}{k_m}\right) \bullet 0.454 \bullet \left[0.216 \bullet \left(\frac{v_m^2}{k_m \bullet g}\right)\right] \quad (4.46b)$$

where the right-hand-side term  $k_m g$  is the peak (positive) rock acceleration expressed in units of length per sec<sup>2</sup>.

Note that Equations 4.46a and 4.46b are the same as Equations 4.44a and 4.44b, indicating consistent results from both regression analyses.

#### 4.3.3 Two-term regression results, linear in common logarithm transformation

The standard error term (*Std. error*) for this regression analysis was determined to be 1.33 for both the non-dimensionalized displacement as well as the standardized displacement for earthquakes of Magnitude 6. This non-dimensionalized two-term displacement equation is identified as Equation Form One with the coefficients and *Std. error* terms summarized in column two of Table 4.7.

#### 4.3.3.1 Mean relationships

The regression analysis of the 38 sets of Magnitude 6 rock acceleration time histories resulted in the mean non-dimensionalized displacement relationship of

$$\frac{d_m \bullet k_m g}{v_m^2} = 0.146 \bullet \left( \frac{k_c}{k_m} \right)^{-2.06} \quad (4.47)$$

where:

- $d_m$  = permanent displacement
- $k_m g$  = peak (positive) rock acceleration expressed in units of length per sec<sup>2</sup>, consistent with units of  $d_m$ (length) and  $v_m$ (length per sec)
- $v_m$  = peak (positive) ground velocity of the earthquake
- $k_c$  = critical acceleration expressed as a fraction of  $g$
- $k_m$  = peak (positive) rock acceleration expressed as a fraction of  $g$ .

This mean relationship is shown in yellow in Figure 4.7.

By a second independent regression analysis, the mean standardized maximum displacement ( $d_s$ ) in units of inches was derived for the standardized velocity,  $v_s = 29.92$  in./sec (0.76 m/sec) and the standardized acceleration  $k_s = 0.5 g$  (193.04 in./sec<sup>2</sup> : 4.90 m/sec<sup>2</sup>)

$$d_s = 0.676 \bullet \left( \frac{k_c}{k_m} \right)^{-2.06} \quad (4.48)$$

The standardized maximum displacement ( $d_s$ ) can be converted to the permanent displacement ( $d_m$ ) by the following transformation,

$$d_m = d_s \bullet \left[ \left( \frac{k_s}{v_s^2} \right) \bullet \left( \frac{v_m^2}{k_m} \right) \right] \quad (\text{bis 4.3})$$

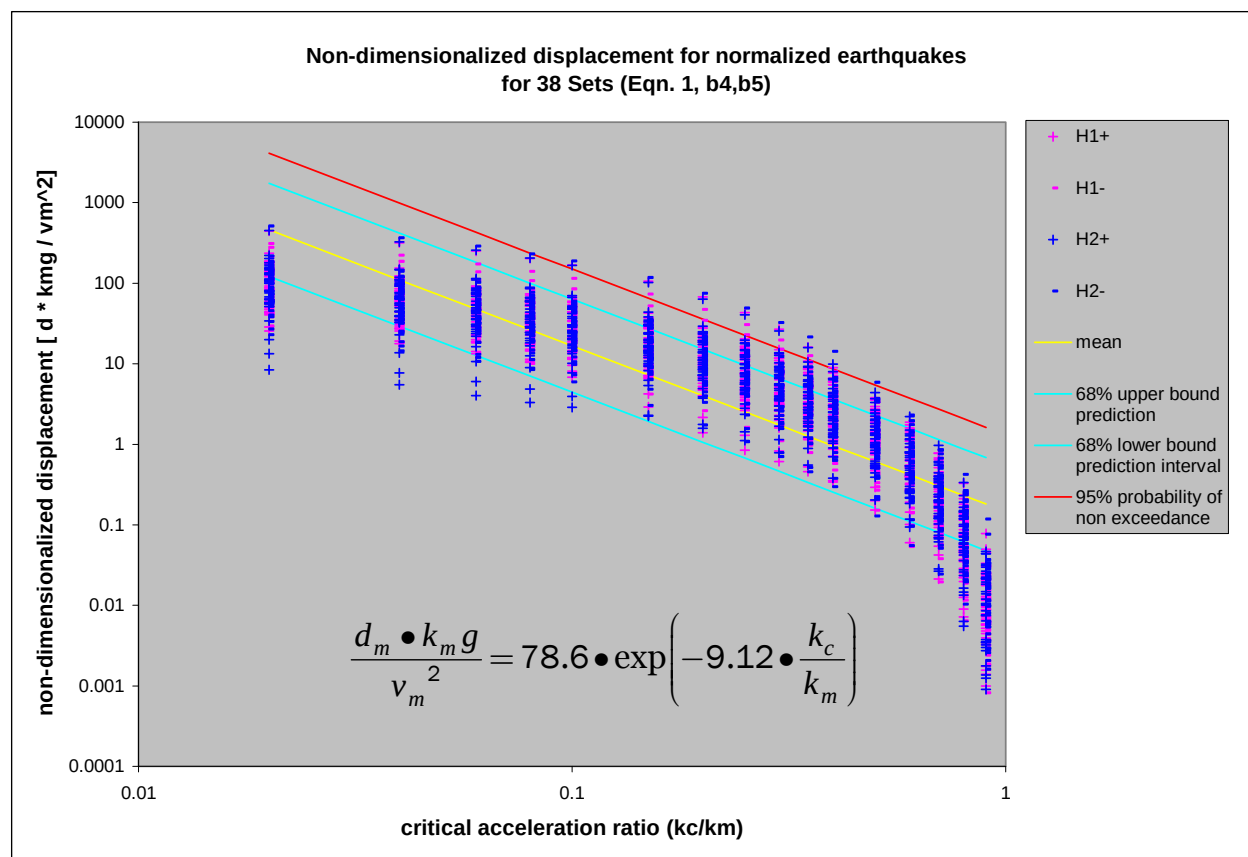


Figure 4.7. Non-dimensionalized displacements with the mean, 68 percent prediction intervals and 95 percent probability of non-exceedance curves.

where:

$k_s$  = standardized acceleration expressed as a fraction of  $g$  (0.5)

$v_s$  = standardized velocity (29.92 in./sec).

The mean permanent displacement is derived by introducing Equation 4.48 into Equation 4.3.

$$d_m = 0.676 \bullet \left(\frac{k_c}{k_m}\right)^{-2.06} \bullet \left[0.216 \bullet \left(\frac{v_m^2}{k_m \bullet g}\right)\right] \quad (4.49)$$

where the right-hand-side term  $k_m g$  is the peak (positive) rock acceleration expressed in units of length per sec<sup>2</sup>.

Note that Equation 4.49 is the same as Equation 4.47, indicating consistent results from both regression analyses.

#### 4.3.3.2 Ninety-five percent probability of non-exceedance

The regression analysis of the 38 sets of Magnitude 6 rock acceleration time histories resulted in the non-dimensionalized displacement for 95 percent probability of non-exceedance of

$$\frac{d_m \bullet k_m g}{v_m^2} = 0.146 \bullet \left( \frac{k_c}{k_m} \right)^{-2.06} \bullet 2.60 \quad (4.50)$$

The 95 percent probability of non-exceedance is shown in red in Figure 4.7.

By the second, independent regression analysis, the standardized maximum displacement ( $d_s$ ) in units of inches, derived using  $v_s = 29.92$  in./sec and  $k_s = 0.5$  g, is

$$d_s = 0.676 \bullet \left( \frac{k_c}{k_m} \right)^{-2.06} \bullet 2.60 \quad (4.51)$$

Introducing Equation 4.3, the corresponding permanent displacement is

$$d_m = 0.676 \bullet \left( \frac{k_c}{k_m} \right)^{-2.06} \bullet 2.60 \bullet \left[ 0.216 \bullet \left( \frac{v_m^2}{k_m \bullet g} \right) \right] \quad (4.52)$$

where the right-hand-side term  $k_m g$  is the peak (positive) rock acceleration expressed in units of length per sec<sup>2</sup>.

Note that Equation 4.52 is the same as Equation 4.50, indicating consistent results from both regression analyses.

#### 4.3.3.3 Sixty-eight percent prediction intervals

The regression analysis of the 38 sets of Magnitude 6 rock acceleration time histories resulted in the non-dimensionalized displacement relationships for the 68 percent prediction intervals of

$$\frac{d_m \bullet k_m g}{v_m^2} = 0.146 \bullet \left( \frac{k_c}{k_m} \right)^{-2.06} \bullet 1.79 \quad (4.53a)$$

$$\frac{d_m \bullet k_m g}{v_m^2} = 0.146 \bullet \left( \frac{k_c}{k_m} \right)^{-2.06} \bullet 0.560 \quad (4.53b)$$

The 68 percent prediction intervals are shown in blue in Figure 4.7.

By the second independent regression analysis, the standardized maximum displacements ( $d_s$ ) in units of inches, derived using  $v_s = 29.92$  in./sec and  $k_s = 0.5$  g, are

$$d_s = 0.676 \bullet \left( \frac{k_c}{k_m} \right)^{-2.06} \bullet 1.79 \quad (4.54a)$$

$$d_s = 0.676 \bullet \left( \frac{k_c}{k_m} \right)^{-2.06} \bullet 0.560 \quad (4.54b)$$

Introducing Equation 4.3, the corresponding permanent displacements are,

$$d_m = 0.676 \bullet \left( \frac{k_c}{k_m} \right)^{-2.06} \bullet 1.79 \bullet \left[ 0.216 \bullet \left( \frac{v_m^2}{k_m \bullet g} \right) \right] \quad (4.55a)$$

$$d_m = 0.676 \bullet \left( \frac{k_c}{k_m} \right)^{-2.06} \bullet 0.560 \bullet \left[ 0.216 \bullet \left( \frac{v_m^2}{k_m \bullet g} \right) \right] \quad (4.55b)$$

where the right-hand-side term  $k_m g$  is the peak (positive) rock acceleration expressed in units of length per sec<sup>2</sup>.

Note that Equations 4.55a and 4.55b are the same as Equations 4.53a and 4.53b, indicating consistent results from both regression analyses.

#### **4.3.4 Comparison of regression results of all three forms of the simplified non-dimensionalized displacement relationships**

The three forms of regression analysis (discussed in Sections 4.3.1, 4.3.2, and 4.3.3), namely, the three-term regression analysis (eqn3 in Figure 4.8), the two-term, linear in Natural Logarithm Transformation (eqn2 in Figure 4.8) and the two-term, linear in common logarithm transformation (eqn1 in Figure 4.8) will have their results compared and evaluated.

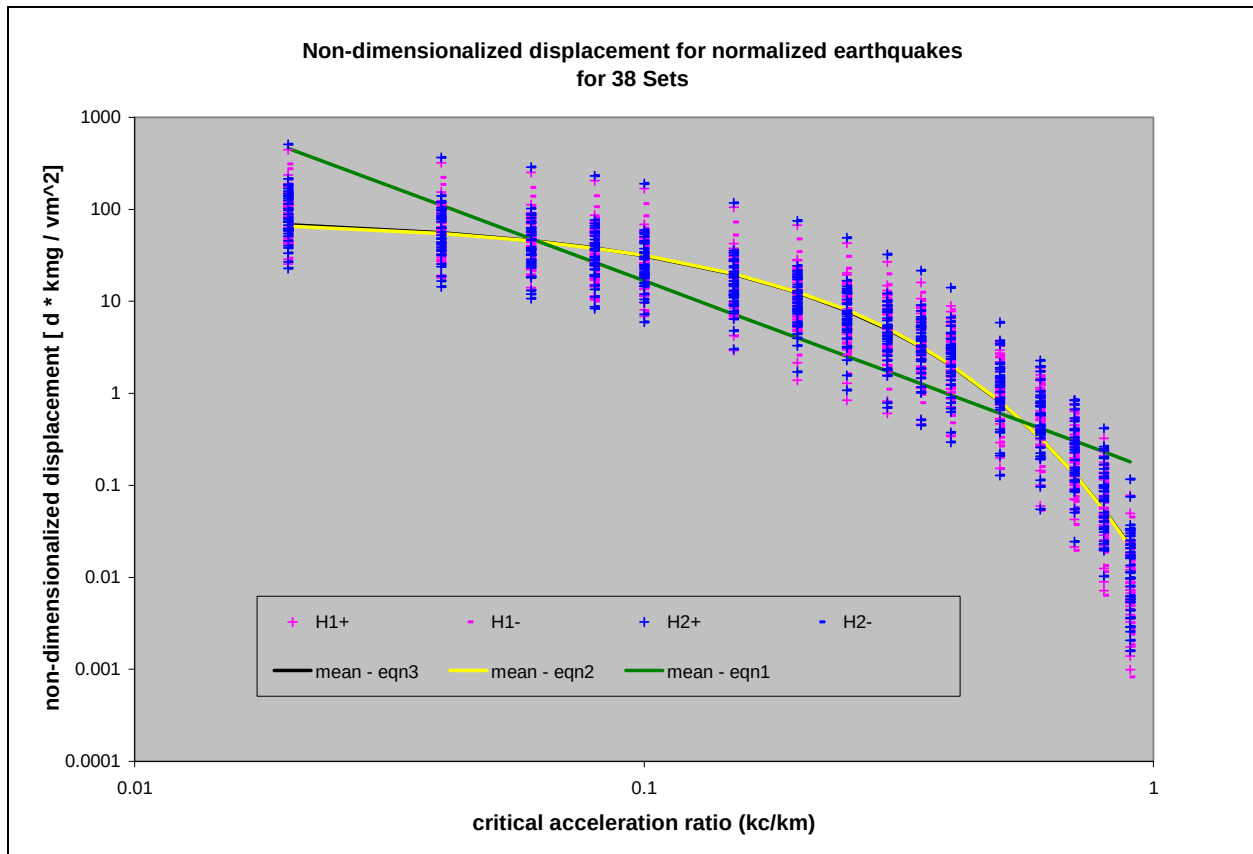


Figure 4.8. Non-dimensionalized displacements and comparisons of the means of the three regression analysis equations for Magnitude 6 earthquakes.

One method of comparison will be the *Std. error* term determined from the error in the estimates. The *Std. error* for eqn3 is 0.79, for eqn2, 0.79 and for eqn1, equal to 1.34 when transformed to a natural logarithm from a common logarithm standard error value of 0.58. These results show that eqn3 and eqn2 have a more accurate estimate as compared to eqn1, and that eqn3 and eqn2 have practically equal values.

Another comparison is the mean relationships as illustrated in Figure 4.8. As can be seen, eqn2 and eqn3 follow the shape of the data and are positioned at the center of the data points while eqn1 does not. Note also that the mean curves of eqn2 and eqn3 are almost superimposing each other which show the similarity of the results.

Lastly, given the small value of the exponent for the  $(k_c/k_m)$  term of eqn3 (-0.032), this explains the comparable results of eqn2 and eqn3.

## 4.4 Regression results of earthquakes covering the Moment Magnitude ( $M_w$ ) range from 4.9 – 6.1 (Magnitude 5)

This subsequent section will discuss the results from regression analyses of the non-dimensionalized displacement relationships described by Equations 3.20, 3.39, and 3.58 previously derived in chapter three. The values for the coefficients summarized by the above mentioned equations and the standard error terms as well as the probabilistic measures of Equation Forms One, Two and Three, as documented in Table 4.8, will be discussed in Sections 4.4.1, 4.4.2, and 4.4.3. These regression analyses were performed for baseline corrected acceleration time histories recorded on rock with  $M_w$  range of 4.9 to 6.1 and an average  $M_w$  of 5.6.

Table 4.8. Values for the regression equations constants for Moment Magnitude ( $M_w$ ) range of 4.9 – 6.1 (Magnitude 5).

| Coefficients and <i>Std. Error</i> | Equation Form One | Equation Form Two | Equation Form Three |
|------------------------------------|-------------------|-------------------|---------------------|
| $\beta_1$                          |                   | 56.980            | 51.077              |
| $\beta_2$                          |                   | -8.579            | -8.436              |
| $\beta_3$                          |                   |                   | -0.039              |
| $\beta_4$                          | -0.153            |                   |                     |
| $\beta_5$                          | -1.940            |                   |                     |
| <i>Std. Error</i>                  | 1.242             | 0.738             | 0.738               |

### 4.4.1 Three-term regression results

The standard error term (*Std. error*) for this regression analysis was determined to be 0.74 for both the non-dimensionalized displacement as well as the standardized displacement for earthquakes of Magnitude 5. This non-dimensionalized three-term displacement equation is identified as Equation Form Three with the coefficients and *Std. error* terms summarized in column four of Table 4.8.

#### 4.4.1.1 Mean relationships

The regression analysis of the 23 sets of Magnitude 5 rock acceleration time histories resulted in the mean non-dimensionalized displacement relationship of

$$\frac{d_m \bullet k_m g}{v_m^2} = 51.1 \bullet \exp \left( -8.44 \bullet \frac{k_c}{k_m} \right) \bullet \left( \frac{k_c}{k_m} \right)^{-0.039} \quad (4.56)$$

where:

- $d_m$  = permanent displacement
- $k_m g$  = peak (positive) rock acceleration expressed in units of length per sec<sup>2</sup>, consistent with units of  $d_m$  (length) and  $v_m$  (length per sec)
- $v_m$  = peak (positive) ground velocity of the earthquake
- $k_c$  = critical acceleration expressed as a fraction of  $g$
- $k_m$  = peak (positive) rock acceleration expressed as a fraction of  $g$ .

This mean relationship is shown in yellow in Figure 4.9.

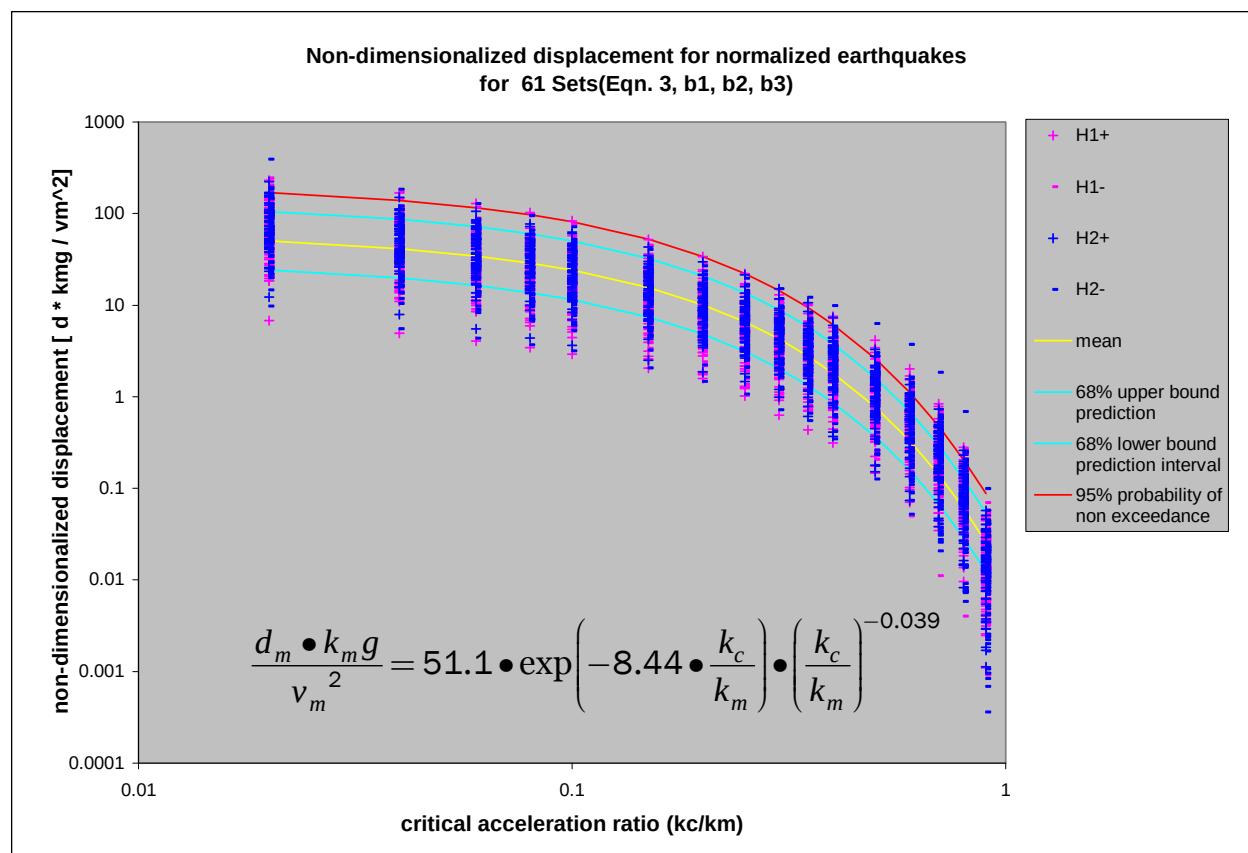


Figure 4.9. Non-dimensionalized displacements with the mean, 68 percent prediction intervals and 95 percent probability of non-exceedance curves.

By a second independent regression analysis, the mean standardized maximum displacement ( $d_s$ ) in units of inches was derived for the standardized velocity,  $v_s = 29.92$  in./sec (0.76 m/sec) and the standardized acceleration  $k_s = 0.5$  g (193.04 in./sec<sup>2</sup> : 4.90 m/sec<sup>2</sup>)

$$d_s = 236.9 \bullet \exp \left( -8.44 \bullet \frac{k_c}{k_m} \right) \bullet \left( \frac{k_c}{k_m} \right)^{-0.039} \quad (4.57)$$

The standardized maximum displacement ( $d_s$ ) can be converted to the permanent displacement ( $d_m$ ) by the following transformation,

$$d_m = d_s \bullet \left[ \left( \frac{k_s}{v_s^2} \right) \bullet \left( \frac{v_m^2}{k_m} \right) \right] \quad (\text{bis 4.3})$$

where:

$k_s$  = standardized acceleration expressed as a fraction of  $g$  (0.5)

$v_s$  = standardized velocity (29.92 in./sec).

The mean permanent displacement is derived by introducing Equation 4.57 into Equation 4.3.

$$d_m = 236.9 \bullet \exp \left( -8.44 \bullet \frac{k_c}{k_m} \right) \bullet \left( \frac{k_c}{k_m} \right)^{-0.039} \bullet \left[ 0.216 \bullet \left( \frac{v_m^2}{k_m \bullet g} \right) \right] \quad (4.58)$$

where the right-hand-side term  $k_m g$  is the peak (positive) rock acceleration expressed in units of length per sec<sup>2</sup>.

Note that Equation 4.58 is the same as Equation 4.56, indicating consistent results from both regression analyses.

#### 4.4.1.2 Ninety-five percent probability of non-exceedance

The regression analysis of the 61 sets of Magnitude 5 rock acceleration time histories resulted in the non-dimensionalized displacement for 95 percent probability of non-exceedance of

$$\frac{d_m \bullet k_m g}{v_m^2} = 51.1 \bullet \exp\left(-8.44 \bullet \frac{k_c}{k_m}\right) \bullet \left(\frac{k_c}{k_m}\right)^{-0.039} \bullet 3.39 \quad (4.59)$$

The 95 percent probability of non-exceedance is shown in red in Figure 4.9.

By the second, independent regression analysis, the standardized maximum displacement ( $d_s$ ) in units of inches, derived using  $v_s = 29.92$  in./sec and  $k_s = 0.5$  g, is

$$d_s = 236.9 \bullet \exp\left(-8.44 \bullet \frac{k_c}{k_m}\right) \bullet \left(\frac{k_c}{k_m}\right)^{-0.039} \bullet 3.39 \quad (4.60)$$

Introducing Equation 4.3, the corresponding permanent displacement is

$$d_m = 236.9 \bullet \exp\left(-8.44 \bullet \frac{k_c}{k_m}\right) \bullet \left(\frac{k_c}{k_m}\right)^{-0.039} \bullet 3.39 \bullet \left[0.216 \bullet \left(\frac{v_m^2}{k_m \bullet g}\right)\right] \quad (4.61)$$

where the right-hand-side term  $k_m g$  is the peak (positive) rock acceleration expressed in units of length per sec<sup>2</sup>.

Note that Equation 4.61 is the same as Equation 4.59, indicating consistent results from both regression analyses.

#### 4.4.1.3 Sixty-eight percent prediction intervals

The regression analysis of the 61 sets of Magnitude 5 rock acceleration time histories resulted in the non-dimensionalized displacement relationships for the 68 percent prediction intervals of

$$\frac{d_m \bullet k_m g}{v_m^2} = 51.1 \bullet \exp\left(-8.44 \bullet \frac{k_c}{k_m}\right) \bullet \left(\frac{k_c}{k_m}\right)^{-0.039} \bullet 2.10 \quad (4.62a)$$

$$\frac{d_m \bullet k_m g}{v_m^2} = 51.1 \bullet \exp\left(-8.44 \bullet \frac{k_c}{k_m}\right) \bullet \left(\frac{k_c}{k_m}\right)^{-0.039} \bullet 0.477 \quad (4.62b)$$

The 68 percent prediction intervals are shown in blue in Figure 4.9.

By the second independent regression analysis, the standardized maximum displacements ( $d_s$ ) in units of inches, derived using  $v_s = 29.92$  in./sec and  $k_s = 0.5 g$ , are

$$d_s = 236.9 \cdot \exp\left(-8.44 \cdot \frac{k_c}{k_m}\right) \cdot \left(\frac{k_c}{k_m}\right)^{-0.039} \cdot 2.10 \quad (4.63a)$$

$$d_s = 236.9 \cdot \exp\left(-8.44 \cdot \frac{k_c}{k_m}\right) \cdot \left(\frac{k_c}{k_m}\right)^{-0.039} \cdot 0.477 \quad (4.63b)$$

Introducing Equation 4.3, the corresponding permanent displacements are

$$d_m = 236.9 \cdot \exp\left(-8.44 \cdot \frac{k_c}{k_m}\right) \cdot \left(\frac{k_c}{k_m}\right)^{-0.039} \cdot 2.10 \cdot \left[0.216 \cdot \left(\frac{v_m^2}{k_m \cdot g}\right)\right] \quad (4.64a)$$

$$d_m = 236.9 \cdot \exp\left(-8.44 \cdot \frac{k_c}{k_m}\right) \cdot \left(\frac{k_c}{k_m}\right)^{-0.039} \cdot 0.477 \cdot \left[0.216 \cdot \left(\frac{v_m^2}{k_m \cdot g}\right)\right] \quad (4.64b)$$

where the right-hand-side term  $k_m g$  is the peak (positive) rock acceleration expressed in units of length per sec<sup>2</sup>

Note that Equations 4.64a and 4.64b are the same as Equations 4.62a and 4.62b, indicating consistent results from both regression analyses.

#### 4.4.2 Two-term regression results, linear in natural logarithm transformation

The standard error term (*Std. error*) for this regression analysis was determined to be 0.74 for both the non-dimensionalized displacement as well as the standardized displacement for earthquakes of Magnitude 5. This non-dimensionalized two-term displacement equation is identified as Equation Form Two with the coefficients and *Std. error* terms summarized in column three of Table 4.8.

#### 4.4.2.1 Mean relationships

The regression analysis of the 61 sets of Magnitude 5 rock acceleration time histories resulted in the mean non-dimensionalized displacement relationship of

$$\frac{d_m \bullet k_m g}{v_m^2} = 57.0 \bullet \exp \left( -8.58 \bullet \frac{k_c}{k_m} \right) \quad (4.65)$$

where:

- $d_m$  = permanent displacement
- $k_m g$  = peak (positive) rock acceleration expressed in units of length per sec<sup>2</sup>, consistent with units of  $d_m$  (length) and  $v_m$  (length per sec)
- $v_m$  = peak (positive) ground velocity of the earthquake
- $k_c$  = critical acceleration expressed as a fraction of  $g$
- $k_m$  = peak (positive) rock acceleration expressed as a fraction of  $g$ .

This mean relationship is shown in yellow in Figure 4.10.

By a second independent regression analysis, the mean standardized maximum displacement ( $d_s$ ) in units of inches was derived for the standardized velocity,  $v_s = 29.92$  in./sec (0.76 m/sec) and the standardized acceleration  $k_s = 0.5 g$  (193.04 in./sec<sup>2</sup> : 4.90 m/sec<sup>2</sup>)

$$d_s = 264.3 \bullet \exp \left( -8.58 \bullet \frac{k_c}{k_m} \right) \quad (4.66)$$

The standardized maximum displacement ( $d_s$ ) can be converted to the permanent displacement ( $d_m$ ) by the following transformation,

$$d_m = d_s \bullet \left[ \left( \frac{k_s}{v_s^2} \right) \bullet \left( \frac{v_m^2}{k_m} \right) \right] \quad (\text{bis 4.3})$$

where:

- $k_s$  = standardized acceleration expressed as a fraction of  $g$  (0.5)
- $v_s$  = standardized velocity (29.92 in./sec).

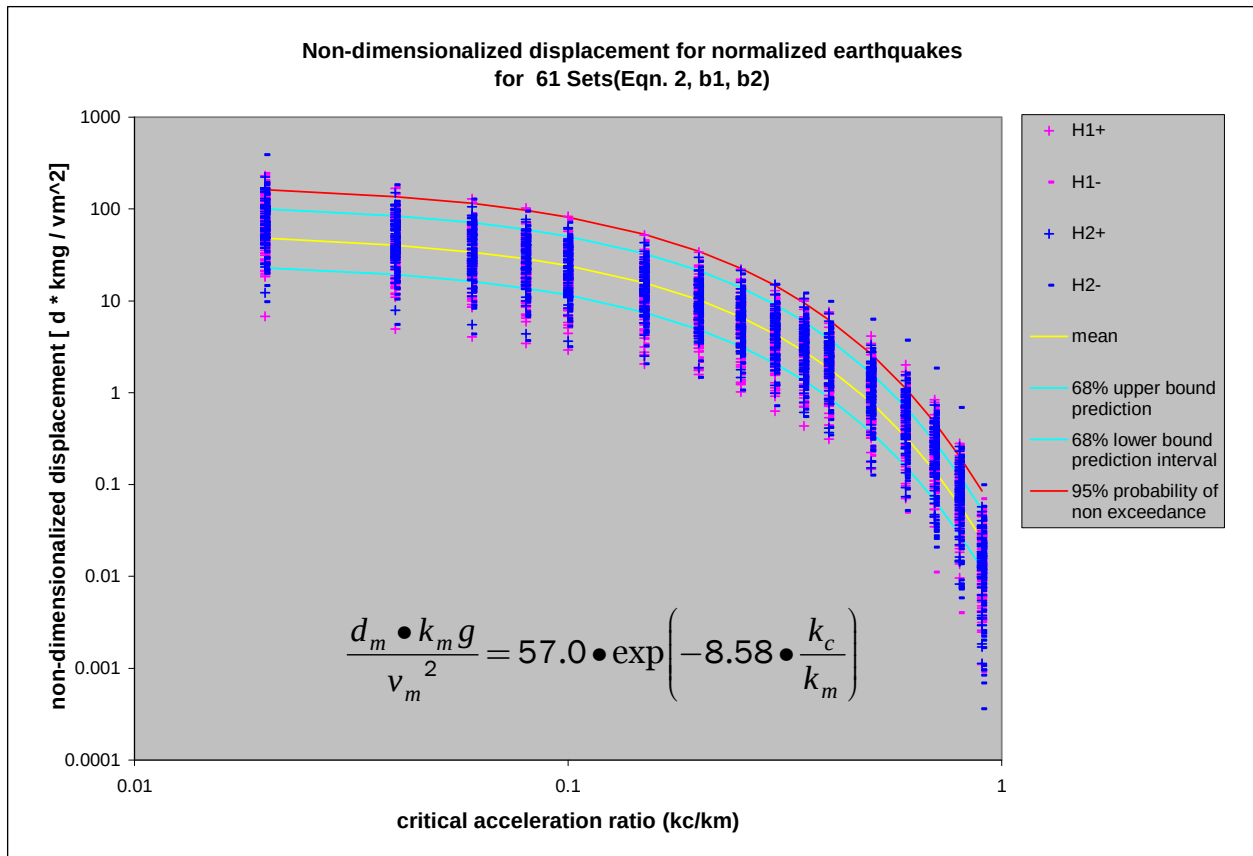


Figure 4.10. Non-dimensionalized displacements with the mean, 68 percent prediction intervals and 95 percent probability of non-exceedance curves.

The mean permanent displacement is derived by introducing Equation 4.66 into Equation 4.3.

$$d_m = 264.3 \bullet \exp \left( -8.58 \bullet \frac{k_c}{k_m} \right) \bullet \left[ 0.216 \bullet \left( \frac{v_m^2}{k_m \bullet g} \right) \right] \quad (4.67)$$

where the right-hand-side term  $k_m g$  is the peak (positive) rock acceleration expressed in units of length per sec<sup>2</sup>.

Note that Equation 4.67 is the same as Equation 4.65, indicating consistent results from both regression analyses.

#### 4.4.2.2 Ninety-five percent probability of non-exceedance

The regression analysis of the 61 sets of Magnitude 5 rock acceleration time histories resulted in the non-dimensionalized displacement for 95 percent probability of non-exceedance of

$$\frac{d_m \bullet k_m g}{v_m^2} = 57.0 \bullet \exp\left(-8.58 \bullet \frac{k_c}{k_m}\right) \bullet 3.39 \quad (4.68)$$

The 95 percent probability of non-exceedance is shown in red in Figure 4.10.

By the second, independent regression analysis, the standardized maximum displacement ( $d_s$ ) in units of inches, derived using  $v_s = 29.92$  in./sec and  $k_s = 0.5 g$ , is

$$d_s = 264.3 \bullet \exp\left(-8.58 \bullet \frac{k_c}{k_m}\right) \bullet 3.39 \quad (4.69)$$

Introducing Equation 4.3, the corresponding permanent displacement is

$$d_m = 264.3 \bullet \exp\left(-8.58 \bullet \frac{k_c}{k_m}\right) \bullet 3.39 \bullet \left[0.216 \bullet \left(\frac{v_m^2}{k_m \bullet g}\right)\right] \quad (4.70)$$

where the right-hand-side term  $k_m g$  is the peak (positive) rock acceleration expressed in units of length per sec<sup>2</sup>.

Note that Equation 4.70 is the same as Equation 4.68, indicating consistent results from both regression analyses.

#### 4.4.2.3 Sixty-eight percent prediction intervals

The regression analysis of the 61 sets of Magnitude 5 rock acceleration time histories resulted in the non-dimensionalized displacement relationships for the 68 percent prediction intervals of

$$\frac{d_m \bullet k_m g}{v_m^2} = 57.0 \bullet \exp\left(-8.58 \bullet \frac{k_c}{k_m}\right) \bullet 2.10 \quad (4.71a)$$

$$\frac{d_m \bullet k_m g}{v_m^2} = 57.0 \bullet \exp\left(-8.58 \bullet \frac{k_c}{k_m}\right) \bullet 0.477 \quad (4.71b)$$

The 68 percent prediction intervals are shown in blue in Figure 4.10.

By the second independent regression analysis, the standardized maximum displacements ( $d_s$ ) in units of inches, derived using  $v_s = 29.92$  in./sec and  $k_s = 0.5$  g, are

$$d_s = 264.3 \bullet \exp\left(-8.58 \bullet \frac{k_c}{k_m}\right) \bullet 2.10 \quad (4.72a)$$

$$d_s = 264.3 \bullet \exp\left(-8.58 \bullet \frac{k_c}{k_m}\right) \bullet 0.477 \quad (4.72b)$$

Introducing Equation 4.3, the corresponding permanent displacements are

$$d_m = 264.3 \bullet \exp\left(-8.58 \bullet \frac{k_c}{k_m}\right) \bullet 2.10 \bullet \left[0.216 \bullet \left(\frac{v_m^2}{k_m \bullet g}\right)\right] \quad (4.73a)$$

$$d_m = 264.3 \bullet \exp\left(-8.58 \bullet \frac{k_c}{k_m}\right) \bullet 0.477 \bullet \left[0.216 \bullet \left(\frac{v_m^2}{k_m \bullet g}\right)\right] \quad (4.73b)$$

where the right-hand-side term  $k_m g$  is the peak (positive) rock acceleration expressed in units of length per sec<sup>2</sup>.

Note that Equations 4.73a and 4.73b are the same as Equations 4.71a and 4.71b, indicating consistent results from both regression analyses.

#### **4.4.3 Two-term regression results, linear in common logarithm transformation**

The standard error term (*Std. error*) for this regression analysis was determined to be 1.24 for both the non-dimensionalized displacement as well as the standardized displacement for earthquakes of Magnitude 5. This non-dimensionalized two-term displacement equation is identified as Equation Form One with the coefficients and *Std. error* terms summarized in column two of Table 4.8.

#### 4.4.3.1 Mean relationships

The regression analysis of the 61 sets of Magnitude 5 rock acceleration time histories resulted in the mean non-dimensionalized displacement relationship of

$$\frac{d_m \bullet k_m g}{v_m^2} = 0.153 \bullet \left( \frac{k_c}{k_m} \right)^{-1.94} \quad (4.74)$$

where:

- $d_m$  = permanent displacement
- $k_m g$  = peak (positive) rock acceleration expressed in units of length per sec<sup>2</sup>, consistent with units of  $d_m$  (length) and  $v_m$  (length per sec)
- $v_m$  = peak (positive) ground velocity of the earthquake
- $k_c$  = critical acceleration expressed as a fraction of  $g$
- $k_m$  = peak (positive) rock acceleration expressed as a fraction of  $g$ .

This mean relationship is shown in yellow in Figure 4.11.

By a second independent regression analysis, the mean standardized maximum displacement ( $d_s$ ) in units of inches was derived for the standardized velocity,  $v_s = 29.92$  in./sec (0.76 m/sec) and the standardized acceleration  $k_s = 0.5 g$  (193.04 in./sec<sup>2</sup> : 4.90 m/sec<sup>2</sup>)

$$d_s = 0.71 \bullet \left( \frac{k_c}{k_m} \right)^{-1.94} \quad (4.75)$$

The standardized maximum displacement ( $d_s$ ) can be converted to the permanent displacement ( $d_m$ ) by the following transformation,

$$d_m = d_s \bullet \left[ \left( \frac{k_s}{v_s^2} \right) \bullet \left( \frac{v_m^2}{k_m} \right) \right] \quad (\text{bis } 4.3)$$

where:

- $k_s$  = standardized acceleration expressed as a fraction of  $g$  (0.5)
- $v_s$  = standardized velocity (29.92 in./sec).

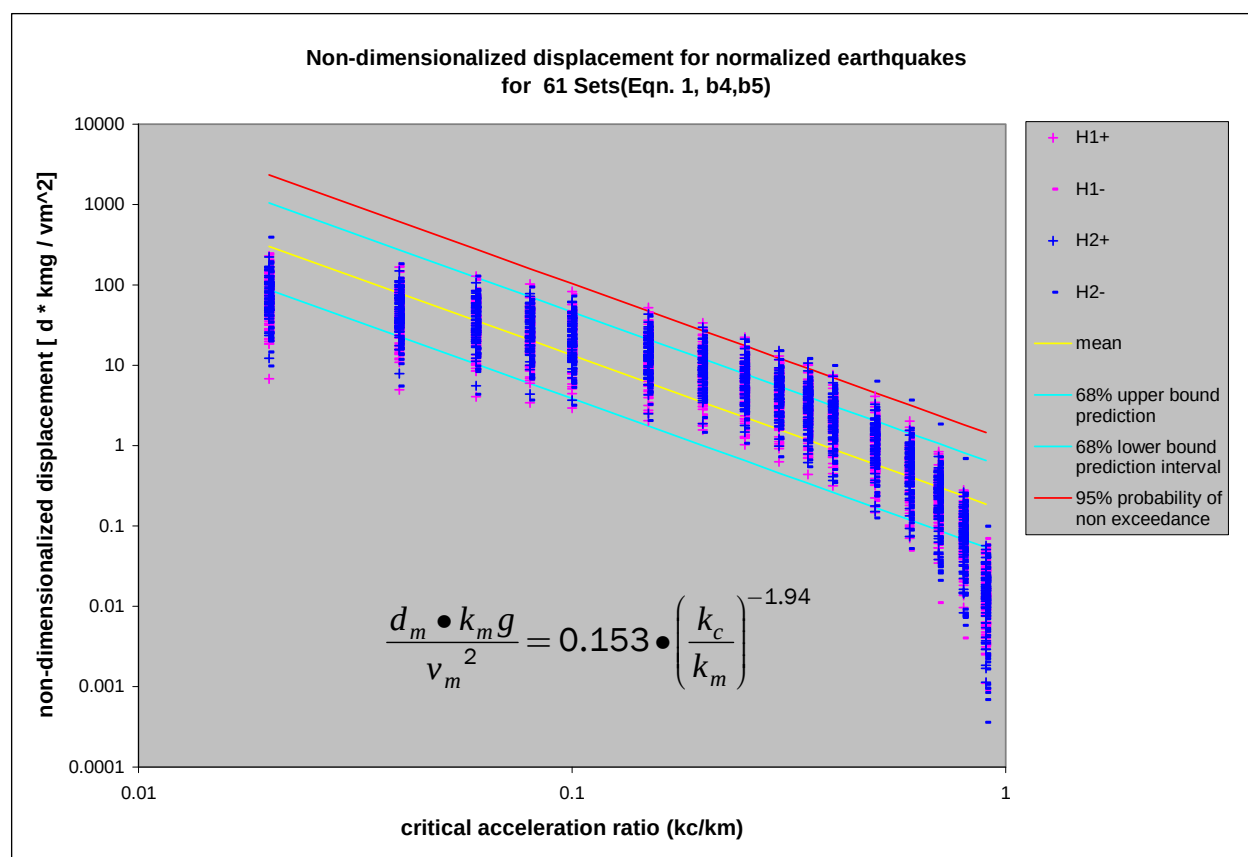


Figure 4.11. Non-dimensionalized displacements with the mean, 68 percent prediction intervals and 95 percent probability of non-exceedance curves.

The mean permanent displacement is derived by introducing Equation 4.74 into Equation 4.3.

$$d_m = 0.71 \cdot \left( \frac{k_c}{k_m} \right)^{-1.94} \cdot \left[ 0.216 \cdot \left( \frac{v_m^2}{k_m \cdot g} \right) \right] \quad (4.76)$$

where the right-hand-side term  $k_m g$  is the peak (positive) rock acceleration expressed in units of length per sec<sup>2</sup>.

Note that Equation 4.76 is the same as Equation 4.74, indicating consistent results from both regression analyses.

#### 4.4.3.2 Ninety-five percent probability of non-exceedance

The regression analysis of the 61 sets of Magnitude 5 rock acceleration time histories resulted in the non-dimensionalized displacement for 95 percent probability of non-exceedance of

$$\frac{d_m \bullet k_m g}{v_m^2} = 0.153 \bullet \left( \frac{k_c}{k_m} \right)^{-1.94} \bullet 2.44 \quad (4.77)$$

The 95 percent probability of non-exceedance is shown in red in Figure 4.11.

By the second independent regression analysis, the standardized maximum displacement ( $d_s$ ) in units of inches, derived using  $v_s = 29.92$  in./sec and  $k_s = 0.5$  g, is

$$d_s = 0.71 \bullet \left( \frac{k_c}{k_m} \right)^{-1.94} \bullet 2.44 \quad (4.78)$$

Introducing Equation 4.3, the corresponding permanent displacement is

$$d_m = 0.71 \bullet \left( \frac{k_c}{k_m} \right)^{-1.94} \bullet 2.44 \bullet \left[ 0.216 \bullet \left( \frac{v_m^2}{k_m \bullet g} \right) \right] \quad (4.79)$$

where the right-hand-side term  $k_m g$  is the peak (positive) rock acceleration expressed in units of length per sec<sup>2</sup>.

Note that Equation 4.79 is the same as Equation 4.77, indicating consistent results from both regression analyses.

#### 4.4.3.3 Sixty-eight percent prediction intervals

The regression analysis of the 61 sets of Magnitude 5 rock acceleration time histories resulted in the non-dimensionalized displacement relationships for the 68 percent prediction intervals of

$$\frac{d_m \bullet k_m g}{v_m^2} = 0.153 \bullet \left( \frac{k_c}{k_m} \right)^{-1.94} \bullet 1.72 \quad (4.80a)$$

$$\frac{d_m \bullet k_m g}{v_m^2} = 0.153 \bullet \left( \frac{k_c}{k_m} \right)^{-1.94} \bullet 0.583 \quad (4.80b)$$

The 68 percent prediction intervals are shown in blue in Figure 4.11.

By the second independent regression analysis, the standardized maximum displacements ( $d_s$ ) in units of inches, derived using  $v_s = 29.92$  in./sec and  $k_s = 0.5 g$ , are

$$d_s = 0.71 \cdot \left( \frac{k_c}{k_m} \right)^{-1.94} \cdot 1.72 \quad (4.81a)$$

$$d_s = 0.71 \cdot \left( \frac{k_c}{k_m} \right)^{-1.94} \cdot 0.583 \quad (4.81b)$$

Introducing Equation 4.3, the corresponding permanent displacements are,

$$d_m = 0.71 \cdot \left( \frac{k_c}{k_m} \right)^{-1.94} \cdot 1.72 \cdot \left[ 0.216 \cdot \left( \frac{v_m^2}{k_m \cdot g} \right) \right] \quad (4.82a)$$

$$d_m = 0.71 \cdot \left( \frac{k_c}{k_m} \right)^{-1.94} \cdot 0.583 \cdot \left[ 0.216 \cdot \left( \frac{v_m^2}{k_m \cdot g} \right) \right] \quad (4.82b)$$

where the right-hand-side term  $k_m g$  is the peak (positive) rock acceleration expressed in units of length per sec<sup>2</sup>.

Note that Equations 4.82a and 4.82b are the same as Equations 4.80a and 4.80b, indicating consistent results from both regression analyses.

#### **4.4.4 Comparison of regression results of all three forms of the simplified non-dimensionalized displacement relationships.**

The three forms of regression analysis (discussed in Sections 4.4.1, 4.4.2, and 4.4.3), namely, the three-term regression analysis (identified as eqn3 in Figure 4.12), the two-term, linear in Natural Logarithm Transformation (eqn2 in Figure 4.12) and the two-term, linear in common logarithm transformation (eqn1 in Figure 4.12) will have their results compared and evaluated.

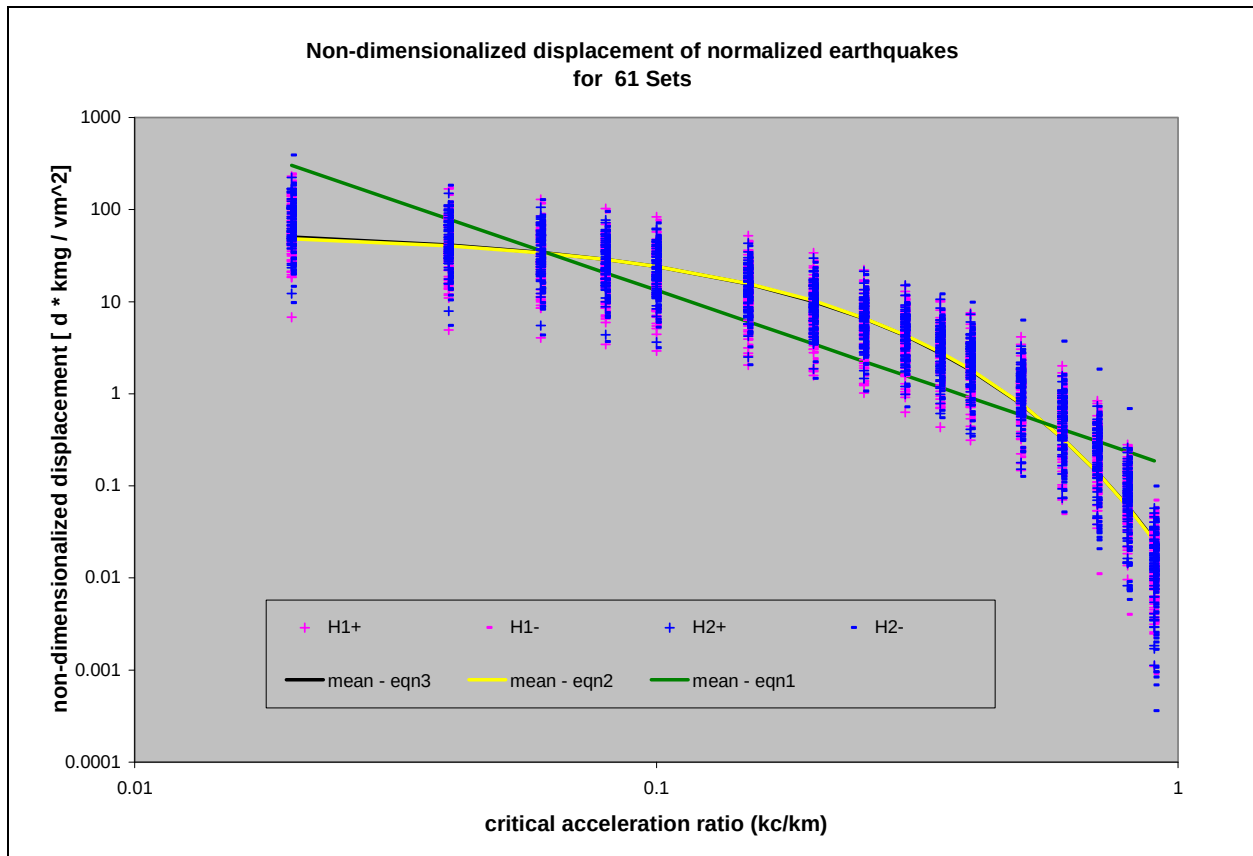


Figure 4.12. Non-dimensionalized displacements and comparisons of the means of the three regression analysis equations for Magnitude 5 earthquakes.

One method of comparison will be the *Std. error* term determined from the error in the estimates. The *Std. error* for eqn3 is 0.74, for eqn2, 0.74 and for eqn1, equal to 1.24 when transformed to a natural logarithm from a common logarithm standard error value of 0.54. These results show that eqn3 and eqn2 have a more accurate estimate as compared to eqn1, and that eqn3 and eqn2 have practically equal values.

Another comparison is the mean relationships as illustrated in Figure 4.12. As can be seen, eqn2 and eqn3 follow the shape of the data and are positioned at the center of the data points while eqn1 does not. Note also that the mean curves of eqn2 and eqn3 are almost superimposing each other, which show the similarity of the results.

Lastly, given the small value of the exponent for the  $(k_c/k_m)$  term of eqn3 (-0.039), this explains the comparable results of eqn2 and eqn3.

## 4.5 Special regression results of Equation Form Two of non-dimensionalized displacement relationships without differentiation of Moment Magnitude

This subsequent section will discuss the results from regression analyses of the non-dimensionalized displacement relationships described by Equation 3.39, previously derived in Chapter 3. The values for the coefficients summarized by the above-mentioned equation and the standard error terms as well as the probabilistic measures of Equation Form Two are documented in Table 4.9 and will be discussed in Sections 4.5.1, 4.5.2, and 4.5.3. The regression analysis was performed for baseline corrected acceleration time histories recorded on rock with  $M_w$  range of 4.9 to 8.1.

Table 4.9. Values for the regression Equation Form Two constants without differentiation of  $M_w$ .

| Coefficients and <i>Std. Error</i> | Equation Form Two |
|------------------------------------|-------------------|
| $\beta_1$                          | 64.439            |
| $\beta_2$                          | -8.862            |
| $\beta_3$                          |                   |
| $\beta_4$                          |                   |
| $\beta_5$                          |                   |
| <i>Std. Error</i>                  | 0.800             |

The standard error term (*Std. error*) for this regression analysis was determined to be 0.80 for both the non-dimensionalized displacement as well as the standardized displacement. This non-dimensionalized two-term displacement equation is identified as Equation Form Two with the coefficients and *Std. error* terms summarized in column two of Table 4.9.

### 4.5.1. Mean relationships

The regression analysis of the 122 sets of Magnitude 5 – 7 rock acceleration time histories resulted in the mean non-dimensionalized displacement relationship of

$$\frac{d_m \bullet k_m g}{v_m^2} = 65.44 \bullet \exp \left( -8.86 \bullet \frac{k_c}{k_m} \right) \quad (4.83)$$

where:

- $d_m$  = permanent displacement
- $k_m g$  = peak (positive) rock acceleration expressed in units of length per sec<sup>2</sup>, consistent with units of  $d_m$  (length) and  $v_m$  (length per sec)
- $v_m$  = peak (positive) ground velocity of the earthquake

$k_c$  = critical acceleration expressed as a fraction of  $g$   
 $k_m$  = peak (positive) rock acceleration expressed as a fraction of  $g$ .

This mean relationship is shown in yellow in Figure 4.13.

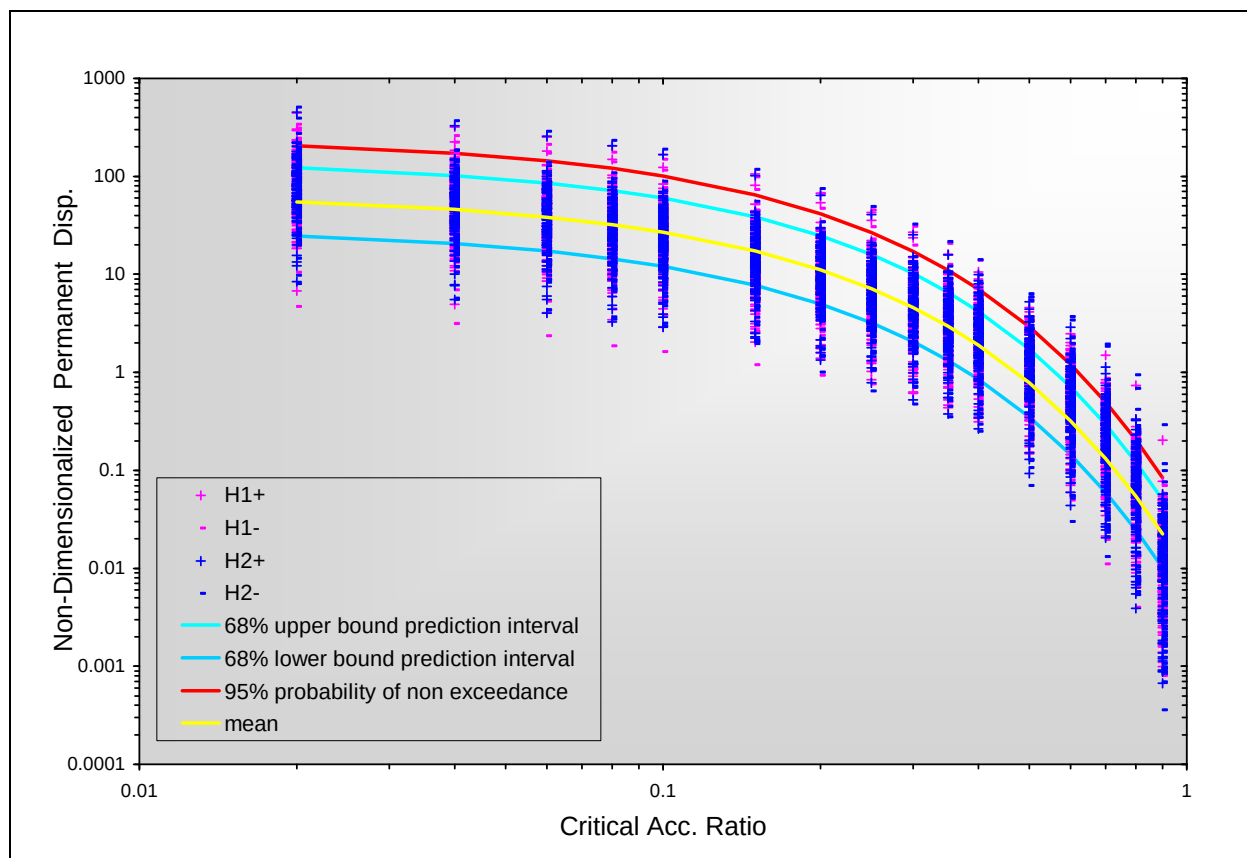


Figure 4.13. Non-dimensionalized displacements for normalized earthquakes without differentiation of Moment Magnitude (Equation Form Two).

By a second independent regression analysis, the mean standardized maximum displacement ( $d_s$ ) in units of inches was derived for the standardized velocity,  $v_s = 29.92$  in./sec (0.76 m/sec) and the standardized acceleration  $k_s = 0.5 g$  (193.04 in./sec<sup>2</sup> : 4.90 m/sec<sup>2</sup>).

$$d_s = 303.484 \bullet \exp \left( -8.862 \bullet \frac{k_c}{k_m} \right) \quad (4.84)$$

The standardized maximum displacement ( $d_s$ ) can be converted to the permanent displacement ( $d_m$ ) by the following transformation,

$$d_m = d_s \cdot \left[ \left( \frac{k_s}{v_s^2} \right) \cdot \left( \frac{v_m^2}{k_m} \right) \right] \quad (\text{bis 4.3})$$

where:

$k_s$  = standardized acceleration expressed as a fraction of  $g$  (0.5)

$v_s$  = standardized velocity (29.92 in./sec).

The mean permanent displacement is derived by introducing Equation 4.66 into Equation 4.3.

$$d_m = 303.484 \cdot \exp \left( -8.862 \cdot \frac{k_c}{k_m} \right) \cdot \left[ 0.216 \cdot \left( \frac{v_m^2}{k_m \cdot g} \right) \right] \quad (4.86)$$

where the right-hand-side term  $k_m g$  is the peak (positive) rock acceleration expressed in units of length per sec<sup>2</sup>.

Note that Equation 4.83 is the approximately the same as Equation 4.86, indicating consistent results from both regression analyses.

#### 4.5.2 Ninety-five percent probability of non-exceedance

The regression analysis of the 122 sets of  $M_w$  5 to 7 rock acceleration time histories resulted in the non-dimensionalized displacement for 95 percent probability of non-exceedance of

$$\frac{d_m \cdot k_m g}{v_m^2} = 65.44 \cdot \exp \left( -8.86 \cdot \frac{k_c}{k_m} \right) \cdot 3.75 \quad (4.87)$$

The 95 percent probability of non-exceedance is shown in red in Figure 4.13.

By the second, independent regression analysis, the standardized maximum displacement ( $d_s$ ) in units of inches, derived using  $v_s = 29.92$  in./sec and  $k_s = 0.5 g$ , is

$$d_s = 303.484 \cdot \exp \left( -8.86 \cdot \frac{k_c}{k_m} \right) \cdot 3.75 \quad (4.88)$$

Introducing Equation 4.3, the corresponding permanent displacement is

$$d_m = 303.484 \bullet \exp\left(-8.86 \bullet \frac{k_c}{k_m}\right) \bullet 3.75 \bullet \left[0.216 \bullet \left(\frac{v_m^2}{k_m \bullet g}\right)\right] \quad (4.89)$$

where the right-hand-side term  $k_m g$  is the peak (positive) rock acceleration expressed in units of length per sec<sup>2</sup>.

Note that Equation 4.89 is the approximately the same as Equation 4.87, indicating consistent results from both regression analyses.

#### 4.5.3 Sixty-eight percent prediction intervals

The regression analysis of the 122 sets of Magnitude 5 - 7 rock acceleration time histories resulted in the non-dimensionalized displacement relationships for the 68 percent prediction intervals of

$$\frac{d_m \bullet k_m g}{v_m^2} = 65.44 \bullet \exp\left(-8.86 \bullet \frac{k_c}{k_m}\right) \bullet 2.23 \quad (4.90a)$$

$$\frac{d_m \bullet k_m g}{v_m^2} = 65.44 \bullet \exp\left(-8.86 \bullet \frac{k_c}{k_m}\right) \bullet 0.449 \quad (4.90b)$$

The 68 percent prediction intervals are shown in blue in Figure 4.13.

By the second independent regression analysis, the standardized maximum displacements ( $d_s$ ) in units of inches, derived using  $v_s = 29.92$  in./sec and  $k_s = 0.5 g$ , are

$$d_s = 303.484 \bullet \exp\left(-8.86 \bullet \frac{k_c}{k_m}\right) \bullet 2.23 \quad (4.91a)$$

$$d_s = 303.484 \bullet \exp\left(-8.86 \bullet \frac{k_c}{k_m}\right) \bullet 0.449 \quad (4.91b)$$

Introducing Equation 4.3, the corresponding permanent displacements are

$$d_m = 303.484 \bullet \exp\left(-8.86 \bullet \frac{k_c}{k_m}\right) \bullet 2.23 \bullet \left[0.216 \bullet \left(\frac{v_m^2}{k_m \bullet g}\right)\right] \quad (4.92a)$$

$$d_m = 303.484 \bullet \exp\left(-8.86 \bullet \frac{k_c}{k_m}\right) \bullet 0.449 \bullet \left[0.216 \bullet \left(\frac{v_m^2}{k_m \bullet g}\right)\right] \quad (4.92b)$$

where the right-hand-side term  $k_m g$  is the peak (positive) rock acceleration expressed in units of length per sec<sup>2</sup>.

Note that Equations 4.92a and 4.92b are approximately the same as Equations 4.90a and 4.90b, indicating consistent results from both regression analyses.

## 5 The Visual Modeler for Newmark – Newmark<sub>VM</sub>

### 5.1 Introduction

This chapter provides guidance on the details of the Visual Modeler (Newmark<sub>VM</sub>), the PC-based Graphical User Interface (GUI) to the program named Newmark. Newmark<sub>VM</sub> gathers the necessary user specified information and provides a simple and expedient means of interpreting the results from a Newmark analysis (by executing Newmark, the FORTRAN engineering formulation discussed in Chapter 2). There will be discussions on how to perform and interpret the results of an analysis.

### 5.2 The Visual Modeling Environment

Newmark is a program that can perform a permanent sliding block displacement analysis given a baseline corrected rock site-specific acceleration time-history. Newmark can also conduct regression analyses for sets of rock founded acceleration time histories in order to develop up to three user selected forms of generalized equations of simplified permanent displacement relationships. The user has the option of performing one of two types of translational (i.e. sliding) analysis, either a single or deterministic analysis, or a multiple analysis that can include regression analyses.

At the onset of Newmark<sub>VM</sub>, the user is automatically introduced to a graphical image representing the results obtained from a typical regression analysis computed by Newmark. In this case, evaluation of 122 sets of (rock) acceleration time histories ranging from earthquake magnitudes of 5 thru 7 were used for the multiple analyses. This image is included in the **Introduction** tab and shown in Figure 5.1. Directly above this tab are two drop down menus. The first, entitled **File**, provides an easy and convenient way to open an existing file, create a new file or save existing data to a file. These files are user created and have an “.nmk” extension. Opening an existing file will immediately replenish the data within all tabs and thereby allow the user to quickly run an analysis from previous data input. The second drop down menu above the **Introduction** tab is labeled **Analysis Type**; here the user is given the option to select the scenario of either a single analysis or multiple analyses that may apply regression.

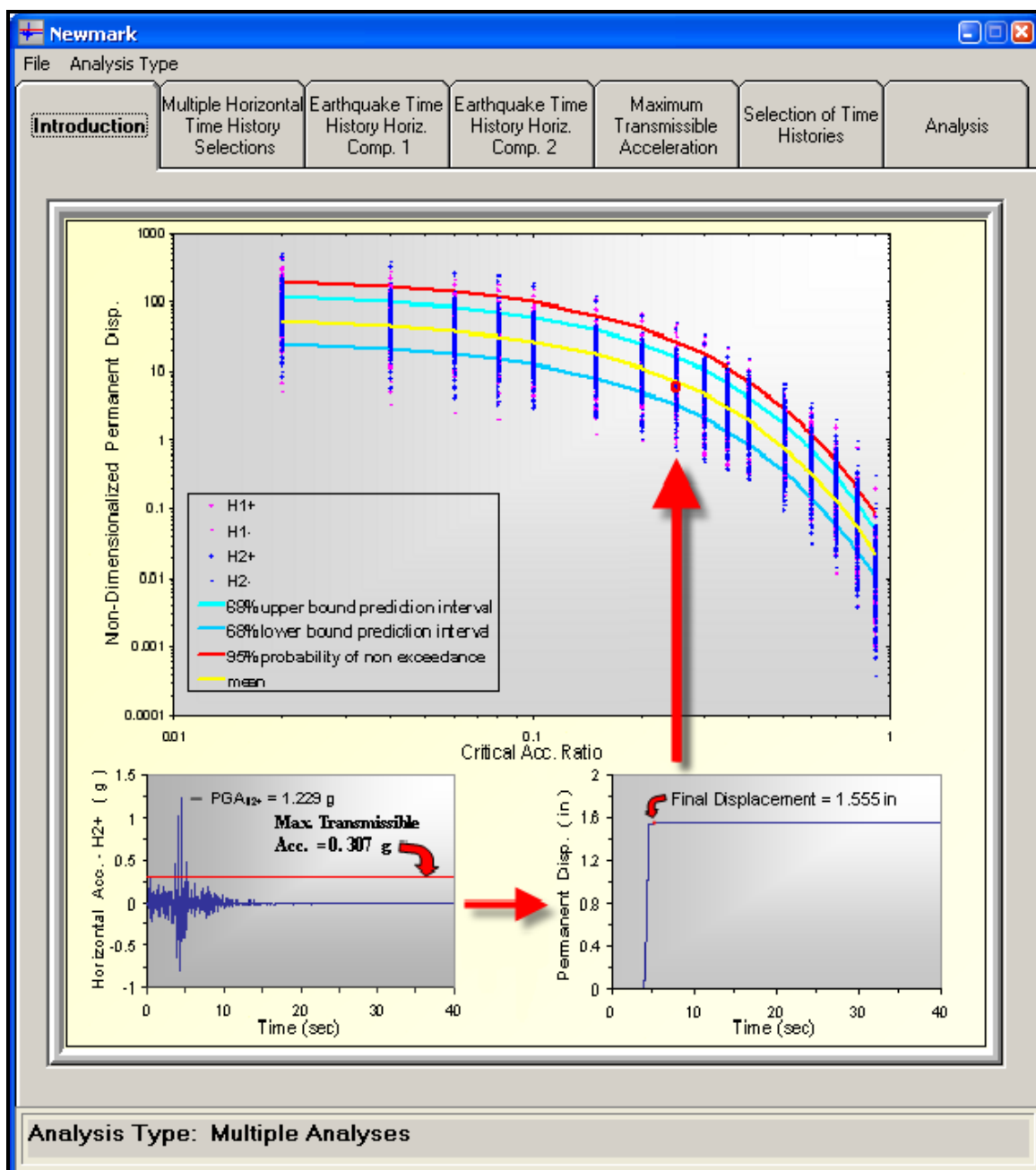


Figure 5.1. The **Introduction** tab features the process of a multiple analysis.

### 5.2.1 Significant Tabs relevant to an analysis

With a single analysis, the input data to Newmark falls into three different groups and Newmark<sub>VM</sub> displays these groups with the following tabs available for user input

- Earthquake Time-History Horizontal Component 1 data
- Maximum Transmissible Acceleration values

- Analysis of specified data

Input data for a multiple or regression analyses falls into six different groups and the Newmark<sub>VM</sub> displays these groups as tabs and available for user input

- Multiple Horizontal Time-History Selections menu
- Earthquake Time-History Horizontal Component 1 data
- Earthquake Time-History Horizontal Component 2 data
- Maximum Transmissible Acceleration values
- Selection of Time Histories for analysis
- Analysis of specified data

In order to perform multiple analyses, it is required that we consider only sets of acceleration time histories. A set is made up of two site-specific acceleration time-history files; each representing a horizontal component. If only one component is available for one or more sets of time histories, Newmark will acknowledge this fact and perform the analyses with the available time histories.

The following subsections of Section 5.2 are listed in the order as shown in the Newmark<sub>VM</sub> tabs. Each subsection describes the function of each tab and identifies whether each tab relates to a single analysis, multiple analyses or both.

### **5.2.2 Multiple Horizontal Time-History Selections (Multiple Analyses only)**

The function of this tab relates to the collection of sets of base-line corrected acceleration time histories as input and consists mainly of file handling. Figure 5.2 shows the many options necessary for the creation of a list of filenames relating to acceleration time histories for an analysis.

The user data entry within this tab will be described in a top-down manner. Data within this tab can be divided into subgroups and is described in the following two sections.

Newmark

File Analysis Type

Introduction **Multiple Horizontal Time History Selections** Earthquake Time History Horiz. Comp. 1 Earthquake Time History Horiz. Comp. 2 Maximum Transmissible Acceleration Selection of Time Histories Analysis

Browse to Select Horizontal Earthquake Time History File(s)

Assign File to

Group#1

Group#2

Add Set

Clear List

New Time History File Set

File (H1) to Group #1: N/A Clear H1

File (H2) to Group #2: N/A Clear H2

Initial Set No# 1 Insert Edit Del

| Set # | Group#1 - H1 | Group #2 - H2 |
|-------|--------------|---------------|
| 1     |              |               |

Select Set by Clicking on Set Id #

Edit Global Earthquake Time History Data

☒ Perform Standardized Displacement Computations

Global Peak Ground Data

Acceleration: 0.5 Acceleration Units: fractional G's Velocity: 0.76 Velocity Units: meter/sec

Analysis Type: Multiple Analyses

Figure 5.2. The **Multiple Horizontal Time-History Selections** tab ready for user input.

#### 5.2.2.1 Selection of Horizontal Earthquake Time-History Files

The **Browse to Select Horizontal Earthquake Time-History File(s)** allows the user to gather all relative acceleration time-history files necessary for computing multiple analyses. Once selected, a file management screen will appear for the user to choose all relevant files. The pull-down menu on the left of the screen (Figure 5.3) gives the path (i.e., drive and directory) to the location of the files. The large center box shows a list

of files contained within the selected directory. The **Copy Selected** button at the right allows the selection of any or all files in the center box. If the user decides to start over or clear the list of files in the center box, the **Clear List** button on the upper right of the previous menu (Figure 5.2) is an option used to remove the selected files. Finally, when the user is satisfied with all files, the **OK** button is accepted and the original screen of Section 5.2.2 will appear with the list of all selected files.

From the list of previously selected acceleration time-history files, the user can start matching the sets, i.e. the horizontal components of these earthquake time histories need to belong to the same set. It is important to correctly pick the files that pertain to horizontal component 1 (group 1) and the files for horizontal component 2 (group 2). This is accomplished by the **Assign File to** frame or container located to the left in Figure 5.2 which contains 3 buttons. To select a set, use the following steps

1. Choose a file for group 1, by selecting the file listed in the center box and then pressing the **Group#1** button
2. This file will appear in the **File (H1) to Group #1:** box within the **New Time-History File Set** frame
3. If file in step 2 is incorrect, select **Clear H1** and start over with step 1
4. Choose a file for group 2, by selecting the file listed in the center box and then pressing the **Group#2** button
5. This group 2 file will appear in the **File (H1) to Group #2:** box within the **New Time-History File Set** frame
6. If file in step 5 is incorrect, select **Clear H2** and start over with step 4 for selection of group 2 files.
7. Select the **Add Set** button located in the **Assign File to** frame to create the set

Note: If there is no file pertaining to either group 1 or group 2, the user can take the default of **N/A** found within the **New Time-History File Set** frame.

After selecting the **Add Set** button, the new set will be added to a scroll-down list with a gray background, and each file will be located within its respective group number.

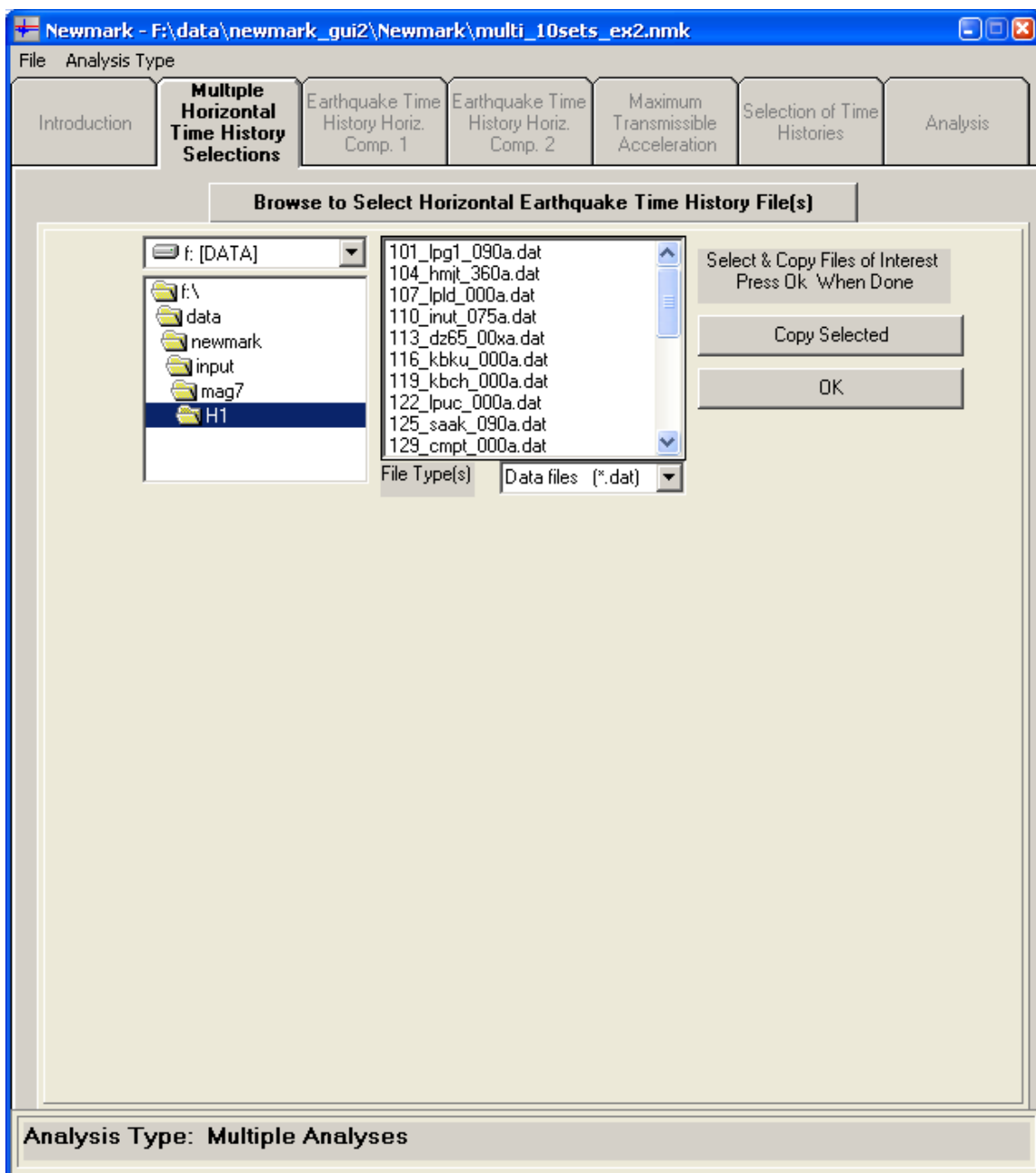


Figure 5.3. Selection of horizontal time-history files.

The first set is given a set number of 1 or the value of the **Initial Set No#** box. The addition of more sets will require the user to go over the above seven steps for each set. As a useful means for the management of these sets, buttons are included for inserting, editing and deleting sets.

The **Initial Set No#** box located above the gray scroll-down list allows the user to enter the set number of interest. This feature will automatically place that particular set at the top of the list.

### 5.2.2.2 Standardized Displacement Computations

At the lower portion of the **Multiple Horizontal Time-History Selections** tab is an option to perform standardized displacement computations. The global peak ground acceleration with its units and the peak velocity with its units can be provided as input. With the selection of this option, the resultant analysis will include the standardized displacement computations.

### 5.2.3 Earthquake Time-History Horizontal Component 1 and 2 input (Single Analysis or Multiple Analyses)

Both horizontal component 1 and horizontal component 2 time-history input follow the same input pattern. First an appropriate, base-line corrected acceleration time-history data file is selected for the Corps project by the user. Given the non-standardized nature of earthquake time-history data files, certain attributes need to be specified to correctly read the input (ASCII) data file. These attributes are entered in the Format section of the Earthquake Time-History (EQTH) tabs – Horizontal Comp. 1 and Horizontal Comp. 2. This is an exceptionally powerful tool for handling multiple format EQTH files. Figure 5.4 shows the horizontal component 1 earthquake time-history tab.

To work with the appropriate EQTH data file, the user must first specify a file to be read in. The user can type a specific filename or select a file using the **Find** button that exists on the **Earthquake Time-History Horz Comp. 1** tab in a single analysis case.

For multiple analyses there will be a dropdown menu next to the file name that allows the user to select which file to work with. The listed files can also be found in the gray shaded area within the **Multiple Horizontal Time-History Selections** tab. These time histories will be listed in Group#1 or Group#2 depending on whether the user is currently working in the **Earthquake Time Horz Comp. 1** or **Earthquake Time-History Horz Comp. 2** tabs. When working with the **Set #** combo box, located at the top right of the tab, the user can either enter the set number of interest or use the arrow buttons to increase/decrease the set number.

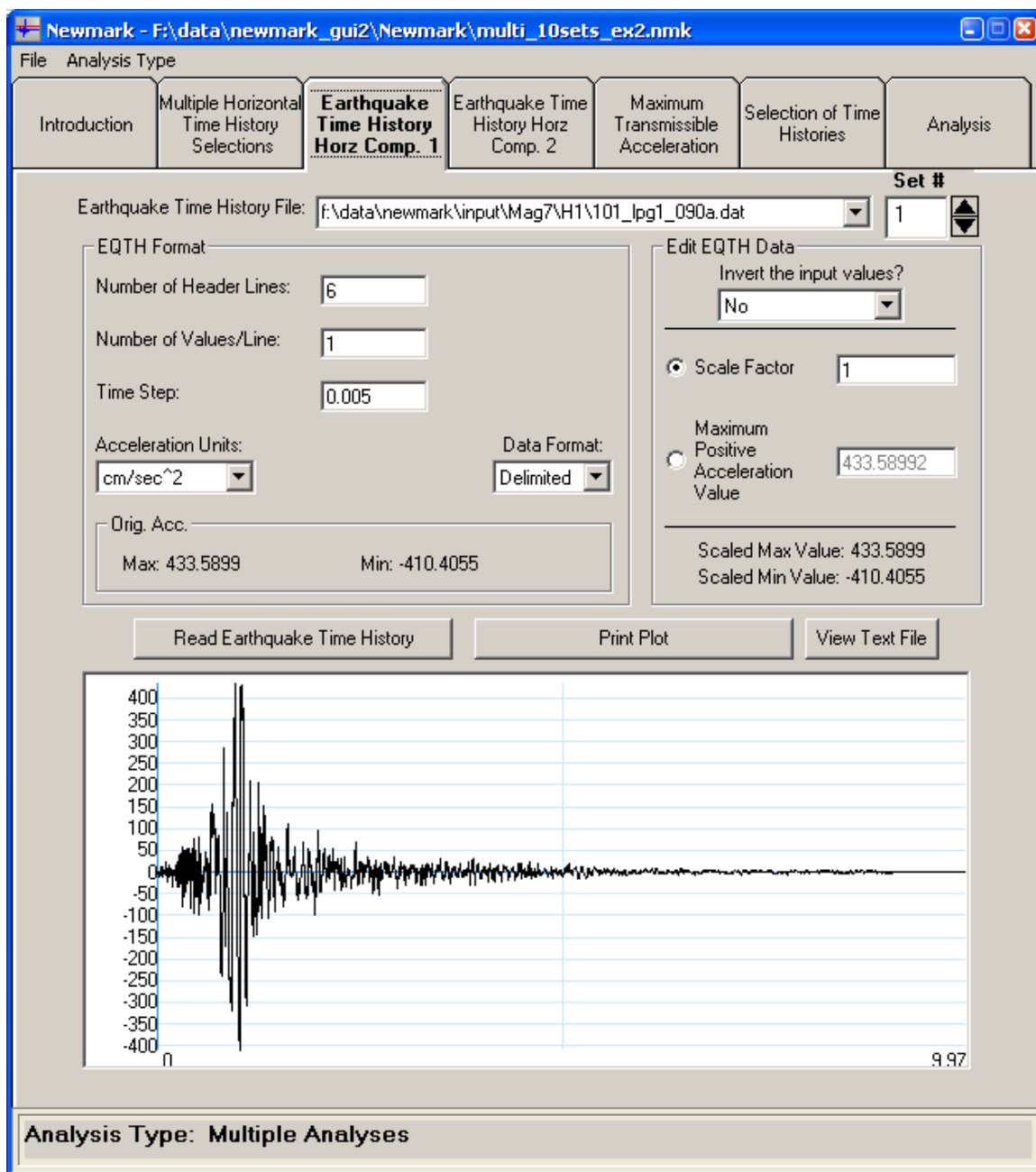


Figure 5.4. Horizontal earthquake time-history ground motion shown in the **Earthquake Time-History Horz Comp. 1** tab.

This set number matches the **Set #** found in the gray area within the **Multiple Horizontal Time-History Selections** tab. Selection of a particular set will update all relevant data within the current earthquake time-history tab, including the graph at the bottom of the form.

When a file has been selected, a format must be built. All specifications for reading a file are grouped in a frame labeled **EQTH Format**. To know what information to enter for reading the file, it will be beneficial to select the **View Text File** button and peruse the file to find each section of data.

The first block of data in each EQTH file is the number of header lines. Entering how many header lines there are allows the program to skip those lines. It is also important to know how many data samples are on each line. Entering the **Number of Values/Line** keeps the program from entering blank samples or ignoring samples. The value entered for **Time Step** should be the amount of time that occurs between samples, establishing the sampling frequency and the total time for the earthquake data.

Since Newmark works from the beginning of an earthquake, it is to be assumed that the first sample, time step 0, will have a value of 0.0 in whatever units chosen. If the EQTH file does not have this zero point, it will be accounted for in the software.

There is a combo box that allows the user to specify the units that the data were recorded in. NOTE: The horizontal component 1 EQTH file uses the same units as the Horizontal component 2 EQTH file. There is no way to mix and match EQTH units.

There is a second combo box that shows several options for a data format. These formats are displayed as if they were in a FORTRAN FORMAT statement. These are especially important in areas where data text may run together. In the **Data Format** pull-down menu, the **Delimited** option is the space.

After an EQTH format has been built for a particular file, the user can read in the Earthquake Time-History. After the button is pressed, the actual values of the maximum and minimum values for that file are displayed in the **Orig. Acc.** sub-frame of the **EQTH Format** frame. A plot of the input data is also displayed at the bottom of the tab. The **Edit EQTH Data** frame will also be enabled.

The **Edit EQTH Data** frame is a tool that allows the user to scale the EQTH data to values more appropriate for modeling the problem at hand. There is a combo-box that allows the user to invert the user specified

earthquake acceleration time-history values, which is valuable for determining whether the direction of peak values influence the computed (permanent displacement) results.

There are also two possible ways of scaling the input data, either by setting an absolute scale value to multiply the samples by or by setting an absolute maximum value for the positive peak value and scaling the other samples to match. To choose the scale method, click the radio button beside that option. Then, type in the value desired.

When this is done, the inactive choice will be updated with the related value. Also, the scaled minimum and maximum values will be displayed, and the data plot at the bottom of the form will reflect the changes.

If the user desires a hardcopy of the scaled data in the same format as at the bottom of the tab, there is a button labeled **Print Plot**.

If the user would like to view the raw data in its original format, there is a button labeled **View Text File**.

#### **5.2.4 Maximum Transmissible Acceleration input (Single Analysis or Multiple Analyses)**

To perform a Newmark sliding block analysis, a maximum transmissible acceleration (as described in Section 1.1.3.2 of this report) has to be specified with this value of acceleration at the incipient of displacement resulting in a factor of safety less than or equal to 1.0. Figure 5.5 allows for user input for either a single analysis or multiple analyses.

In a single analysis, the user has the option of providing the maximum transmissible acceleration ( $k_c$ ) and its units or the ratio of  $k_c$  and the peak acceleration ( $k_m$ ) as user input.

For multiple analyses, the maximum transmissible acceleration is given as a fraction of the peak acceleration. Multiple  $k_c/k_m$  values are necessary and the user has the option to add any values or accept the defaults (selected by the authors). The Multiple Analyses frame allows the user to modify the values by directly editing the existing 16 values; add additional values at the end of the list, delete and/or insert values.

The screenshot shows the 'Maximum Transmissible Acceleration' tab in the Newmark GUI. The window title is 'Newmark - F:\data\newmark\_gui2\Newmark\multi\_10sets\_ex2.nmk'. The 'Analysis Type' is set to 'Multiple Analyses'. The 'Maximum Transmissible Acceleration' tab is active, showing two main sections: 'Single Analysis' and 'Multiple Analyses'.

**Single Analysis:**

- ☒ **kc g**: A text box with '0' and a dropdown menu for 'Acceleration Units' set to 'cm/sec^2'.
- ☐ **kc/km**: A text box with '0' and a range indicator 'Range: [ 0.0 < (kc/km) < 1.0 ]'.

**Multiple Analyses:**

- Range: [ 0.0 < (kc/km) < 1.0 ]
- Table of kc/km values:

|   | kc/km values |
|---|--------------|
| 1 | .02          |
| 2 | .04          |
| 3 | .06          |
| 4 | .08          |
| 5 | .1           |
| 6 | .15          |
| 7 | .2           |
| 8 | .25          |
| 9 | .3           |

- Buttons: Add, Insert, Del.
- Enter Number of kc/km: 16

At the bottom, the 'Analysis Type' is confirmed as 'Multiple Analyses'.

Figure 5.5. **Maximum Transmissible Acceleration** tab for multiple analyses data entry.

### 5.2.5 The Selection of Time Histories (Multiple Analyses)

This section summarizes a simple way of including all or excluding some files previously selected in the **Multiple Horizontal Time-History Selections** tab (Figure 5.6) for an analysis. The acceleration time histories (i.e. the horizontal component 1 (H1) and horizontal component 2 (H2)) chosen will be used for user specified regression analyses and

displayed after the completion of the execution of Newmark in the **Analysis** tab.

**Newmark**

File Analysis Type

Introduction Multiple Horizontal Time History Selections Earthquake Time History Horiz. Comp. 1 Earthquake Time History Horiz. Comp. 2 Maximum Transmissible Acceleration **Selection of Time Histories** Analysis

**Selection of Time Histories for Plotting Purposes and Used in Regression Analyses**

View Earthquake Time History Set

Choose Set to View: 1

File (H1): N/A

File (H2): N/A

Global Select

All H1(+) H1(-) H2(+) H2(-) None

| Set ID | H1(+) | H1(-)                    | H2(+)                    | H2(-)                    |
|--------|-------|--------------------------|--------------------------|--------------------------|
| 1      | All   | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| 2      | All   | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| 3      | All   | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| 4      | All   | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| 5      | All   | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |

Analysis Type: Multiple Analyses

Figure 5.6. The **Selection of Time Histories** tab for data entry used for multiple analyses.

The first horizontal acceleration time-history set (i.e. H1 and H2) is displayed within the **View Earthquake Time-History Set** frame and each labeled by **File(H1):** and **File(H2):** for the respective horizontal components. If either component was not available there would be an **N/A** placed instead of the name of the file. There is also a **Choose Set to View**

entry/selection box with a default of 1 that allows the user to specify which set to list. This can be used to verify the files being used and is by no means a way of sorting the entire set of lists.

The earthquake time-history horizontal components **H1** and **H2** can further be evaluated by inverting the values of each horizontal component time-history. The reasoning for this is to determine whether the magnitudes of **H1** and/or **H2** have an effect on the resultant (permanent displacement) analysis. Therefore, a separate time-history was created that is the inverse of the original. Thus, **H1** is now **H1(+)**, with an **H1(-)** as its inverse. The same logic is applied for **H2**.

About the center of this tab, there is the **Global Select** frame which allows the user an easy way to select any of the possible four horizontal components in a vertical sense (i.e. the selection of the **H1(+)** button will mark all the **H1(+)** buttons listed vertically in the sub-frame directly below). This feature also applies for the **H1(-)**, **H2(+)**, **H2(-)** buttons.

There is an **All** button, which accepts all files, and a **None** button, which clears out the files previous selected and un-marks all of the buttons.

The sub-frame located beneath the **Global Select** frame is used for selecting time histories on a set-by-set basis. For set 1, the user can mark or unmark any of the 4 buttons, i.e., **H1(+)**, **H1(-)**, **H2(+)**, **H2(-)**. There is an **All** button which accepts all files in this set and a **None** button which un-marks all the buttons of the current set. The sliding bar to the right allows the user to view which sets are marked or unmarked.

### 5.2.6 Analysis results (Single Analysis or Multiple Analyses)

The Figure 5.7 **Analysis** tab can be divided into three sections: **Input Parameters**, **Run Newmark Analyzer** and **View Output**. The **Input Parameters** section allows the user to select the regression analysis type and also set the output units from an execution of Newmark. The **Run Newmark Analyzer** section is a button that will execute the Newmark program. The **View Output** section contains options for viewing the many outputs of the Newmark Analysis, including the **Regression Analysis** subsection that allows the user to view the data and the statistic parameters derived from a multiple analysis.

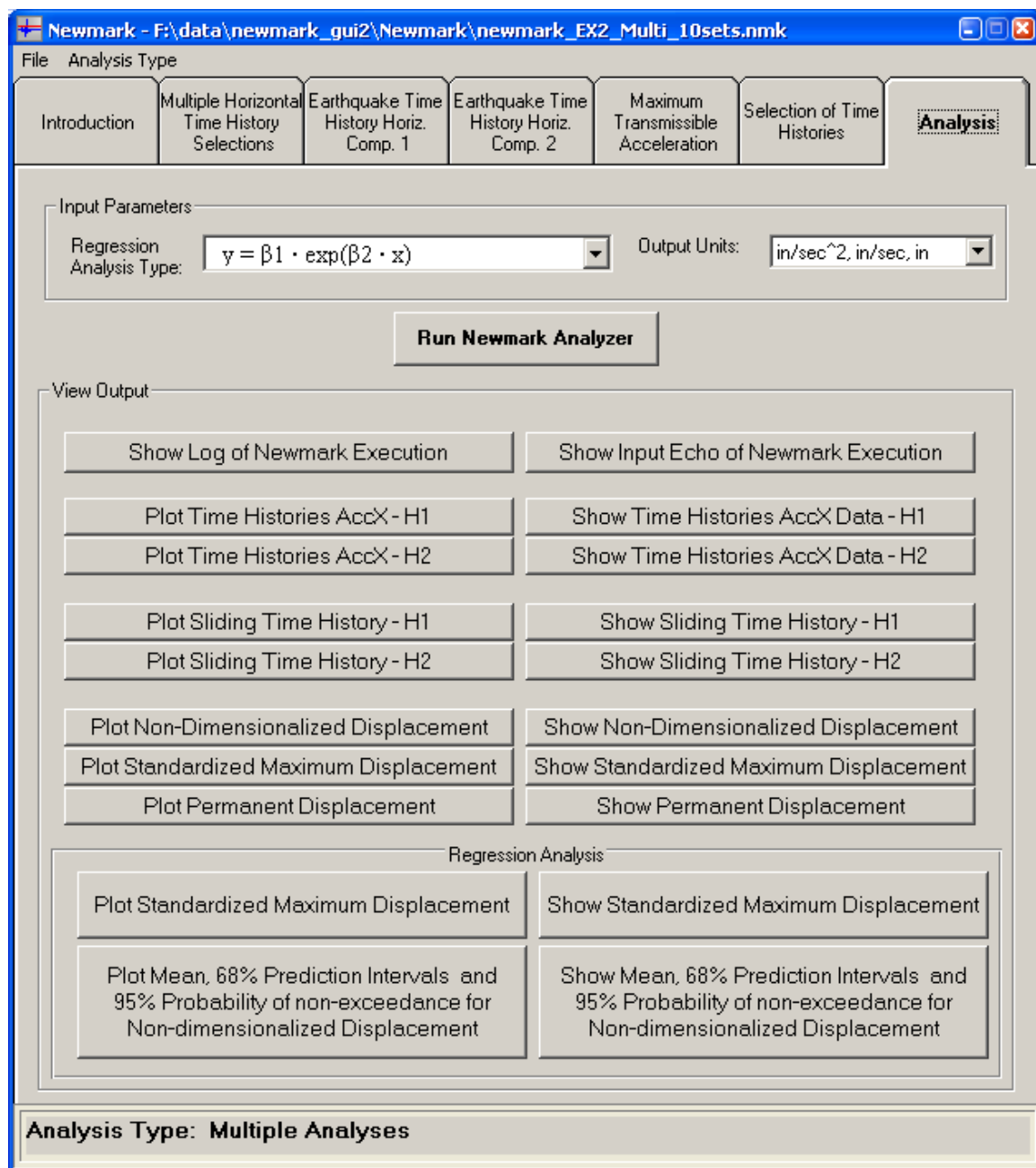


Figure 5.7. The **Analysis** tab used for all analyses.

In the **Input Parameters** frame of the **Analysis** tab, the user can select inputs from two combo boxes. The **Regression Analysis Type** combo box shows the option of no regression, performing regression analyses with three different forms of equations and the combinations of these equations.

Figure 5.8 shows a snapshot of the **Regression Analysis Type** combo box. Upon observation, Equation Form Type 2 (Chapter 3 - Table 3.1) is selected for the analysis. The second combo box in the **Input Parameters** frame is the Output Units box where the user has the option to select the resultant output units of the analysis.

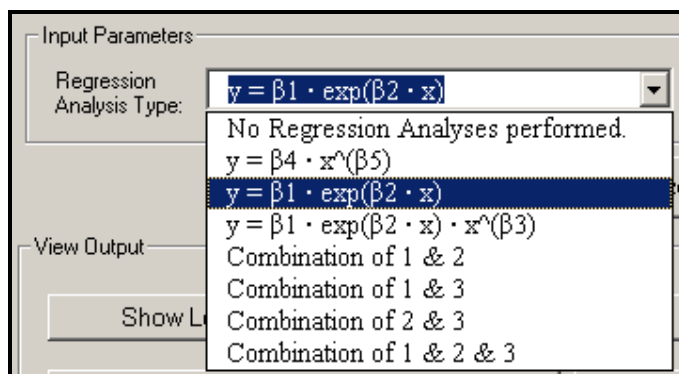


Figure 5.8. Single and combinations of three equations available for Regression Analyses.

Immediately prior to execution (or termination of an execution) of Newmark, it is a good idea to create a restart file containing all of the input information. This is accomplished by using the **File** drop-down menu with the save option which is located at the top left corner of the Newmark<sub>VM</sub>. The file created has an “nmk” extension. This file may also be read in by the Newmark<sub>VM</sub>, using this same file drop-down menu and will populate the same data contained within all tabs at a later point in time.

As soon as the **Run Newmark Analyzer** button is activated, a Newmark.in ASCII data input file, described in Appendix A, is created by the Newmark<sub>VM</sub> and the FORTRAN engineering program, Newmark, is executed. Newmark creates the output and plot data files that are used in the **View Output** frame of the **Analysis** tab (Figure 5.7). Appendix B lists and summarizes the contents of these output and plot data files. The ASCII data file created by Newmark<sub>VM</sub> becomes the input to FORTRAN Newmark.

A display will show (Figure 5.9) the stability analysis being performed by Newmark for each set of time histories. Note: A set of time histories represent two horizontal acceleration time histories, namely **H1** and **H2**. With each being represented as two separate calculations; namely; **H1(+)**, **H1(-)** and **H2(+)**, **H2(-)**. This process could take a minute or two, depending on the number of sets being evaluated (and the speed of the computer). Upon completion, the execution window disappears and a pop-up window waits for the user to select the OK button.

```

F:\data\newmark_gui2\Newmark\newmark.exe
Processing 4000 of 4995 time increments
Processing 4995 of 4995 time increments completed
4996 10.9826572414596 9.82823501162929
Processing 0 of 4995 time increments
Processing 1000 of 4995 time increments
Processing 2000 of 4995 time increments
Processing 3000 of 4995 time increments
Processing 4000 of 4995 time increments
Processing 4995 of 4995 time increments completed
4996 14.6435429886128 6.98413413116565
Processing 0 of 4995 time increments
Processing 1000 of 4995 time increments
Processing 2000 of 4995 time increments
Processing 3000 of 4995 time increments
Processing 4000 of 4995 time increments
Processing 4995 of 4995 time increments completed
4996 18.3044287357660 4.96039301379251
Processing 0 of 4995 time increments
Processing 1000 of 4995 time increments
Processing 2000 of 4995 time increments
Processing 3000 of 4995 time increments
Processing 4000 of 4995 time increments
Processing 4995 of 4995 time increments completed
4996 21.9653144829192 3.55179650737859

```

Figure 5.9. Illustrative example of Newmark during execution.

The focus now returns to the Analysis Tab and the View Output section. The user has many options available for viewing and evaluating the data by the selection of any particular button. There are logs of input and run-time data for the user to examine. The scaled horizontal time-history results of acceleration, velocity and displacement are readily available for inspection. A sliding block analysis with the given maximum transmissible acceleration will report the value of the cumulative (permanent) horizontal relative wall displacement. In the event where multiple sets were used in the analysis, another window will appear (Figure 5.10) to allow the user to view the output data pertaining to any set.

In a multiple analyses simulation, resultant non-dimensionalized, standardized if elected, and permanent displacement data for each time-history set will be available for evaluation. A similar form of Figure 5.10 will also be available for the viewing of these displacement results. Regression analyses can be performed when specified, with resultant data and statistical parameters available for assessment. Figure 5.11 shows a portion of the output data from an ASCII text file resulting from a regression analysis.

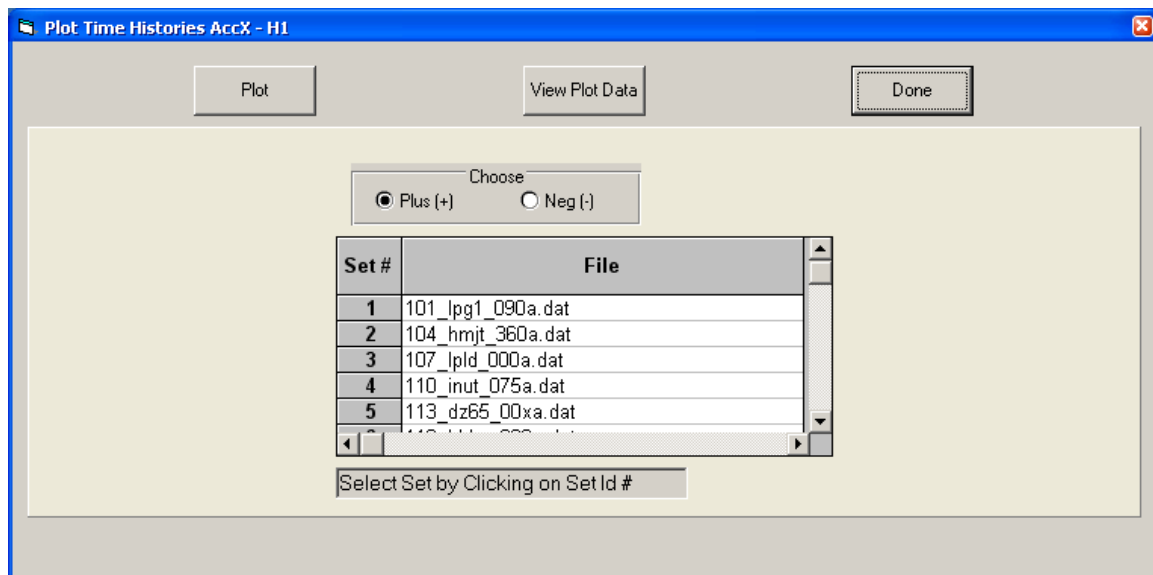


Figure 5.10. Resultant output data from multiple analyses.

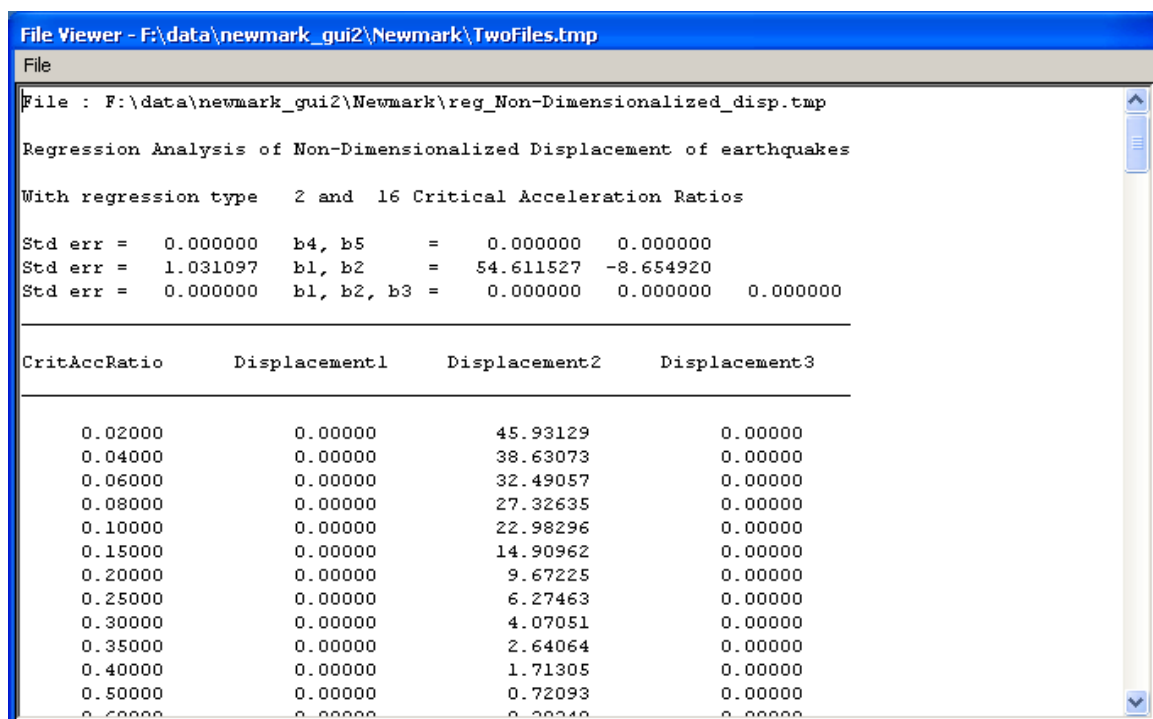


Figure 5.11. Resultant output data from a regression analysis.

### 5.3 Example 1 – Single Analysis or Sliding Block Analysis

In this first example, a single acceleration time-history is considered. The tabs that will be used for this example are described in Section 5.2.1. From the **File** pull-down menu, select **Open** and accept the file “single\_analysis\_kcg.nmk”. This particular horizontal earthquake time-history was recorded having a moment magnitude of 6.6. The next step is to decide on the maximum transmissible acceleration or critical acceleration used for this analysis. At the **Maximum Transmissible Acceleration** Tab, for a single analysis, select the **kc\_g** option and enter a value of 0.3 with the **Acceleration Units** as fractional G. Finally, in the **Analysis** tab (Figure 5.12), set the Output Units to values of inches. Run the analysis by selecting the **Run Newmark Analyzer**.

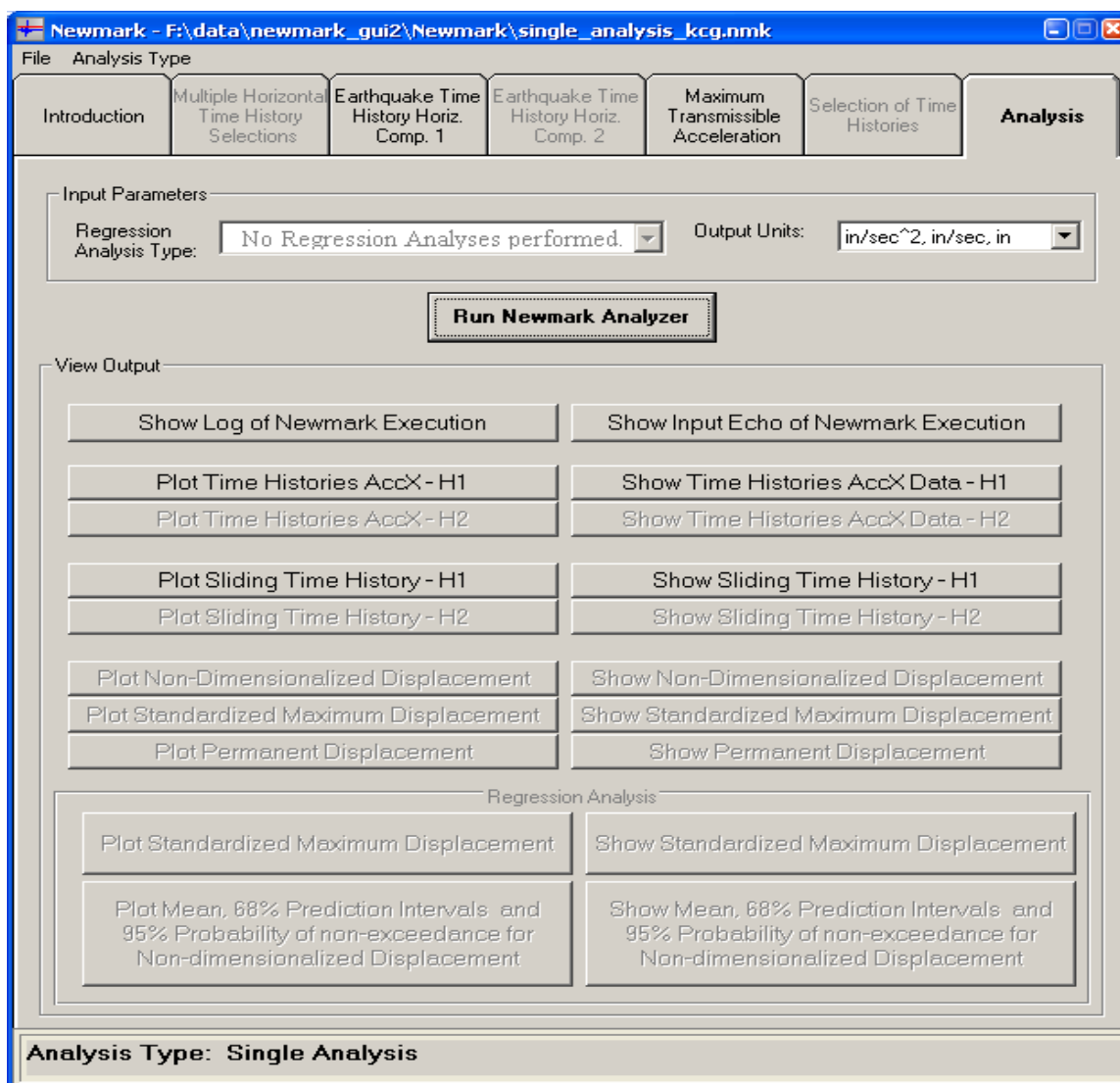


Figure 5.12. The **Analysis** tab for Example 1.

The results for the time-history permanent displacement analysis for this problem are shown in Figure 5.13. This figure is seen by activating the **Plot Sliding Time-History – H1** button on the **Analysis** tab. (Note the **Show Sliding Time-History – H1** button (or, equivalently, in the singlePLOTslideTH11.TMP1 ACSII output file) also reports the value for the cumulative (permanent) horizontal relative wall displacement). The first or upper figure is a plot of the horizontal acceleration time-history and the red line designates the maximum transmissible acceleration (or, equivalently, the yield acceleration) value of  $0.3\ g$ . Permanent structural displacements start to occur the first time the acceleration trace plots above this red line. Observe that permanent wall translation starts at about 3.8 seconds after initial shaking and concludes by about 5 seconds out of a total of 38 seconds of ground shaking. The cumulative permanent displacement of the structural block is about 1.625 inches, which occurs over about 3 significant relative (structural) velocity and displacement pulses (refer to the second and third figure down from the top, respectively).

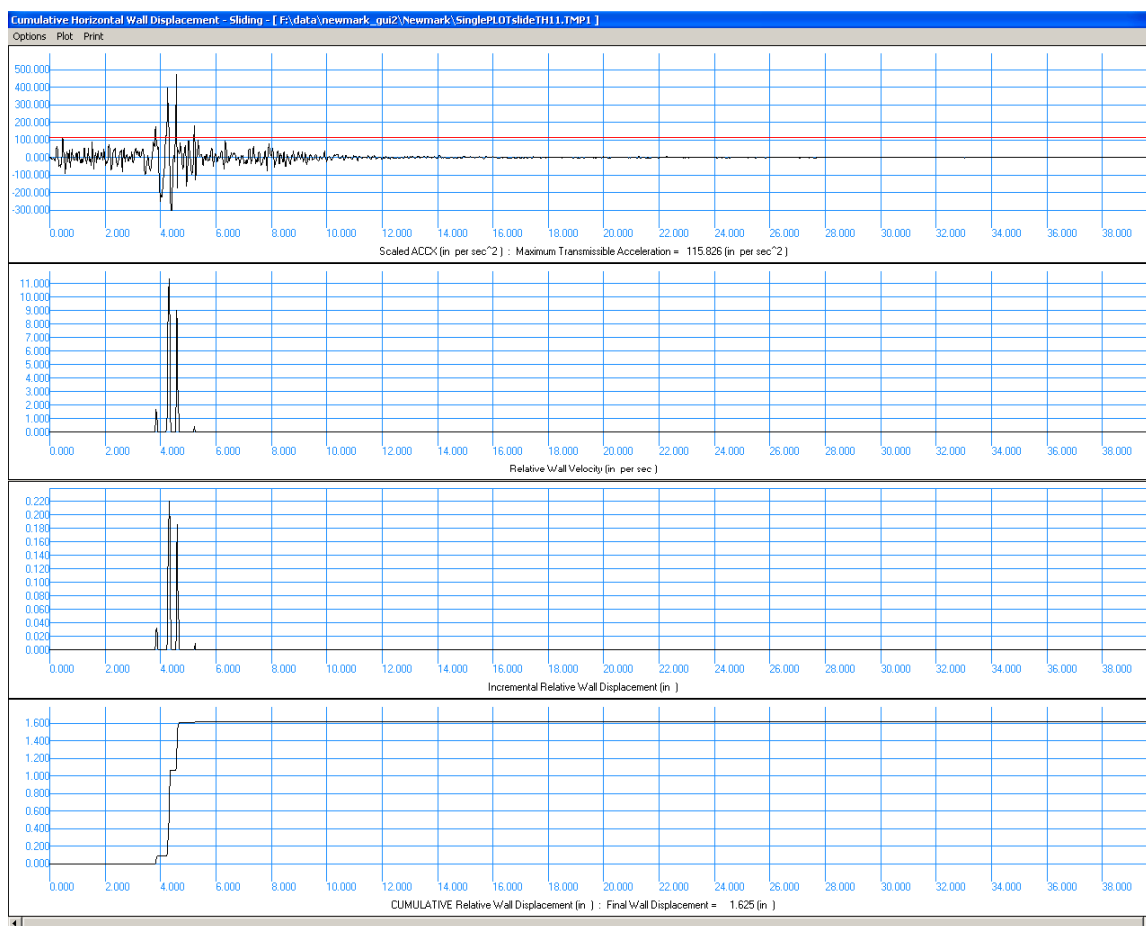


Figure 5.13. Sliding block time-history results for Example 1.

## 5.4 Example 2 – Multiple Analyses with Regression using Equation Form Two.

In this second example and with compactness in mind, a set of 10 pairs of baseline corrected acceleration time histories are considered. These sets of horizontal earthquake time histories were recorded on rock and for moment magnitudes in the 7 range.

Starting from the **File** pull-down menu, select **Open** and accept the file “multi\_10sets\_ex2.nmk”. From this input file, the user can browse through data within tabs two through four. Data entry and information regarding these tabs are listed within the multiple analyses segment of Section 5.2.1 and also in Sections 5.2.2 and 5.2.3. Please note that for this example, standardized displacement computations have not been requested.

The next step is to decide on the maximum transmissible acceleration or critical acceleration used for this analysis. From the **Maximum Transmissible Acceleration** tab and for multiple analyses, there are 16  $k_c/k_m$  values listed. These values are the default and will be used for this example. At the **Selection of Time Histories** tab, all of the various combinations will be included for this example.

In the **Analysis** tab, the regression form type two expression is the equation of choice and the output units will be in inches, as shown in Figure 5.14.

After this selection, run the analysis by selecting the **Run Newmark Analyzer**.

The results for the time-history permanent displacement analysis for this example 2 can be seen for each individually time-history or set, by activating the **Plot Sliding Time-History – H1** or **Plot Sliding Time-History – H2** button on the **Analysis** tab. (Note the **Show Sliding Time-History – H1** button (or, equivalently, in the output ASCII texts file as described in Appendix B) also reports the value for the cumulative (permanent) horizontal relative structural displacement).

An observation from viewing the output of the non-dimensionalized displacement of set 1, Figure 5.15, shows for this analysis that the **H2(-)** graph has the largest magnitude.

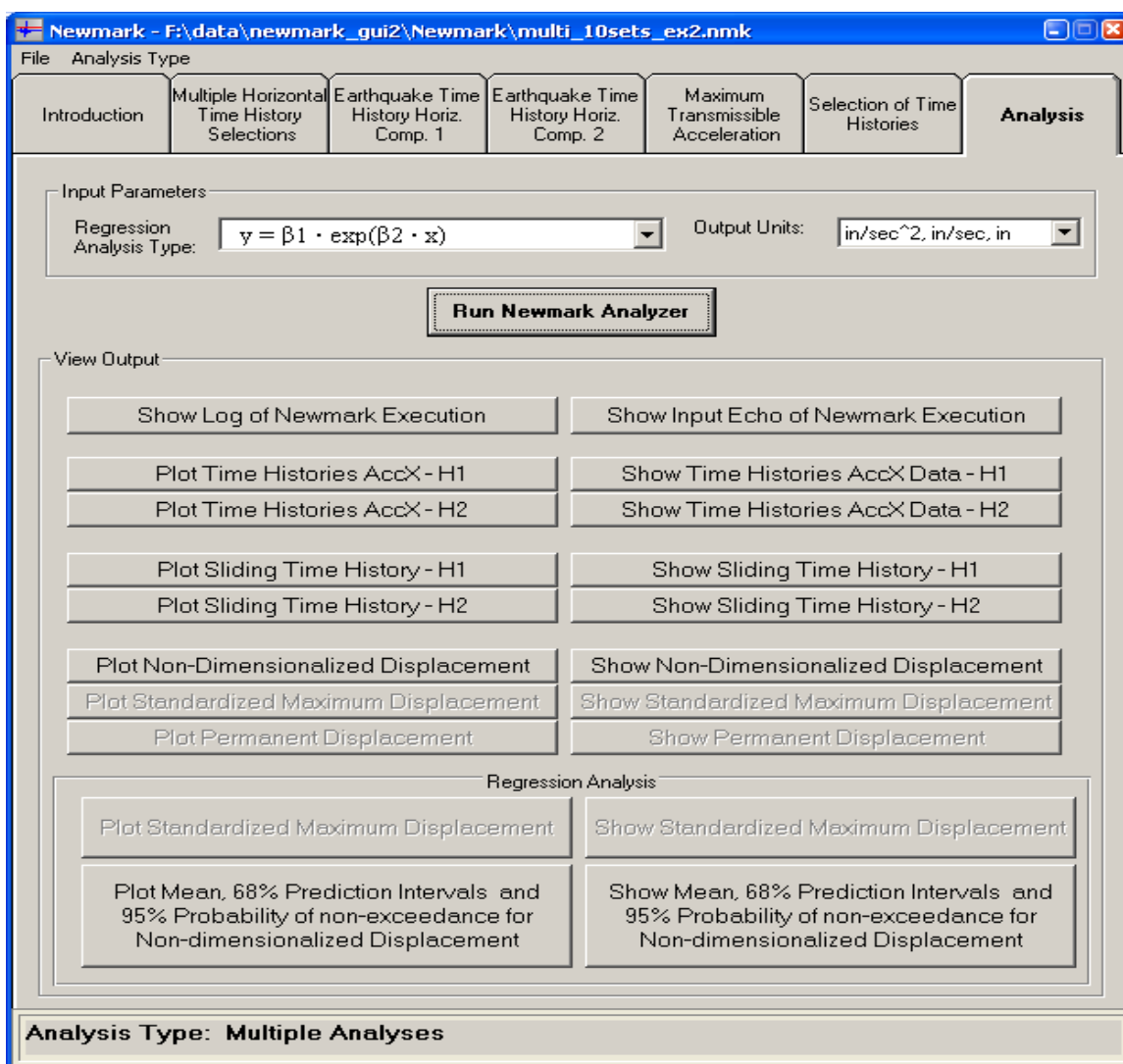


Figure 5.14. The **Analysis** tab for Example 2.

Upon inspection of the regression analysis for this example 2, Figure 5.16, shows that all of the data below a  $k_c/k_m$  value of 0.4 is contained below the curve representing the 95 percent probability of non-exceedance relationship. Some of the data greater than a  $k_c/k_m$  value of 0.4 does fall above the curve and lies above the 95 percent probability of non-exceedance relationship. An ideal data set would have a few data points falling above the 95 percent probability of non-exceedance relationship for all  $k_c/k_m$  data point values. This example illustrates the importance of including larger number of sets of horizontal time histories in order to more efficiently represent the data when performing a regression analysis. As a final note, observe the plotted data from the **Introduction** tab (Figure 5.1).

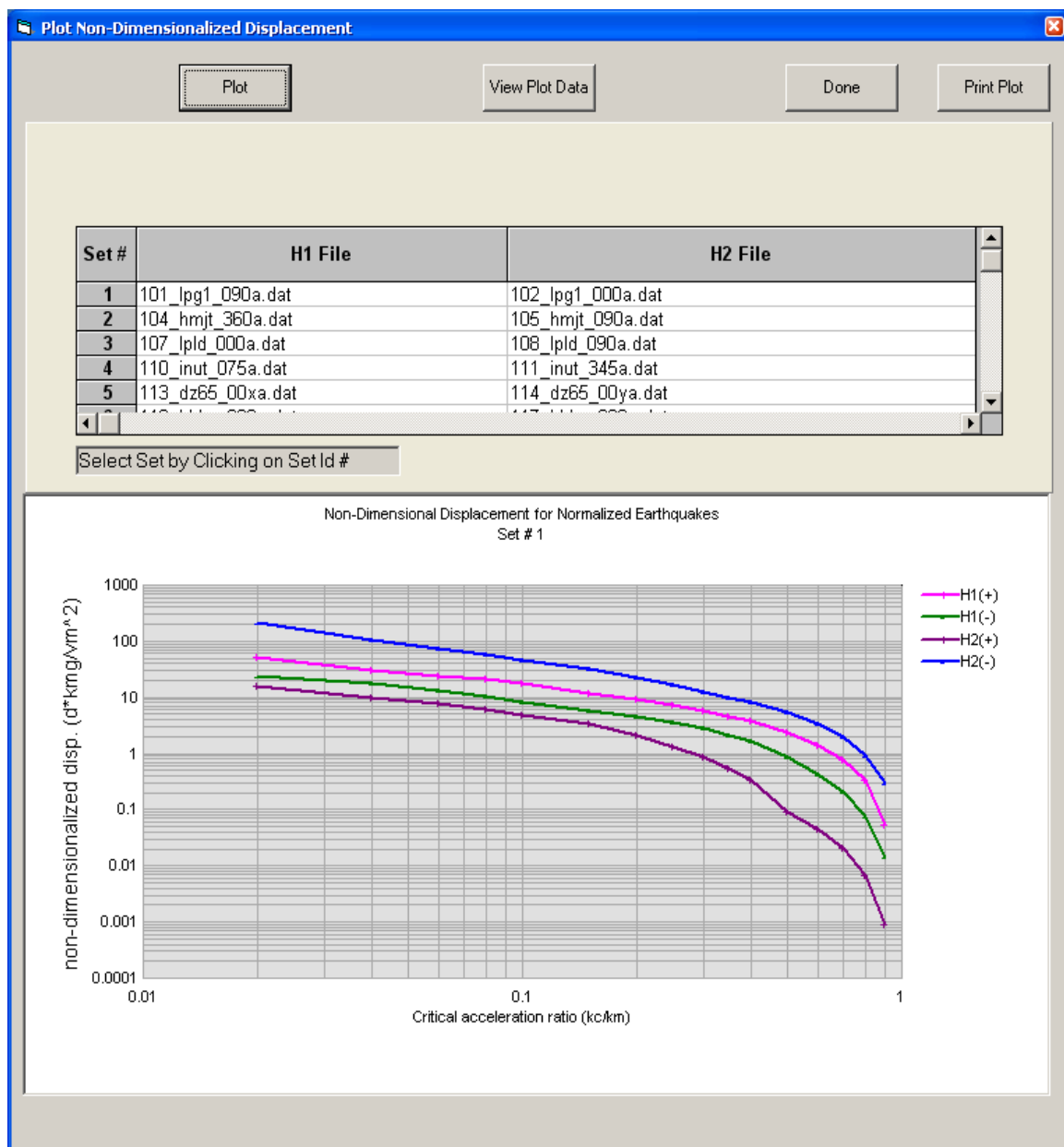


Figure 5.15. Non-dimensionalized earthquake displacements.

The authors of this report believe that the resultant plot from the regression analysis shows a reasonable data set base which results in reasonable statistical relationships for the 122 sets of horizontal earthquake time histories and over the entire range of  $k_c/k_m$  data point values.

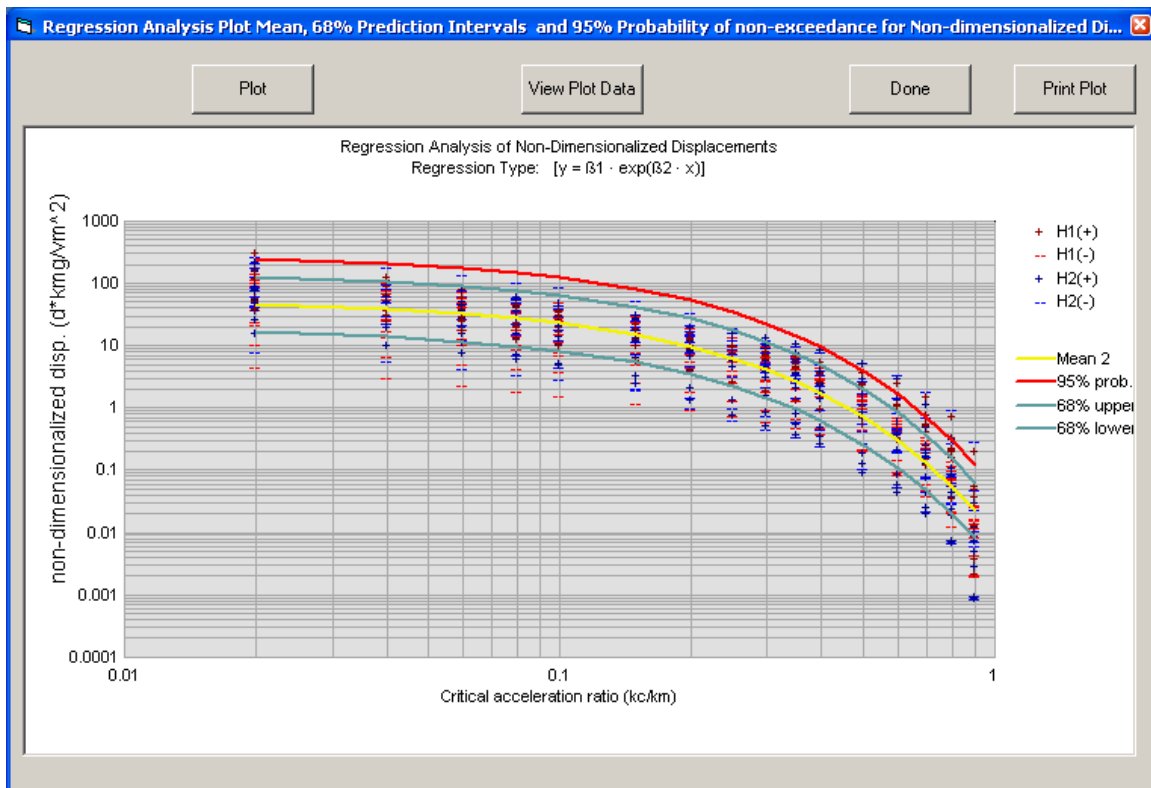


Figure 5.16. The mean, 68 percent prediction intervals and 95 percent probability of non-exceedance.

## 6 Conclusions and Recommendations

### 6.1 Introduction

This report describes the results of a series of numerical investigations using the PC-based software named Newmark that performs a permanent sliding block displacement analysis. The authors of this report note that baseline corrected acceleration time histories must be used in these permanent deformation analyses. Newmark can also perform regression analyses in order to develop up to three user selected forms of generalized equations of simplified permanent displacement relationships for sets of user defined acceleration time histories. In Chapter 4, a series of regression analyses were summarized for baseline corrected acceleration time histories recorded on rock for three earthquake moment magnitude  $M_w$  ranges of 4.85 to 6.06, 6.06 to 6.8, and 6.9 to 8.1, with average  $M_w$  values of 5.6, 6.5, and 7.3 for each of the three groups. An assessment discussed in Chapter 4 concluded that Equation Form Two, the two-term regression results for a form of equation that is linear in natural logarithm transformation, provides both the best fit to the (non-dimensionalized) permanent displacement data as well as the lowest order relationship without compromising accuracy. Lastly, as a special case established in Chapter 4, Equation Form Two regression results were evaluated for the entire 122 sets of baseline corrected acceleration time histories recorded on rock, without differentiation of  $M_w$  (group four). This chapter summarizes the probabilistic relationships derived from Equation Form Two of all four groups of earthquake magnitudes.

### 6.2 Ninety-five percent probability of non-exceedance

The next four subsections (6.2.1 – 6.2.4) report the 95 percent probability of non-exceedance relationships for each of the three magnitude groups with the last subsection, the fourth group, encompassing all three groups.

#### 6.2.1 Non-dimensionalized displacements of 23 sets of Moment Magnitude 7 group.

The regression analysis of the 23 sets of Magnitude 7 rock acceleration time histories resulted in the non-dimensionalized displacement for 95 percent probability of non-exceedance of

$$\frac{d_m \bullet k_m g}{v_m^2} = 70.1 \bullet \exp\left(-9.2 \bullet \frac{k_c}{k_m}\right) \bullet 4.64 \quad (\text{bis 4.14})$$

where:

- $d_m$  = permanent displacement
- $k_m g$  = peak (positive) rock acceleration expressed in units of length per sec<sup>2</sup>, consistent with units of  $d_m$  (length) and  $v_m$  (length per sec)
- $v_m$  = peak (positive) ground velocity of the earthquake
- $k_c$  = critical acceleration expressed as a fraction of  $g$
- $k_m$  = peak (positive) rock acceleration expressed as a fraction of  $g$ .

The corresponding 95 percent probability of non-exceedance permanent displacement relationship is

$$d_m = 325.4 \bullet \left[ \frac{v_m^2}{k_m \bullet g} \right] \bullet \exp\left(-9.2 \bullet \frac{k_c}{k_m}\right) \quad (6.1)$$

where the right-hand-side term  $k_m g$  is the peak (positive) rock acceleration expressed in units of length per sec<sup>2</sup>.

## 6.2.2 Non-dimensionalized displacements of 38 sets of Moment Magnitude 6 group

The regression analysis of the of the 38 sets of Magnitude 6 rock acceleration time histories resulted in the non-dimensionalized displacement for 95 percent probability of non-exceedance of

$$\frac{d_m \bullet k_m g}{v_m^2} = 78.6 \bullet \exp\left(-9.12 \bullet \frac{k_c}{k_m}\right) \bullet 3.68 \quad (\text{bis 4.41})$$

The corresponding 95 percent probability of non-exceedance permanent displacement relationship is

$$d_m = 289.5 \bullet \left[ \frac{v_m^2}{k_m \bullet g} \right] \bullet \exp\left(-9.12 \bullet \frac{k_c}{k_m}\right) \quad (6.2)$$

where the right-hand-side term  $k_m g$  is the peak (positive) rock acceleration expressed in units of length per sec<sup>2</sup>.

### 6.2.3 Non-dimensionalized displacements of 66 sets of Moment Magnitude 5 group

The regression analysis of the 61 sets of Magnitude 5 rock acceleration time histories resulted in the non-dimensionalized displacement for 95 percent probability of non-exceedance of

$$\frac{d_m \bullet k_m g}{v_m^2} = 57.0 \bullet \exp\left(-8.58 \bullet \frac{k_c}{k_m}\right) \bullet 3.39 \quad (\text{bis 4.68})$$

The corresponding 95 percent probability of non-exceedance permanent displacement relationship is

$$d_m = 193.2 \bullet \left[ \frac{v_m^2}{k_m \bullet g} \right] \bullet \exp\left(-8.58 \bullet \frac{k_c}{k_m}\right) \quad (6.3)$$

where the right-hand-side term  $k_m g$  is the peak (positive) rock acceleration expressed in units of length per sec<sup>2</sup>.

### 6.2.4 Non-dimensionalized displacements of 122 sets of Moment Magnitude 5 - 7 groups

The regression analysis of the 122 sets of all Magnitudes 5 - 7 of rock acceleration time histories resulted in the non-dimensionalized displacement for 95 percent probability of non-exceedance of

$$\frac{d_m \bullet k_m g}{v_m^2} = 65.44 \bullet \exp\left(-8.86 \bullet \frac{k_c}{k_m}\right) \bullet 3.75 \quad (\text{bis 4.87})$$

The corresponding 95 percent probability of non-exceedance permanent displacement relationship is

$$d_m = 245.4 \bullet \left[ \frac{v_m^2}{k_m \bullet g} \right] \bullet \exp\left(-8.86 \bullet \frac{k_c}{k_m}\right) \quad (6.4)$$

where the right-hand-side term  $k_m g$  is the peak (positive) rock acceleration expressed in units of length per sec<sup>2</sup>.

The non-dimensionalized displacement relationships for the four earthquake magnitude groups are shown in Figure 6.1, plotted as function of the critical acceleration ratio  $k_c/k_m$ , with their corresponding values summarized in Table 6.1. Figure 6.1 and Table 6.1 show the resulting (95 percent probability of non-exceedance) non-dimensionalized permanent displacements. The Magnitude 7 relationship lies above the Magnitude 6 relationship which, in turn, lies above the Magnitude 5 relationship. The Magnitude 5 – 7 earthquake group of 122 rock ground motion sets falls above the Magnitude 5 relationship and below the Magnitude 6 relationship; this is possibly due to the fact that more than half of the data set resides within the Magnitude 5 relationship.

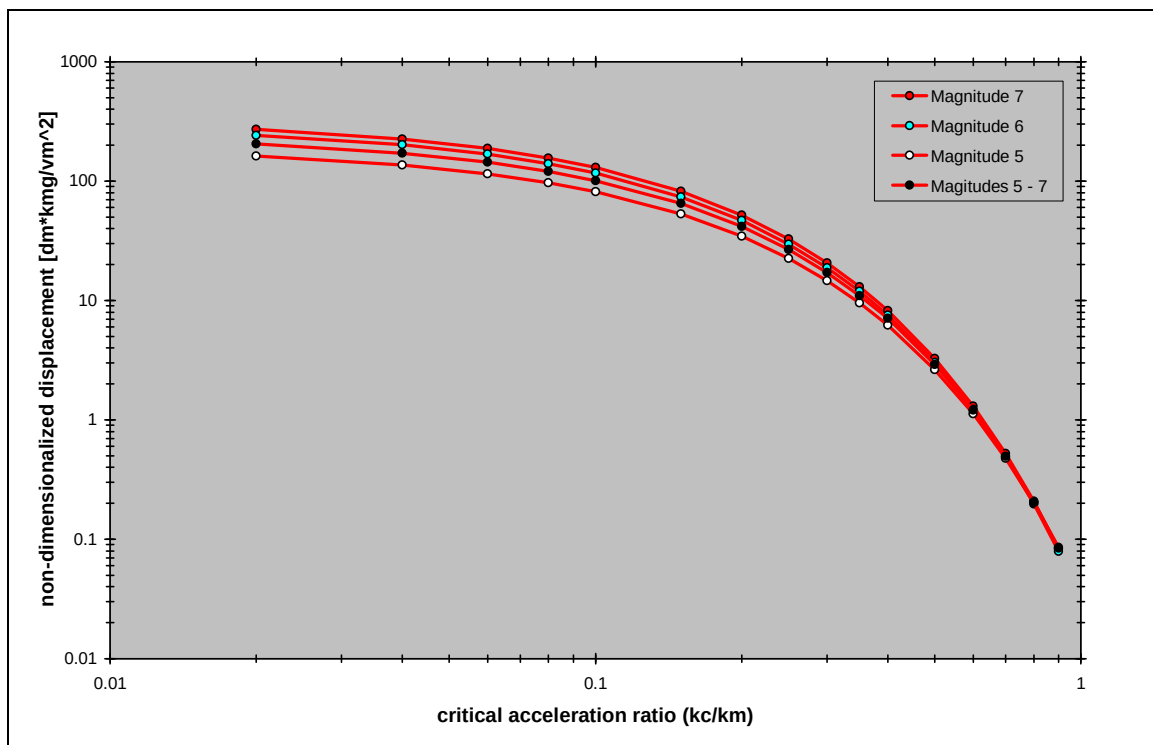


Figure 6.1. 95 percent probability of non-exceedance relationships of non-dimensionalized displacements of four magnitude groups.

Table 6.1. 95 percent probability percent of non-exceedance relationships of non-dimensionalized displacements of four magnitude groups.

| $\frac{k_c}{k_m}$ | Magnitude 5 | Magnitude 6 | Magnitude 7 | Magnitude 5 - 7 |
|-------------------|-------------|-------------|-------------|-----------------|
| 0.02              | 162.2120    | 242.0580    | 271.6762    | 205.30615       |
| 0.04              | 136.6378    | 201.6964    | 226.0193    | 171.95999       |
| 0.06              | 115.0956    | 168.0649    | 188.0354    | 144.02997       |
| 0.08              | 96.9498     | 140.0412    | 156.4349    | 120.63639       |
| 0.1               | 81.6648     | 116.6902    | 130.1450    | 101.04243       |
| 0.15              | 53.1807     | 73.9574     | 82.1604     | 64.87351        |
| 0.2               | 34.6317     | 46.8736     | 51.8678     | 41.65154        |
| 0.25              | 22.5525     | 29.7081     | 32.7441     | 26.74205        |
| 0.3               | 14.6863     | 18.8288     | 20.6713     | 17.16953        |
| 0.35              | 9.5639      | 11.9335     | 13.0498     | 11.02356        |
| 0.4               | 6.2281      | 7.5634      | 8.2383      | 7.07759         |
| 0.5               | 2.6412      | 3.0382      | 3.2833      | 2.91751         |
| 0.6               | 1.1200      | 1.2204      | 1.3085      | 1.20265         |
| 0.7               | 0.4750      | 0.4902      | 0.5215      | 0.49576         |
| 0.8               | 0.2014      | 0.1969      | 0.2078      | 0.05456         |
| 0.9               | 0.0854      | 0.0791      | 0.0828      | 0.02249         |

## 6.3 Mean relationships

The next four subsections (6.3.1 – 6.3.4) report the mean relationships for each of the three magnitude groups with the last subsection, the fourth group, encompassing all three groups.

### 6.3.1 Non-dimensionalized displacements of 23 sets of Moment Magnitude group 7

The regression analysis of the 23 sets of Magnitude 7 rock acceleration time histories resulted in the mean non-dimensionalized displacement relationship of

$$\frac{d_m \bullet k_m g}{v_m^2} = 70.1 \bullet \exp \left( -9.2 \bullet \frac{k_c}{k_m} \right) \quad (\text{bis 4.11})$$

where:

- $d_m$  = permanent displacement
- $k_m g$  = peak (positive) rock acceleration expressed in units of length per sec<sup>2</sup>, consistent with units of  $d_m$  (length) and  $v_m$  (length per sec)
- $v_m$  = peak (positive) ground velocity of the earthquake
- $k_c$  = critical acceleration expressed as a fraction of  $g$
- $k_m$  = peak (positive) rock acceleration expressed as a fraction of  $g$ .

The corresponding mean permanent displacement relationship is

$$d_m = 70.1 \bullet \left[ \frac{v_m^2}{k_m \bullet g} \right] \bullet \exp \left( -9.2 \bullet \frac{k_c}{k_m} \right) \quad (6.5)$$

where the right-hand-side term  $k_m g$  is the peak (positive) rock acceleration expressed in units of length per sec<sup>2</sup>.

### 6.3.2 Non-dimensionalized displacements of 38 sets of Moment Magnitude group 6

The regression analysis of the of the 38 sets of Magnitude 6 rock acceleration time histories resulted in the mean non-dimensionalized displacement relationship of

$$\frac{d_m \bullet k_m g}{v_m^2} = 78.6 \bullet \exp \left( -9.12 \bullet \frac{k_c}{k_m} \right) \quad (\text{bis 4.38})$$

The corresponding mean permanent displacement relationship is

$$d_m = 78.6 \bullet \left[ \frac{v_m^2}{k_m \bullet g} \right] \bullet \exp \left( -9.12 \bullet \frac{k_c}{k_m} \right) \quad (6.6)$$

where the right-hand-side term  $k_m g$  is the peak (positive) rock acceleration expressed in units of length per sec<sup>2</sup>.

### 6.3.3 Non-dimensionalized displacements of 66 sets of Moment Magnitude group 5

The regression analysis of the 61 sets of Magnitude 5 rock acceleration time histories resulted in the mean non-dimensionalized displacement relationship of

$$\frac{d_m \bullet k_m g}{v_m^2} = 57.0 \bullet \exp\left(-8.58 \bullet \frac{k_c}{k_m}\right) \quad (\text{bis 4.65})$$

The corresponding mean permanent displacement relationship is

$$d_m = 57.0 \bullet \left[ \frac{v_m^2}{k_m \bullet g} \right] \bullet \exp\left(-8.58 \bullet \frac{k_c}{k_m}\right) \quad (6.7)$$

where the right-hand-side term  $k_m g$  is the peak (positive) rock acceleration expressed in units of length per sec<sup>2</sup>.

### 6.3.4 Non-dimensionalized displacements of 122 sets of Moment Magnitude 5 – 7 groups

The regression analysis of the 122 sets of Magnitude 5 - 7 rock acceleration time histories resulted in the mean non-dimensionalized displacement relationship of

$$\frac{d_m \bullet k_m g}{v_m^2} = 65.44 \bullet \exp\left(-8.86 \bullet \frac{k_c}{k_m}\right) \quad (\text{bis 4.83})$$

The corresponding mean permanent displacement relationship is

$$d_m = 65.44 \bullet \left[ \frac{v_m^2}{k_m \bullet g} \right] \bullet \exp\left(-8.86 \bullet \frac{k_c}{k_m}\right) \quad (6.8)$$

where the right-hand-side term  $k_m g$  is the peak (positive) rock acceleration expressed in units of length per sec<sup>2</sup>.

The non-dimensionalized displacement relationships for the four earthquake magnitude groups are shown in Figure 6.2, plotted as functions of the critical acceleration ratio  $k_c/k_m$ , with their corresponding values summarized in Table 6.2. The data contained in the table and the figure show the Magnitude 6 non-dimensionalized permanent displacement mean relationship to be greater than that for the Magnitude 5 relationship. However, the relationship for the Magnitude 7 relationship falls between the Magnitude 5 and 6 relationships. The authors of this report speculate that this may possibly be due to the smaller acceleration time-history data set used in the regression analysis for the Magnitude 7 earthquake group (23 sets) compared to the larger data sets used in the regression analyses for both the Magnitude 5 and 6 earthquake groups (61 sets and 38 sets, respectively). The Magnitude 5 – 7 earthquake group fits between these three groups.

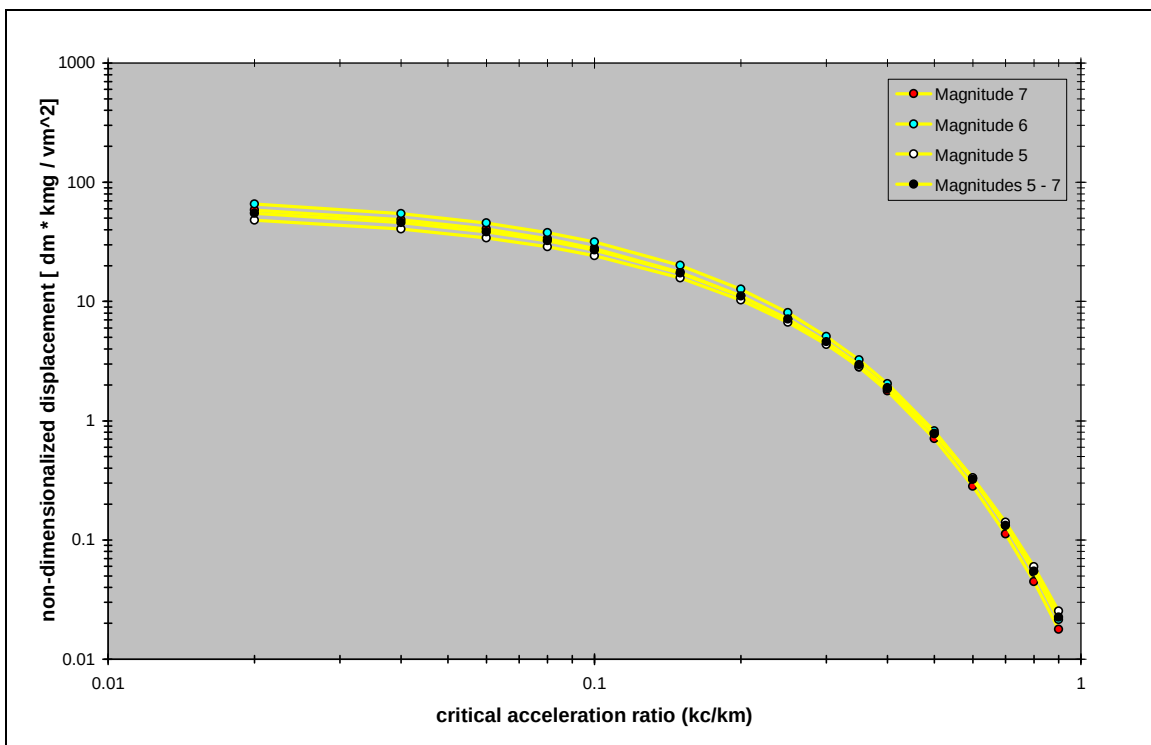


Figure 6.2. Mean relationships of non-dimensionalized displacements of all four magnitude groups.

Table 6.2. Mean relationships of non-dimensionalized displacements of all four magnitude groups.

| $\frac{k_c}{k_m}$ | Magnitude 5 | Magnitude 6 | Magnitude 7 | Magnitude 5 - 7 |
|-------------------|-------------|-------------|-------------|-----------------|
| 0.02              | 47.9965     | 65.5091     | 58.3576     | 54.81028        |
| 0.04              | 40.4294     | 54.5859     | 48.5502     | 45.9079         |
| 0.06              | 34.0554     | 45.4841     | 40.3911     | 38.45147        |
| 0.08              | 28.6862     | 37.8999     | 33.6031     | 32.20612        |
| 0.1               | 24.1636     | 31.5803     | 27.9559     | 26.97515        |
| 0.15              | 15.7355     | 20.0154     | 17.6485     | 17.31918        |
| 0.2               | 10.2471     | 12.6856     | 11.1415     | 11.11965        |
| 0.25              | 6.6730      | 8.0400      | 7.0336      | 7.13929         |
| 0.3               | 4.3455      | 5.0957      | 4.4403      | 4.58372         |
| 0.35              | 2.8298      | 3.2296      | 2.8032      | 2.94294         |
| 0.4               | 1.8428      | 2.0469      | 1.7696      | 1.88949         |
| 0.5               | 0.7815      | 0.8222      | 0.7053      | 0.77888         |
| 0.6               | 0.3314      | 0.3303      | 0.2811      | 0.32107         |
| 0.7               | 0.1405      | 0.1327      | 0.1120      | 0.13235         |
| 0.8               | 0.0596      | 0.0533      | 0.0446      | 0.05456         |
| 0.9               | 0.0253      | 0.0214      | 0.0178      | 0.02249         |

## 6.4 Recommendations

As mentioned previously, the resultant mean non-dimensionalized displacement relationships of both Magnitude 5 and Magnitude 6 earthquake groups showed reasonable results. However, there was a noticeable magnitude influence in the Magnitude 7 earthquake group on the mean relationship. It is speculated that this may be due to an incomplete/limited data set of only 23 sets of baseline corrected acceleration time histories. Recall that there were 38 sets of Magnitude 6 and 61 sets of Magnitude 5 rock acceleration time histories used in this study. A recommendation would be the addition of supplemental data sets of the Magnitude 7 earthquake group as recorded rock acceleration time histories become available in the future with a repeat of the regression analysis for the Magnitude range 7 events.

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## **Appendix A: Listing and Description of the Newmark ASCII Input Data File (file name: Newmark.in)**

### **A.1 Introduction**

This appendix lists and describes the contents of the ASCII input data file to the FORTRAN engineering computer program portion of Newmark. This input data file, always designated as Newmark.in, is created by the graphical user interface (GUI), the visual modeler portion of Newmark. The FORTRAN code of Newmark evolved from CorpsWallRotate\_Wet (Ebeling et al. 2007)<sup>1</sup> which encompasses similar engineering concepts and computations.

The ASCII input data to Newmark is provided in 6 groups of data. They are as follows:

### **A.2 Group 1 – Designate the type of Newmark Analysis**

#### **KEY\_NEWMARK\_Analysis**

with

- KEY\_NEWMARK\_Analysis = 1, Single Newmark analysis using one horizontal acceleration time-history.
- = 2, Multiple Newmark time history analyses using multiple acceleration time histories are required.

### **A.3 Group 2 – Designate global parameters and horizontal components with the input listed in two parts**

*<sup>1</sup>Note: Part 1 will be skipped for a single Newmark analysis (KEY\_NEWMARK\_Analysis = 1)*

#### **Part 1: Key\_GlobalAccVel**

---

<sup>1</sup> All references cited in this appendix are included in the Reference section at the end of the main text.

### **Spga, SpgaUnits, Spgv, SpgvUnits**

with

Key\_GlobalAccVel = 0, No Standardized displacement computations performed.

= 1, Standardized displacement computations performed.

and

Spga = the global peak ground acceleration used for normalizing all the horizontal acceleration time-history sets of data.

SpgaUnits = identifies the units of Spga.

| Value for SpgaUnits | Units Acceleration   |
|---------------------|----------------------|
| 32.174              | ft/sec <sup>2</sup>  |
| 386.086             | in./sec <sup>2</sup> |
| 9.80665             | m/sec <sup>2</sup>   |
| 980.665             | cm/sec <sup>2</sup>  |
| 9806.65             | mm/sec <sup>2</sup>  |
| 1.0                 | g's                  |
| 980.665             | gal's                |

Spgv = the global peak ground velocity used for normalizing the peak ground velocity.

SpgvUnits = identifies the units of the Spgv global velocity value.

| Value for SpgvUnits | Units Velocity |
|---------------------|----------------|
| 32.174              | ft/sec         |
| 386.086             | in./sec        |
| 9.80665             | m/sec          |
| 980.665             | cm/sec         |
| 9806.65             | mm/sec         |

*Note: Second Row of Part 1 data will not be read when no standardized displacement computations are to be performed. (Key\_GlobalAccVel = 0)*

**Part 2: TH\_State, Nset, H1set, H2set**

with

|          |                                                           |
|----------|-----------------------------------------------------------|
| TH_State | = 1, time-history for horizontal component 1.             |
|          | = 2, time-history for horizontal component 2.             |
|          | = 3, both time-histories for horizontal components 1 & 2. |
|          | Always used for multiple time-history analyses.           |
| Nset     | = the overall number of sets of horizontal components     |
| H1set    | = the number of sets available for horizontal component 1 |
| H2set    | = the number of sets available for horizontal component 2 |

Depending on the value of TH\_State, the following input will either have one or two filenames.

#### **A.4 Group 3 –Time-history information with input listed in two parts**

**Part 1: Acceleration time-history parameters and data for horizontal component 1**

*Note: For TH\_State=2, the time-history information will be specified for horizontal component 2 and Part 2 will be omitted.*

The data given in the following two sections list the acceleration time-history file[s] and summarize the parameters used to characterize each

acceleration time-history. The horizontal component[s] evaluated will be dependent on the values of TH\_State and Nset of information.

### **Section 1: SetId, DT, GACC, Xscale, NheaderLines, NvalsPerLine, DataFmt**

#### **H1\_TimehistoryFile**

with

- SetId = the index of Nset (i.e., 1, 2, ... to Nset, sequentially).
- DT = the time step in seconds.
- GACC = the constant of acceleration due to gravity. The value for GACC identifies the units of acceleration, velocity and intrinsic displacement according to following tabulation.

| Value for GACC | Units of Acceleration | Units of Velocity | Units of Intrinsic Displacement |
|----------------|-----------------------|-------------------|---------------------------------|
| 32.174         | ft/sec <sup>2</sup>   | ft/sec            | feet                            |
| 386.086        | in./sec <sup>2</sup>  | in./sec           | inches                          |
| 9.80665        | m/sec <sup>2</sup>    | m/sec             | meters                          |
| 980.665        | cm/sec <sup>2</sup>   | cm/sec            | centimeters                     |
| 9806.65        | mm/sec <sup>2</sup>   | mm/sec            | millimeters                     |
| 32.174         | ft/sec <sup>2</sup>   | ft/sec            | feet                            |

- Xscale = the scale factor applied to the horizontal acceleration time history (negative value when time-history is inverted).
- NheaderLines = number of header lines within the H1\_TimehistoryFile.

NvalsPerLine = number of horizontal acceleration time-history values per line within the H1\_TimehistoryFile.

DataFmt = 0, free format, the horizontal acceleration time history values are delimited by either a comma or space[s].

= 1, fixed format, the horizontal acceleration time history values are expressed as 8 characters per value (F8.).

= 2, fixed format, the horizontal acceleration time history values are expressed as 9 characters per value (F9.).

and

H1\_TimehistoryFile = name of file containing the horizontal acceleration time-history data.  
(Complete path to file is required.)

#### Contents of H1\_TimehistoryFile

### Section 2: ACCX (I = 1 to NOACC)

with

ACCX = Horizontal acceleration time-history data at every DT. Data is located within the H1\_TimehistoryFile.

## Part 2: Acceleration time-history parameters and data for horizontal component 2 (Not included for single time-history analysis)

The data given in the following two sections list the acceleration time-history file[s] and summarize the parameters used to characterize each acceleration time-history. The horizontal component[s] evaluated will be dependent on the value of TH\_State and Nset of information.

### Section 1: SetId, DT, GACC, Xscale, NheaderLines, NvalsPerLine, DataFmt

#### H2\_TimehistoryFile

with

- SetId = the index of Nset. (i.e., 1, 2, ... to Nset, sequentially).
- DT = the time step in seconds.
- GACC = the constant of acceleration due to gravity. The value for GACC identifies the units of acceleration, velocity and intrinsic displacement according to the following tabulation.

| Value for GACC | Units of Acceleration | Units of Velocity | Units of Intrinsic Displacement |
|----------------|-----------------------|-------------------|---------------------------------|
| 32.174         | ft/sec <sup>2</sup>   | ft/sec            | feet                            |
| 386.086        | in./sec <sup>2</sup>  | in./sec           | inches                          |
| 9.80665        | m/sec <sup>2</sup>    | m/sec             | meters                          |
| 980.665        | cm/sec <sup>2</sup>   | cm/sec            | centimeters                     |
| 9806.65        | mm/sec <sup>2</sup>   | mm/sec            | millimeters                     |
| 32.174         | ft/sec <sup>2</sup>   | ft/sec            | feet                            |

- Xscale = the scale factor applied to the horizontal acceleration time history

(negative value when time-history is inverted).

- NheaderLines = number of header lines within the H2\_TimehistoryFile.
- NvalsPerLine = number of horizontal acceleration values per line within the H2\_TimehistoryFile.
- DataFmt = 0, free format, the horizontal acceleration time-history values are delimited by either a comma or space[s].
- = 1, fixed format, the horizontal acceleration time-history values are expressed as 8 characters per value (F8.).
- = 2, fixed format, the horizontal acceleration time-history values are expressed as 9 characters per value (F9.).

and

- H2\_TimehistoryFile = name of file containing the horizontal acceleration time-history data.  
(Complete path to file is required.)

#### Contents of H2\_TimehistoryFile

### Section 2: ACCX (I = 1 to NOACC)

with

- ACCX = Horizontal acceleration time-history data at every DT. Data is located within the H2\_TimehistoryFile.

*Note: Values for the horizontal accelerations used in NEWMARK are equal to ACCX(I) times XSCALE times GACC.*

## A.5 Group 4 – Regression Analysis for multiple acceleration time histories with input listed in two parts

*Note: For a single Newmark analysis (KEY\_NEWMARK\_Analysis = 1) there will be no regression analysis: Group 4 will be skipped.*

### Part 1: KEY\_REGRESSION

with

- |                |                                                                                                                |
|----------------|----------------------------------------------------------------------------------------------------------------|
| KEY_REGRESSION | = 0, No Regression Analyses performed.<br>(Default)                                                            |
|                | = 1, Common Log transformation for<br>estimation of two parameters ( $\beta_4$ , $\beta_5$ )                   |
|                | = 2, Natural Log transformation for<br>estimation of two parameters ( $\beta_1$ , $\beta_2$ )                  |
|                | = 3, Natural Log transformation for<br>estimation of three parameters ( $\beta_1$ , $\beta_2$ ,<br>$\beta_3$ ) |
|                | = 4, combination of KEY_REGRESSION<br>1 & 2                                                                    |
|                | = 5, combination of KEY_REGRESSION<br>1 & 3                                                                    |
|                | = 6, combination of KEY_REGRESSION<br>2 & 3                                                                    |
|                | = 7, combination of KEY_REGRESSION<br>1 & 2 & 3                                                                |

**Part 2: SetId, KeyH1p, KeyH1n, KeyH2p, KeyH2n (lines of input from SetId = 1 to Nset)**

with

SetId = the index of Nset. (i.e., 1, 2, ... to Nset, sequentially).

KeyH1p = 0, No regression required.

= 1, Regression analysis of horizontal component 1 on the positive side for SetId.

KeyH1n = 0, No regression required

= 1, Regression analysis of horizontal component 1 on the negative side for SetId.

KeyH2p = 0, No regression required

= 1, Regression analysis of horizontal component 2 on the positive side for SetId.

KeyH2n = 0, No regression required

= 1, Regression analysis of horizontal component 2 on the negative side for SetId.

*Note: Part 2 data will not be read when there is no regression analysis.  
(KEY\_REGRESSION=0)*

**A.6 Group 5 – The classification and value[s] of the Maximum Transmissible Acceleration provide input in two parts, with part 2 only valid for Crit\_Acc\_State = 2.**

**Part 1: Crit\_Acc\_State, Crit\_Acc\_Units, Crit\_Acc\_Value**

with

Crit\_Acc\_State = 1, value of  $(k_c g)$ , the maximum transmissible acceleration

with

Crit\_Acc\_Units = identifies the units of the maximum transmissible acceleration  $(k_c g)$  or input variable Crit\_Acc\_Value.

| Value for Crit_Acc_Units | Units Acceleration   |
|--------------------------|----------------------|
| 32.174                   | ft/sec <sup>2</sup>  |
| 386.086                  | in./sec <sup>2</sup> |
| 9.80665                  | m/sec <sup>2</sup>   |
| 980.665                  | cm/sec <sup>2</sup>  |
| 9806.65                  | mm/sec <sup>2</sup>  |
| 1.0                      | g's                  |
| 980.665                  | gal's                |

and

Crit\_Acc\_Value =  $k_c g$ , the maximum transmissible acceleration.

or

Crit\_Acc\_State = 2, value[s] of  $\left(\frac{k_c}{k_m}\right)$ , the ratio of the maximum transmissible acceleration value for the retaining wall  $(k_c g)$  and the peak ground acceleration  $(k_m g)$ .

with

Crit\_Acc\_Units = 1.0, (Not Used)

and

Crit\_Acc\_Value = 1.0, One  $\frac{k_c}{k_m}$  value, for single Newmark analysis.

> 1.0, Number of  $\frac{k_c}{k_m}$  values

Experience by the authors suggests a minimum of 15 well spaced values (as judged by natural logarithm plotting requirements) are needed to conduct meaningful regression analyses as well as producing useful graphs of permanent earthquake displacements.

## **Part 2: Crit\_Acc\_Ratio (I = 1 to Crit\_Acc\_Value)**

with

Crit\_Acc\_Ratio = value[s] of  $\frac{k_c}{k_m}$

For valid values between  $0 < \frac{k_c}{k_m} < 1$ , and in ascending order, the authors recommend the following,

| Values for<br>Crit_Acc_Ratio |
|------------------------------|
| 0.02                         |
| 0.04                         |
| 0.06                         |
| 0.08                         |
| 0.1                          |
| 0.15                         |
| 0.2                          |

|      |
|------|
| 0.25 |
| 0.3  |
| 0.35 |
| 0.4  |
| 0.5  |
| 0.6  |
| 0.7  |
| 0.8  |
| 0.9  |

### A.7 Group 6 – Designate the output units for computed displacements.

#### DISPACC

with

DISPACC = identifies the units of the scaled acceleration, computed velocity and computed displacements according to the following tabulation in a Complete Time-History Analysis.

| Value for DISPACC | Units of Acceleration | Units of Velocity | Units of Displacement |
|-------------------|-----------------------|-------------------|-----------------------|
| 32.174            | ft/sec <sup>2</sup>   | ft/sec            | feet                  |
| 386.086           | in./sec <sup>2</sup>  | in./sec           | inches                |
| 9.80665           | m/sec <sup>2</sup>    | m/sec             | meters                |
| 980.665           | cm/sec <sup>2</sup>   | cm/sec            | centimeters           |
| 9806.65           | mm/sec <sup>2</sup>   | mm/sec            | millimeters           |

## Appendix B: Listing of Newmark ASCII Data Output Files

This appendix lists the Newmark ASCII Output Data Files. Table B.1 lists the output box labels and corresponding files for the visual modeler analysis tabs and briefly describes the contents.

Table B.1. Output data files used by output buttons in the visual modeler analysis tab.

| Visual Modeler View<br>Output Label  | Name of File                            | Description                                                                                                                                       |
|--------------------------------------|-----------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------|
| Show Log of Newmark Execution        | Newmark.run                             | Displays a listing of the runtime execution process.                                                                                              |
| Show Input Echo of Newmark Execution | Newmark.out                             | Displays a listing of the input as read from Newmark.in                                                                                           |
| Plot Time Histories<br>AccX – H1     | PLOTaccX1[xxxx].TMP[1/2]                | Scaled acceleration time-history for horizontal component 1.                                                                                      |
|                                      | StandardizedPlotaccX1[xxxx].TMP[1/2]    | For a standardized displacement computation, a corresponding file for horizontal component 1 with the standardized computations will be provided. |
| Plot Time Histories<br>AccX – H2     | PLOTaccX2[xxxx].TMP[1/2]                | Scaled acceleration time-history for horizontal component 2.                                                                                      |
|                                      | StandardizedPlotaccX2[xxxx].TMP[1/2]    | For a standardized displacement computation, a corresponding file for horizontal component 2 with the standardized computations will be provided. |
| Plot Sliding Time-History – H1       | PLOTslideTH1[xxxx].TMP[1/2]             | Time-history of sliding block analysis for horizontal component 1.                                                                                |
|                                      | StandardizedPLOTslideTH1[xxxx].TMP[1/2] | For a standardized displacement computation, a corresponding file for horizontal component 1 with the standardized computations will be provided. |
|                                      | SinglePLOTslideTH11.TMP[1/2]            | For a single analysis, and with the critical acceleration as a fractional g.                                                                      |

| Visual Modeler View<br>Output Label                                                                                          | Name of File                                                                 | Description                                                                                                                                                                                                                                                                                                  |
|------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Plot Sliding Time-History – H2                                                                                               | PLOTslideTH2[xxxx].TMP[1/2]<br><br>StandardizedPLOTslideTH2[xxxx].TMP[1/2]   | Time-history of sliding block analysis for horizontal component 2.<br><br>For a standardized displacement computation, a corresponding file for horizontal component 2 with the standardized computations will be created.                                                                                   |
| Plot Non-Dimensionalized Displacement                                                                                        | Non-Dimensionalized_disp[xxxx].tmp                                           | Resultant non-dimensionalized displacement is provided for each set of horizontal time histories.                                                                                                                                                                                                            |
| Plot Standardized Maximum Displacement                                                                                       | Standardized Maximum_disp[xxxx].tmp                                          | For a standardized displacement computation, the resultant standardized maximum displacement is provided for each set of horizontal time histories.                                                                                                                                                          |
| Plot Permanent Displacement                                                                                                  | Permanent_disp[xxxx].tmp                                                     | For a standardized displacement computation, the resultant permanent displacement is provided for each set of horizontal time histories.                                                                                                                                                                     |
| Plot Standardized Maximum Displacement                                                                                       | Reg_standardized_disp.tmp<br>and<br>StandardizedMaximum_sets.tmp             | For a regression analysis with a standardized displacement computation, the resultant standardized displacements and their representative mean and both upper and lower 68 percent prediction intervals are presented for the defined regression analysis type. This output data is provided from two files. |
| Plot Mean, 68 percent Prediction Intervals and 95 percent Probability of non-exceedance for Non-dimensionalized Displacement | Reg_Non-Dimensionalized_disp.tmp<br>and<br>Non_Dimensionalized_disp_sets.tmp | For a regression analysis, the resultant non-dimensionalized displacements and their representative mean, 95 percent probability of non-exceedance and both upper and lower 68 percent prediction intervals are presented for the defined regression analysis type from output data within two files.        |

Note: Part of the file names with [xxxx] as listed in Table B.1 represent the number id of the output file. This establishes the maximum number of time-history sets for an analysis to be 9999 files.

| REPORT DOCUMENTATION PAGE                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |                             |                                |                            | Form Approved<br>OMB No. 0704-0188                           |                                           |
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| 1. REPORT DATE (DD-MM-YYYY)<br>February 2009                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |                             | 2. REPORT TYPE<br>Final report |                            | 3. DATES COVERED (From - To)                                 |                                           |
| 4. TITLE AND SUBTITLE<br><br>Permanent Seismically Induced Displacement of Rock-Founded Structures Computed by the Newmark Program                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |                             |                                |                            | 5a. CONTRACT NUMBER                                          |                                           |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |                             |                                |                            | 5b. GRANT NUMBER                                             |                                           |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |                             |                                |                            | 5c. PROGRAM ELEMENT NUMBER                                   |                                           |
| 6. AUTHOR(S)<br><br>Robert M. Ebeling, Moira T. Fong, Donald E. Yule, Amos Chase, Sr., and Raju V. Kala                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                             |                                |                            | 5d. PROJECT NUMBER                                           |                                           |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |                             |                                |                            | 5e. TASK NUMBER                                              |                                           |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |                             |                                |                            | 5f. WORK UNIT NUMBER<br>142082                               |                                           |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)<br><br>U.S. Army Engineer Research and Development Center<br>Information Technology Laboratory and Geotechnical and Structures Laboratory<br>3909 Halls Ferry Road, Vicksburg, MS 39180-6199;<br>Science Applications International Corporation<br>3532 Manor Drive, Suite 4, Vicksburg, MS 39180                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |                             |                                |                            | 8. PERFORMING ORGANIZATION REPORT NUMBER<br><br>ERDC TR-09-2 |                                           |
| 9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)<br><br>Headquarters, U.S. Army Corps of Engineers<br>Washington, DC 20314-1000                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |                             |                                |                            | 10. SPONSOR/MONITOR'S ACRONYM(S)                             |                                           |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |                             |                                |                            | 11. SPONSOR/MONITOR'S REPORT NUMBER(S)                       |                                           |
| 12. DISTRIBUTION / AVAILABILITY STATEMENT<br><br>Approved for public release; distribution is unlimited.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |                             |                                |                            |                                                              |                                           |
| 13. SUPPLEMENTARY NOTES                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                             |                                |                            |                                                              |                                           |
| 14. ABSTRACT<br><br>This research report describes the engineering formulation and corresponding software developed for the translational response of rock-founded structural systems to earthquake ground motions. The PC software Newmark (and Newmark <sub>VM</sub> ) is developed to perform an analysis of the permanent sliding displacement response for a structural system founded on rock for a user specified earthquake acceleration time history via a Complete Time History Analysis, also know as the Newmark sliding block method of analysis. The PC-based program Newmark performs a permanent sliding block displacement analysis given a baseline corrected rock site-specific acceleration time history. Newmark can also conduct regression analyses for sets of rock founded acceleration time histories in order to develop up to three user selected forms of generalized equations of simplified permanent displacement relationships. The rock-founded structural system can be a variety of structural feature types; a concrete gravity dam, a concrete monolith, a retaining wall, etc.<br><br>(Continued) |                             |                                |                            |                                                              |                                           |
| 15. SUBJECT TERMS                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                             | Newmark sliding block analysis |                            | Rock earthquake ground motions                               |                                           |
| Baseline corrected                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |                             | Permanent displacement         |                            | Yield Acceleration                                           |                                           |
| Maximum transmissible acceleration                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |                             | Rock                           |                            | Seismic Translation                                          |                                           |
| 16. SECURITY CLASSIFICATION OF:                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |                             |                                | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES<br><br>203                               | 19a. NAME OF RESPONSIBLE PERSON           |
| a. REPORT<br>UNCLASSIFIED                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | b. ABSTRACT<br>UNCLASSIFIED | c. THIS PAGE<br>UNCLASSIFIED   |                            |                                                              | 19b. TELEPHONE NUMBER (include area code) |

#### 14. ABSTRACT (Concluded).

The results of the regression analyses discussed in this report resulted in Simplified permanent displacement relationships that were developed using data generated by Newmark for an extensive data base of 122 sets of baseline corrected rock acceleration time histories in the moment magnitude 5 to 7 range. The resulting simplified permanent displacement relationships allow the engineer to rapidly determine the earthquake-induced permanent displacement for a given rock-founded structural system. This alternative procedure requires only rudimentary design/analysis ground motion characterization and use of a simplified permanent seismic displacement relationship for a sliding block (structural) system model. The resulting simplified permanent displacement relationships discussed in this report are being implemented in other Corps permanent (seismically-induced) displacement software such as  $C_{\text{corps}}W_{\text{allSlip}}$ , and  $C_{\text{corps}}D_{\text{amSlip}}$ .