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COMPENSATING GRAVITY EFFECTS IN I-G SMALL-SCALE STRUCTURAL MODELING

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19. ABSTRACT (Continue on reverse if necessary and identify by block number) This report presents the results of a study to develop viable concepts to compensate for the gravity effects in 1-g small-scale tests. These tests simulate the effects of nonnuclear weapons on protective structures. Two viable concepts associated material preparation procedures were developed on the basis of theoretical and experimental evidence governing equations, similarity requirements, and known material behavior. Although Phase II work is necessary to demonstrate the viability of the developed concepts, no major obstacles to the success of these concepts are apparent. The first concept is applicable to close-in blasts where the effects of gravity are likely to be insignificant. The second concept was developed for general application and can compensate for gravity effects regardless of significance. Preliminary planning for the Phase II scope and work plan is also included in this report. The successful completion of the Phase II program would culminate in the development of a powerful and economic means to provide necessary data in establishing improved design and upgrade methodologies for protective structures subjected to nonnuclear weapons attacks. <i>Phase II work</i>					
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PREFACE

This report was prepared by The Earth Technology Corporation, 3777 Long Beach Blvd., Long Beach, CA 90807-3309, under contract F08635-87-C-0427, for the Air Force Engineering and Services Center (AFESC), Tyndall Air Force Base, Florida. The report summarizes work done between August 1987 and March 1988. Lt Col Robert Majka and Capt Isaac Schantz were the Air Force project officers.

This report has been reviewed by the Public Affairs Office and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

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LIST OF SYMBOLS

a	radius or length of one side of rectangular plate
c	cohesion intercept
C_L	wave speed based on constrained modulus
E	Young's modulus
f_i	i th modal frequency or body force in the i th direction
f_{ij}	modal frequency of plate or shell
f^*	body force scaling factor
g	acceleration due to gravity
G	shear modulus
G_c	scaled hysteretic compaction parameter
h	thickness of tubular section of plate or shell
I	moment of inertia or impulse
I_p	polar area moment of inertia
l or L	length
m	subscript represents quantity for model
M	mass density per unit length
p	subscript represents quantity for prototype
r	ratio of loading to unloading constrained modulus
R	distance from the detonation source
S	shear strength
t	time
t^*	time scaling factor
u	pore pressure
u_i	displacement in i th direction
u_i^*	displacement scaling factor
$\dot{u}_i$	velocity in i th direction

$\dot{u}_i^*$	velocity scaling factor
$\ddot{u}_i$	acceleration
$\ddot{u}_i^*$	acceleration scaling factor
W	weapons yield (weight) in pounds
ϵ_{ij}	strain tensor on the j th face and in the i th direction
ϵ^*	strain scaling factor
λ	geometric scaling factor
ρ	mass density per unit volume
ρ^*	mass density scaling factor
σ_{ff}	total stress normal to failure plane
σ_n'	effective stress normal to failure plane
σ_{ij}	stress tensor on the j th face and in the i th direction
σ^*	stress scaling factor

SECTION I INTRODUCTION

A. OBJECTIVES

The objective of this Phase I study is to develop concepts and procedures that can compensate for gravity effects in 1-g small-scale model tests simulating the effects of near miss (close-in) and shallowly buried detonation of nonnuclear weapons on protective structures. The ultimate aim of this testing is to improve design and upgrade methodologies for protective structures subjected to nonnuclear weapons attacks.

B. BACKGROUND

Critical, hardened strategic structures represent high priority targets. Survival of such structures under nonnuclear weapon attacks is of significant concern. These hardware sites and command and control centers, especially in overseas countries such as Korea and West Germany, house vital operational functions and contain sensitive and valuable equipment.

The design or upgrade of these structures against nonnuclear weapons attacks requires a detailed understanding of the groundshock propagation in the geologic material and the interaction between the surrounding geologic medium and the structure when subjected to an intense dynamic loading field. The nature of nonnuclear weapons blasts and their effects on nearby protective structures are complex. Our current understanding is limited and primarily based on limited experimental data and analytical developments which are inadequate for general applications. Further understanding can be achieved by experimental or analytical development. Experimental development can be either full-scale prototype or small-scale model tests. Small-scale model tests are much less costly and preferred.

Small-scale model tests can be either 1-g small-scale model or conducted in a centrifuge to simulate gravity effects. 1-g small-scale model tests are

preferred if they can properly account for gravity effects. This is because 1-g small-scale model tests can alleviate various concerns usually associated with centrifuge tests. These concerns include limited availability, limited payload, and insufficient size to allow modeling of structural detail and response.

Development of feasible 1-g small-scale model concepts and procedures to compensate for gravity effects in simulating nonnuclear weapons effects on protective structures is urgently needed. This is the objective of this Phase I study. The success of this Phase I study and subsequent completion of the needed SBIR Phase II and Phase III programs would culminate in the development of a powerful and economic means of simulating structural responses under nonnuclear weapons blasts, leading to a safe and economic design or upgrade of protective structures.

C. SCOPE

The scope of the Phase I study consists of the following tasks:

- o Task 1 - Literature Review and Evaluation
- o Task 2 - Engineering Analysis of One-g Model
- o Task 3 - Engineering Evaluations of Supplementary Concepts
- o Task 4 - Concept and Procedure Development
- o Task 5 - Preliminary Planning for Phase II Study.

The results of literature review and evaluation (Task 1) are presented in Section II. Section III presents engineering analysis of a 1-g scale modeling concept where gravity effects are insignificant (Task 2). A versatile concept (Task 3) which can compensate for any gravity effects is detailed in Section IV. The concept and procedure to produce appropriate model materials for a wide variety of geologic materials and structural materials (Task 4) are presented in Section IV. Our recommendation for Phase II work (Task 5) with rough order of magnitude cost and schedule estimates are presented in Section V. The conclusions of this Phase I study are presented in Section VI.

SECTION II

LITERATURE REVIEW AND EVALUATION

A. GENERAL

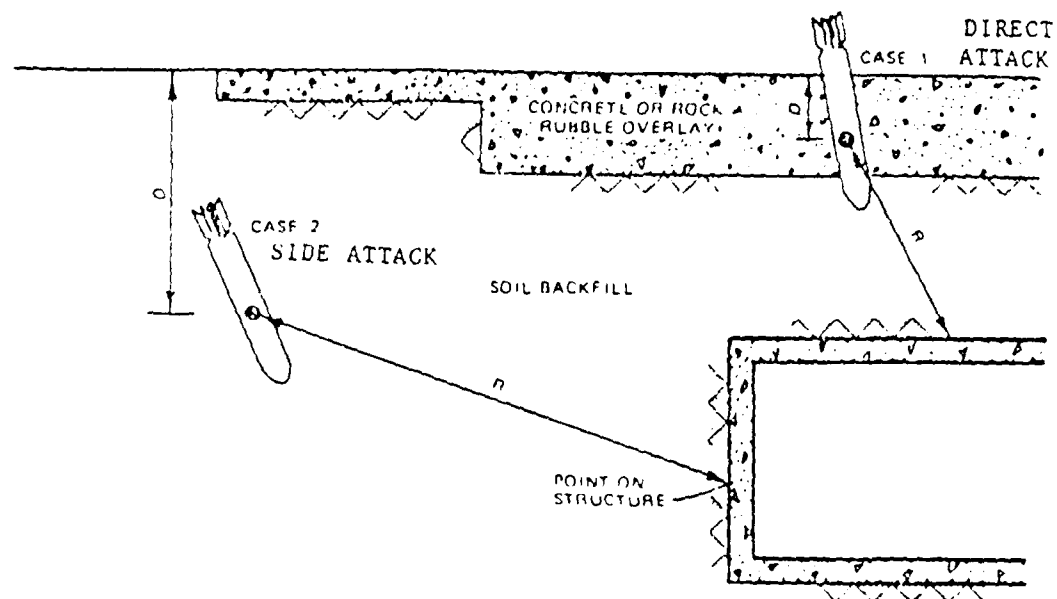
One of the primary objectives of near-surface structures (shelters) is to provide a system that would acceptably survive under direct and/or near-miss side attacks (Figure 1). Semiburied or shallow buried, hardened strategic structures such as hardware sites and Command Control Centers represent high priority targets in a conventional attack. An initial conventional attack on a structure would be designed to destroy emplaced equipment and human resources through ground shocks. Therefore, it is important to understand the interaction between the surrounding soil mass and hardened, buried, and/or semiburied structures subjected to a dynamic loading field of intense magnitude. With this understanding, it would be possible to design improved support systems for hardened structures to withstand the maximum credible attack. As noted by Higgins (Reference 1), the close-in range of interest is from 0.5 to 1.5 feet per cubic root of weapon yield in pounds (i.e., 5 to 15 feet for a 1,000-pound bomb).

A review of available literature has been performed to:

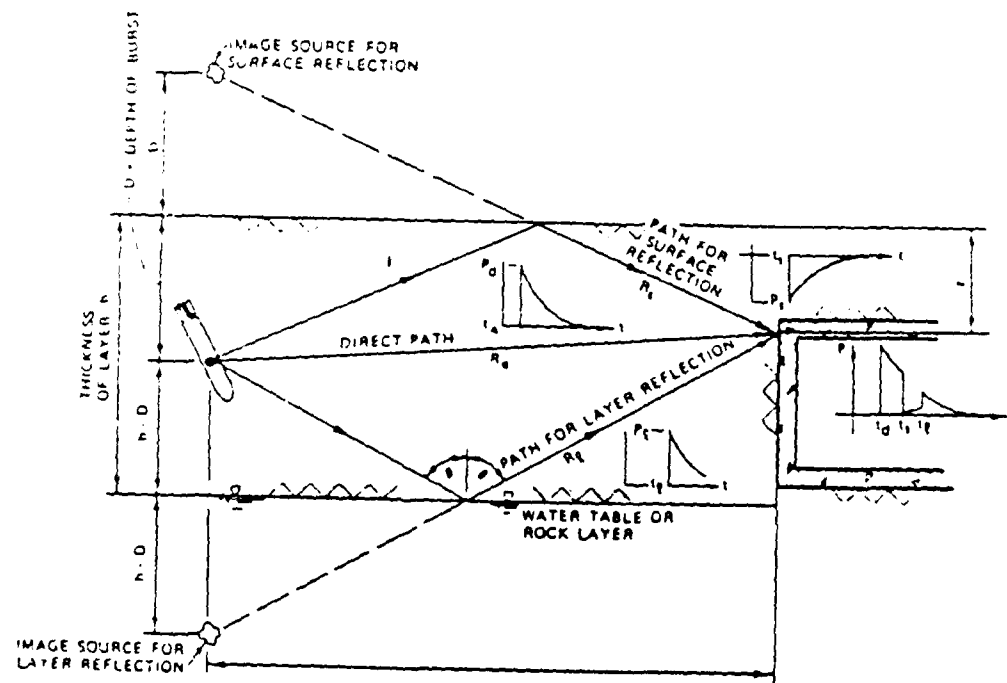
- (1) Assess current knowledge
- (2) Identify variables and factors most influenced by gravity effects
- (3) Identify technology gaps which will require further consideration in the Phase II program.

The literature on nonnuclear weapons effects is widely scattered. The primary sources of information in this literature review included:

- (1) Published materials in the engineering literature, including proceedings of specialty conferences on similar subjects, and nonclassified publications by various branches of the Department of Defense
- (2) The project data file and our project team experience.



(a) Attack Scenarios



(b) Ground Shock Propagation and Soil-Structure Interaction

Figure 1. Schematic Sketch Showing the Subject of this SBIR Study

The Earth Technology Corporation also requested the Air Force Engineering and Services Center (AFESC) to provide relevant unpublished information, if any, and was informed that no such information existed.

B. EXPERIMENTAL AND NUMERICAL TECHNIQUES

The phenomena of nonnuclear munitions blasts and their effects on shallow buried and semiburied structures are so complex that mathematical closed-form solutions are extremely difficult, if not impossible. The common practice is to evaluate the effects experimentally or numerically, and to develop empirical relations from experimental or calculated response data.

Numerical techniques can model different geometries and material/structure types. Various numerical codes for modeling soil-structure interaction under nonnuclear and nuclear weapons blasts developed for the defense and other industries, are available in the literature. Although some of these codes have been partially verified by limited experimental data, simplifications in constitutive modeling preclude them from universal application. The available analytical codes do provide an excellent means of identifying potential physical trends of a soil-structure interaction problem, guiding the experiments to better simulate the problem, and extrapolating the results to similar problems of different configurations and dimensions.

Prototype large-scale field or model testing can provide the means to verify numeric codes or constitutive relations, and to understand the physical phenomena that govern the effects of nuclear/nonnuclear weapon effects on protective structures. A number of free-field (i.e., without structures) prototype and large-scale model tests have been performed since early 1950 (References 2 and 3). The results of such tests provide a basis for the framework of various empirical design manuals (Reference 4) and scaling relationships (Reference 1). In addition to being expensive, which necessitates minimizing parameter variations, these tests generally have one or a combination of shortcomings:

- (1) Little or no characterization of material properties--mostly limited to material types, seismic velocity, and density data (Table 1)

- (2) No close-in measurements (References 1 and 2)
- (3) Mostly performed for special purposes.

Well-documented prototype large-scale field tests of blast effects on buried or semiburied structures are invaluable in providing meaningful data to verify small-scale experiments and analytical techniques. Two such test series have been performed by the Air Force Weapon Laboratory (AFWL). These two test series (MUST and BDCC series), based on our recent discussions with Captain Bennett of AFWL, have been conducted to simulate effects of full-scale buried blasts on buried and semiburied modular structures with extensive instrumentation and monitoring programs. Details of these two test series will be evaluated for potential Phase II applications.

Centrifuge modeling techniques can provide an excellent means of simulating gravity effects in a wide variety of static and dynamic problems. This technique is gaining popularity in simulating blast-related problems (References 5, 6, 7, and 8) and should be considered as a viable experimental alternative to evaluate nonnuclear weapons effects on protective structures. Although this technique is not the subject of this study, it should be considered as one of the viable supplementary concepts for the problems considered in this study.

1-g scale modeling is based on modeling geometry and material properties in accordance with a set of similitude (scaling) relations for physically similar systems. A prototype problem can then be experimentally simulated in a smaller scale model under a 1-g gravity field. Since 1914 (Reference 9), the fundamentals of such concepts have been applied to a number of engineering dynamics problems (References 10 and 11). This method has not gained popularity in simulating nonnuclear weapons effects on protective structures probably due to difficulties in simultaneously simulating the constitutive behavior of and the potential gravity effects on geologic deposits, which are more complex than most construction materials for structures. Rocha (References 12 and 13) is one of the first researchers to investigate the possibility of solving soil mechanics problems using similarity modeling. Soil dynamic simulation using the 1-g modeling technique has been attempted by

various investigators. These include dynamic bearing capacity (Reference 14), dynamic loading on footing (Reference 15), dynamic response of underground structures (Reference 16), explosive cratering research (Reference 17), and impact penetration (Reference 18). In these studies, soil models of simple strength and stiffness parameters (in terms of modulus, seismic velocity, or subgrade modulus) have been used.

In determining the appropriate geometrical scaling relationships, the most common scaling relation in blast studies is the Hopkinson's or "cube-root" scaling rule. This states that ground shock waves are produced at identically scaled distances when two explosive charges of same type and similar geometry, but of different sizes, are detonated in the same material. This law was first suggested in 1915 (Reference 19) and subsequently verified experimentally by various investigators (References 1, 3, and 20; Figures 2 and 3). The scaling law can be expressed as

$$\frac{R_m}{R_p} = \frac{t_m}{t_p} = \frac{I_m}{I_p} = \left(\frac{W_m}{W_p}\right)^{1/3} = \lambda$$

where λ = scaling factor

R = distance from the source

t = time

I = impulse

W = Weapon yield in pounds or blast energy

Subscripts m and p represent model and prototype, respectively.

As shown in Figure 4, the law implies that all quantities, in terms of peak stress and peak particle velocity, will remain identical at homologous locations and times for the model and prototype, respectively. However, frequency content of the stress and velocity pulses will be changed because of the time scaling change (Figure 4).

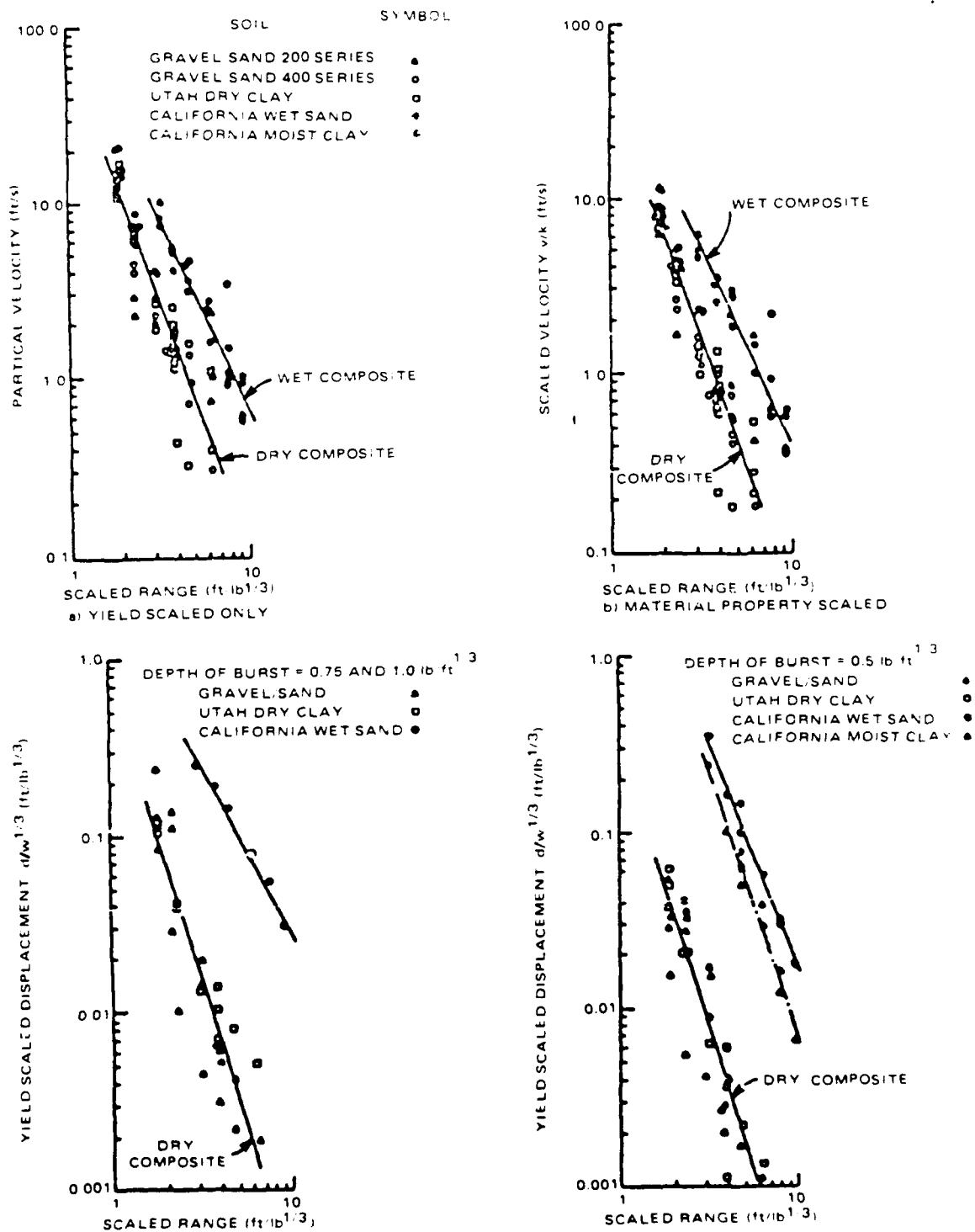
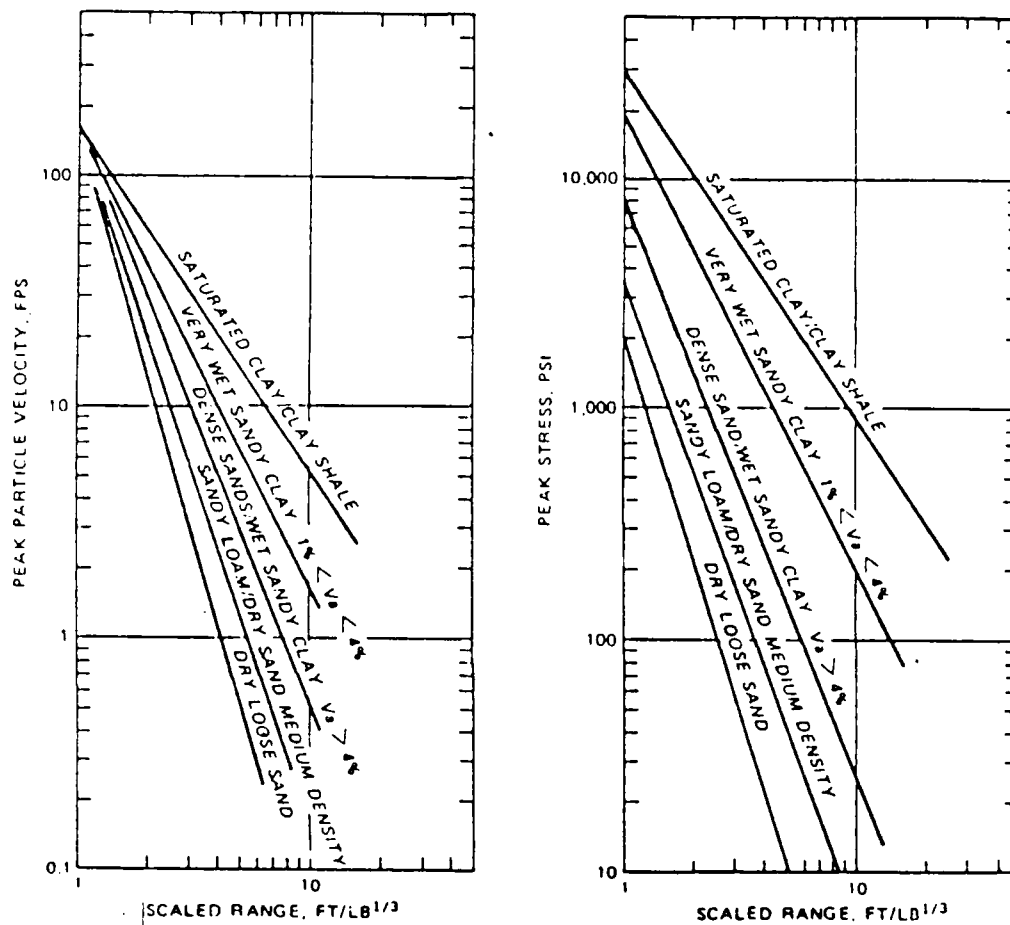


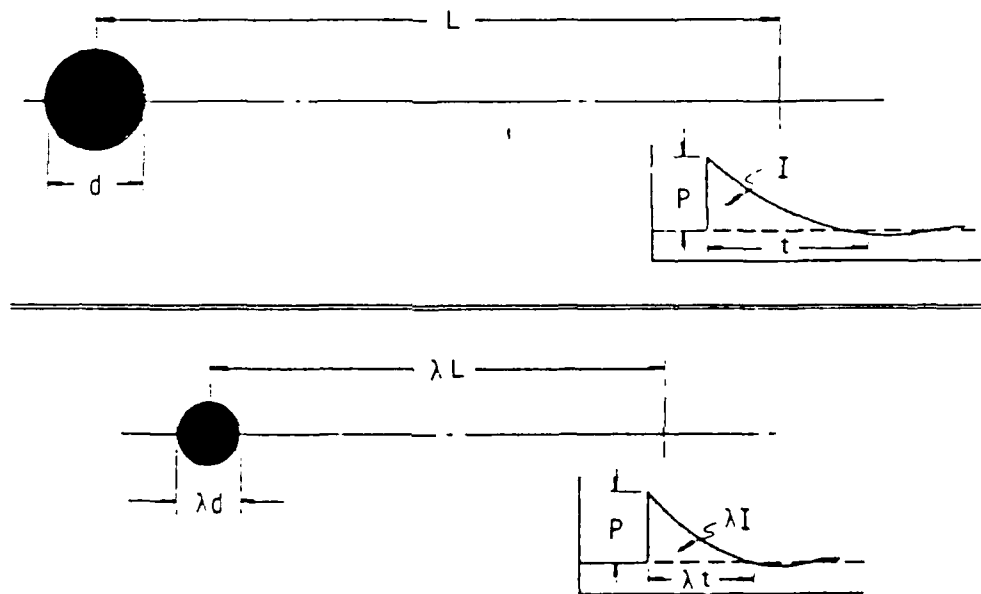
Figure 2. Particle Velocity and Displacement Measurement from Mole Test Series



Notes:

1. Adapted from reference 3
2. Refer to Table 1 for Associated Soil Properties

Figure 3. Peak Stress and Particle Velocity from Contained Explosions in Various Soils



Adapted from Reference 10.

Figure 4. Schematic Sketch Showing Hopkinson's Scaling Rule for Blast Wave

C. GROUND SHOCK GENERATION AND PROPAGATION

Gravity influences the initial stress field and geologic material characteristics. If the partial gravity effects are insignificant, prototype materials can be used in 1-g scale models (Section III). However, if the effects are significant, only dissimilar materials from the prototype are appropriate for 1-g scale models (Section IV).

A necessary initial step to accomplish this objective is to understand the mechanisms involved in a nonnuclear weapons blast. As shown in Figure 1, a direct attack, a near-miss (close-in), or shallow buried side blast in a geologic medium (soils or rock) involves the following phenomena:

- o Detonation, Ground Shock Generation, and Propagation
- o Loading on and Response of Structure.

The factors influencing the magnitude and characteristics of weapon-induced ground shock, and its propagation and interaction with structures, include (References 1 and 4):

- o Weapon shape and case properties
- o Explosive type and yield
- o Orientation of weapon at detonation
- o Depth of burial [depth of blast (DOB)]
- o Geologic material properties
- o Distance from detonation
- o Geologic layering
- o Stiffness and damping characteristics of structures.

1. Depth of Burial

The first three factors above are beyond the scope of this study. Depth of burial is a direct result of bombs and projectiles penetrating the geologic materials. Thus, it depends on characteristics of penetrating objects (weight, caliber, shape, case properties, fuzing, etc.), impact con-

ditions (impact velocity, angle of incident, yaw, etc.), and properties of target materials (strength, density, ductility, porosity, etc.). Experimental data (Reference 21), analytical treatment using various target response (strength) models (References 22, 18, and 17), scaling relationships (References 10 and 23), and empirical treatment (e.g., Chapter 4 in Reference 4) are available for this subject. Impact penetration is not within the study scope. However, it should be mentioned that penetration of a projectile into geologic materials will inevitably generate some ground shock before its detonation. Such a ground shock, its propagation and potential effects on structures, has generated little attention in the literature. Intuitively the magnitude of such ground shock and its effects on structures should be relatively small and secondary when compared with those generated by detonation.

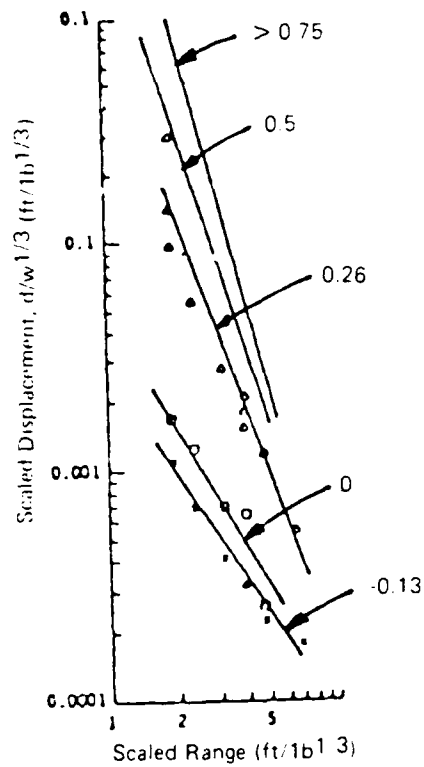
Available data (Reference 1) indicate that depth of burial improves coupling and increases the range to which ground shock levels of a given amount persist. Available field test data from the Mole test series (References 2 and 1), as shown in Figures 2 and 5, indicate that the overall amplitude and the attenuation characteristics (in terms of attenuation coefficients) of ground shock change with depth of burst. Thus, the common practice of using a single coupling factor (References 24 and 4) cannot fully explain the observed phenomena.

The main reason that ground shock magnitude increases with depth of burst is due to confinement. Although it is not mentioned in the literature, a secondary reason may be that a certain portion of the energy generated from a shallower burst is used in forming crater and producing ejecta. The mechanisms of crater forming and ejecta behavior have been described (References 4 and 25).

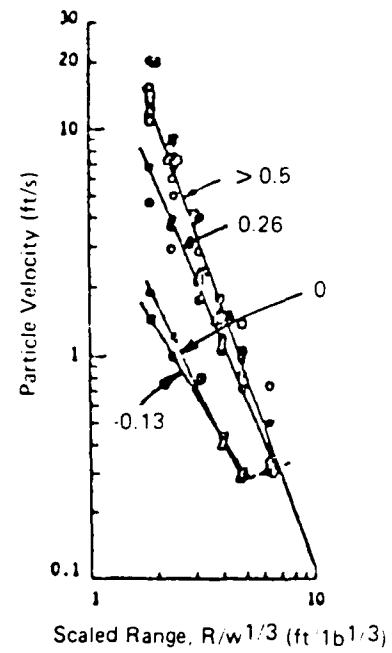
2. Material Properties

The material properties of geologic deposits will affect the magnitude and attenuation characteristics of ground shock as well as loading-on struc-

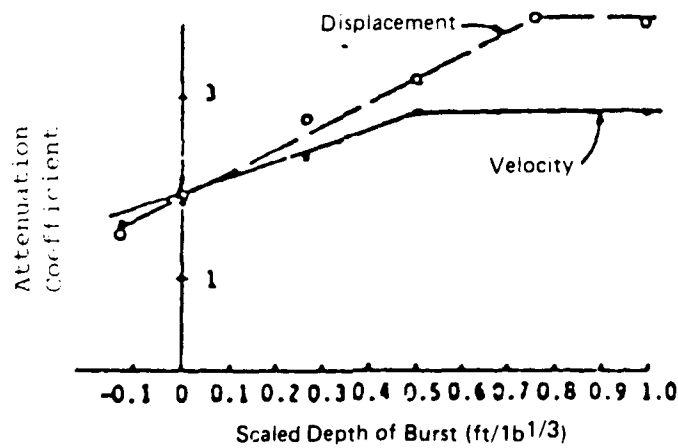
NOTES: Number Indicates Scaled
Depth of Burst



(a) Displacement



(b) Particle Velocity



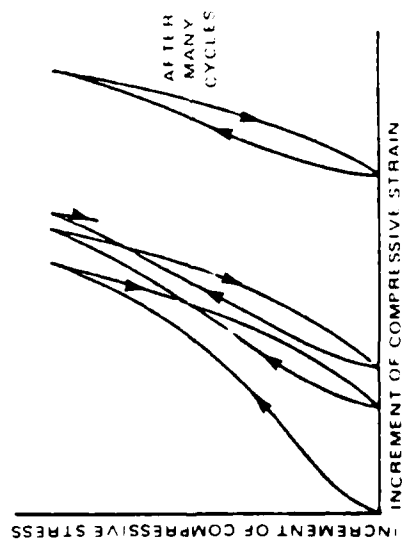
(c) Attenuation Coefficient

Figure 5. Mole Test Series Data Showing Effect of
Depth of Burst (Reference 1)

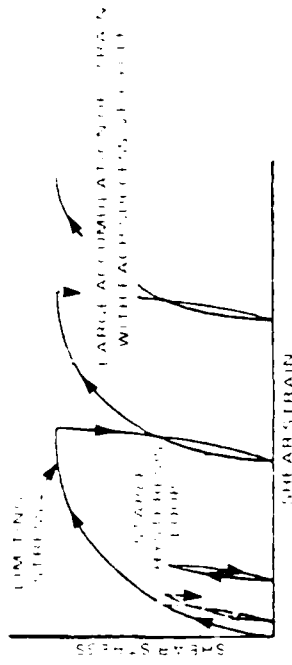
tures (soil-structure interaction). It is generally recognized (References 26 and 27) that material properties of importance include porosity, soil type, moisture content, and deformation and strength characteristics. Geologic materials, by nature of their deposition and composition process, are more complex than other construction engineering materials (i.e., concrete, steel, etc.). For example, soil is particulate and its behavior depends on the nature of particle contacts and bonding, and the movement and deformation of particles at the contacts (Reference 28). It is also multiphased and consists of pore spaces filled with air, water, or both. It can be expected to exhibit complex stress-strain behavior including nonlinearity, anisotropy, irreversibility (plastic deformation), time-dependency; as well as stress, stress history, strain, or strain-rate dependency (Reference 26). Similarly, rocks are mineral aggregates bonded together by consolidation and/or cementation (sedimentary rock), solidification of a molten magma (igneous rock); or recrystallization due to high pressure, heat, or hydrothermal alteration (metamorphic rock). Although quantitatively different, their behavior is qualitatively similar to that of soil to a varying extent. In addition, most in situ rock masses contain discontinuity features in the forms of joints, bedding planes, foliation surfaces, localized cracks, and/or faults. Such discontinuities further complicate their stress-strain behavior. Examples of stress-strain behavior for soil and rock are shown in Figures 6 and 7. More detailed discussions are presented in Section II-E.

3. Ground Shock Generation and Propagation

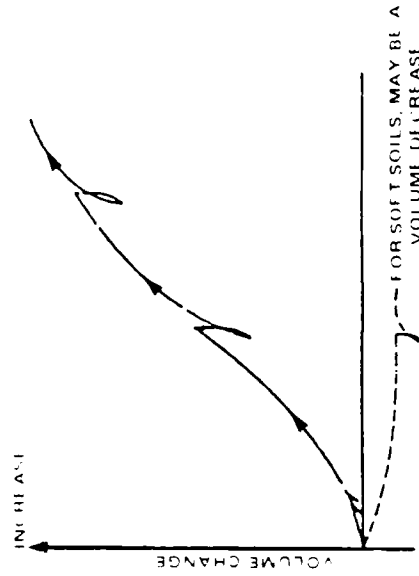
At or near the detonation point, the stress and particle velocity pulses will be exceedingly high causing rupture, yielding, or crater formation (if the depth of burst is shallow). The difficulty of designing instrumentation to survive such a high strain environment precludes close-in stress and particle velocity measurement data being found in literature. Extrapolation of some of the available test data (Reference 3) shown in Figure 3, would indicate that the peak stress at a scaled distance of about 0.2 feet per cubic root of weapon yield in pounds (2 feet for a 1,000-pound bomb) would be on the order of 300,000 psi, which is significantly higher than the gravity overburden stress (on the order of about 1 psi per foot of burial depth).



(a) UNDER HYDROSTATIC OR UNIAXIAL COMPRESSION

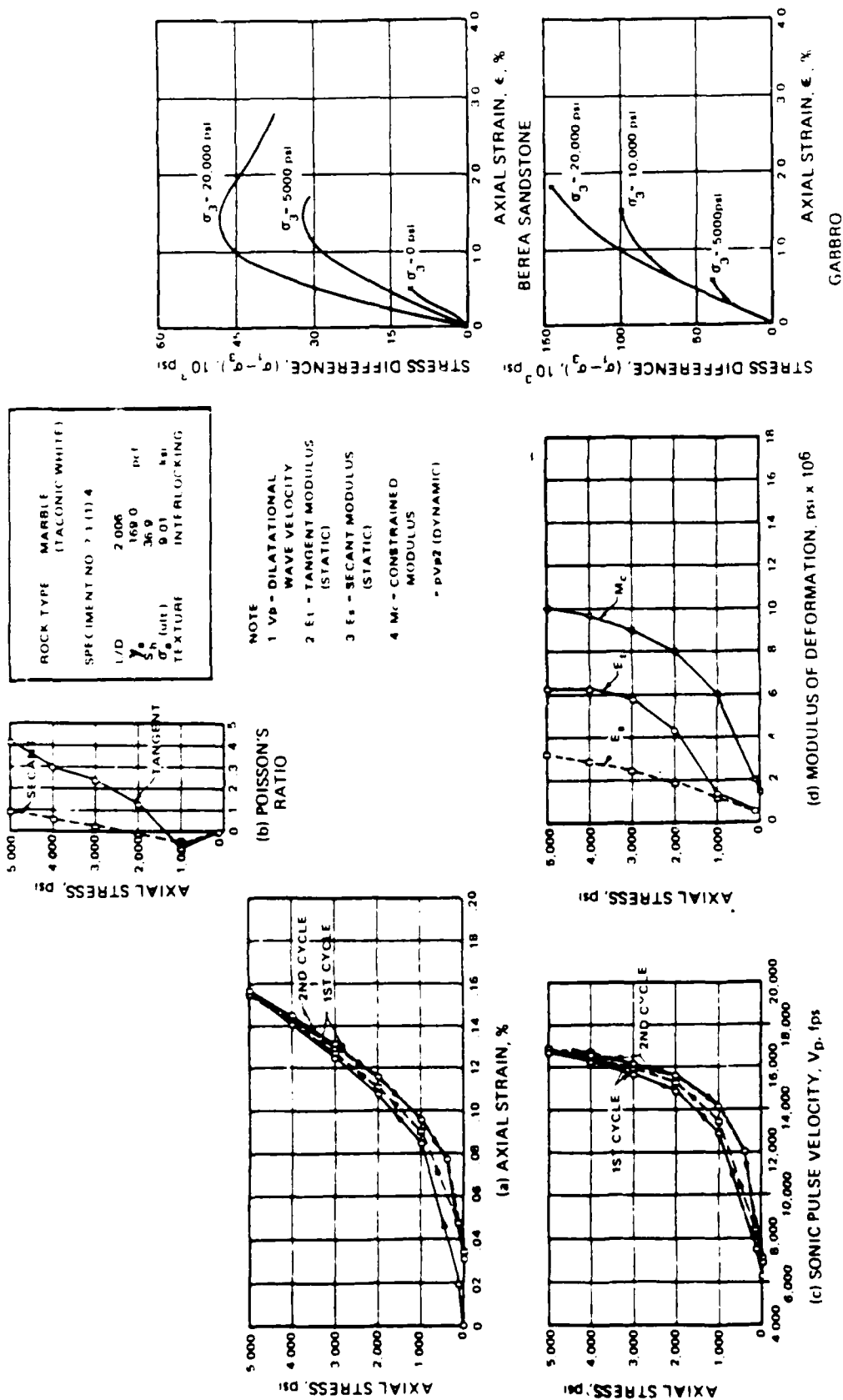


(b) UNDER SHEAR STRESS



(c) SHEAR DILATANCY BEHAVIOR

Figure 6. Typical Deformation Behavior of Soils



STRESS STRAIN BEHAVIOR AND SONIC PULSE
VELOCITY FOR ROCK IN UNIAXIAL COMPRESSION
REFERENCE 29

THE VARIATION OF STRESS STRAIN AND
STRENGTH PROPERTIES OF GABBRO AND
SANDSTONE WITH CONFINING PRESSURE
REFERENCE 30

Figure 7. Selected Examples of Stress Strain Relations for Rock

As the high-intensity ground shock propagates outward from the detonation source, stress and velocity pulses attenuate. As shown in Figures 2 and 3, material types have significant effects on the attenuation. Soil properties associated with the explosion test results shown in Figure 3 are listed in Table 1. An examination of these data indicates that attenuation rate (i.e. attenuation coefficient, n , in Table 1) increases with the decrease of seismic velocity. The observed attenuation patterns can be expressed as

$$\sigma_r = C_\sigma (R/W)^{1/3} n_\sigma$$

$$v = C_v (R/W)^{1/3} n_v$$

$$d = C_d (R/W)^{1/3} n_d$$

where σ_r = peak radial stress

v = particle velocity

d = displacement

C_σ, C_v, C_d = constants

n_σ, n_v, n_d = attenuation coefficients

Reference 1 reported an attempt to model soil (with a seismic velocity of 900 m/sec) and rock (with a seismic velocity of 2440 m/sec) as elastic materials to evaluate stress, particle velocity, and displacement attenuation patterns has been made using the computer code STEALTH. The results indicate a constant value of 1.6 for n_σ and n_v and a value of 1.25 for n_d for both soil and rock materials. These attenuation values are not corroborated by the experimental results shown in Figures 2 and 3. Thus, modeling geologic materials as linear elastic materials does not appear reasonable.

Reference 31 reported calculations by modeling geologic materials as inelastic material using a simple nonlinear model in terms of loading and unloading constrained modulus, and shear strength of the material. The hysteretic damping was represented by a scaled hysteretic compaction parameter, G_c , defined

$$G_c = (1-r)/C_L$$

where

r = ratio of the loading constrained modulus to unloading constrained modulus

C_L = wave speed calculated from the loading constrained modulus

TABLE 1. SOIL PROPERTIES FROM EXPLOSION TESTS SHOWN IN FIGURE 3

Soil Description	Dry Unit Weight γ dry pcf	Total Unit Weight γ dry pcf	Air-Filled Voids %	Seismic Velocity c fps	Acoustic Impedance psi/fps	Attenuation Coefficient n
Dry desert alluvium and playa, partially cemented	87	93-100	>25	2,100-4,200 ^a	40	3-3.25
Loose, dry, poorly graded sand	80	90	>30	600	11.6	3-3.5
Loose, wet, poorly graded sand with free-standing water	97	116	10	500-600	12.5-15	3
Dense, dry sand, poorly graded	99	104	32	900-1,300	25	2.5-2.75
Dense, wet sand, poorly graded, with free-standing water	108	124	9	1,000	22	2.75
Very dense, dry sand, relative density = 100%	105	109	30	1,600	44	2.5
Silty-clay, wet	95-100	120-125	9	700-900	18-25	2.75-3
Moist loess, clayey sand	100	122	5-10	1,000	28	2.75-3
Wet sandy clay, above water table	95	120-125	4	1,800	48	2.5
Saturated sand, below water table in marsh	--	--	1-4 ^b	4,900	125	2.25-2.5
Saturated sandy clay, below water table	78-100	110-124	1-2	5,000-6,000	130	2-2.5
Saturated sandy clay, below water table	100	125	<1	5,000-6,600	130-180	1.5
Saturated stiff clay, saturated clay-shale	--	120-130	0	>5,000	135	1.5

^a High because of cementation.^b Estimated.

Their results for Coulomb materials (shear strength increases with confinement) and von-Mises materials (shear strength independent of confinement) are shown in Figure 8. Their results, although not fully corroborated with available test data (Figures 2 and 3), are qualitatively promising.

The available data (Figures 2 and 3) and the above quoted analytical results suggest a minimal possibility of obtaining a single universal attenuation relationship to cover a wide spectrum of geologic materials. Different geologic materials have different material characteristics in terms of inelastic, nonlinear, and strength behaviors. However, after further experimental and analytical studies it may be possible to establish ground shock propagation and attenuation patterns in terms of geologic material grouping (i.e., dry or saturated cohesionless soil, cohesive soils, weathered rock, competent rock, etc.).

4. Effect of Geometry

As noted by various investigators (Reference 1), the ground shock stress and velocity pulses are nonuniform in time and space, resulting from (1) reflected waves from geologic layering and ground surface and (2) weapon inclination before its detonation. For a shallow-buried close-in blast, the ground surface and the structure are relatively near the detonation source resulting in a complex combination pattern of the incident waves and reflection waves. For the same reason, the ground shock waves are also three-dimensional in nature. The nonuniform and three-dimensional nature of ground shock also indicates that loads on a close-in protective structure will be equally as complex.

D. LOADS ON STRUCTURE

The presence of a structure will modify the free-field ground shock stress and velocity pulses through a process commonly known as "soil-structure interaction" (References 26 and 32). Thus, the stresses acting on the structure will be different from the free field stress pulse patterns (i.e., in the absence of the structure). The difference in stiffness (deformability) between the structure and the surrounding geologic materials may amplify or reduce the loads on

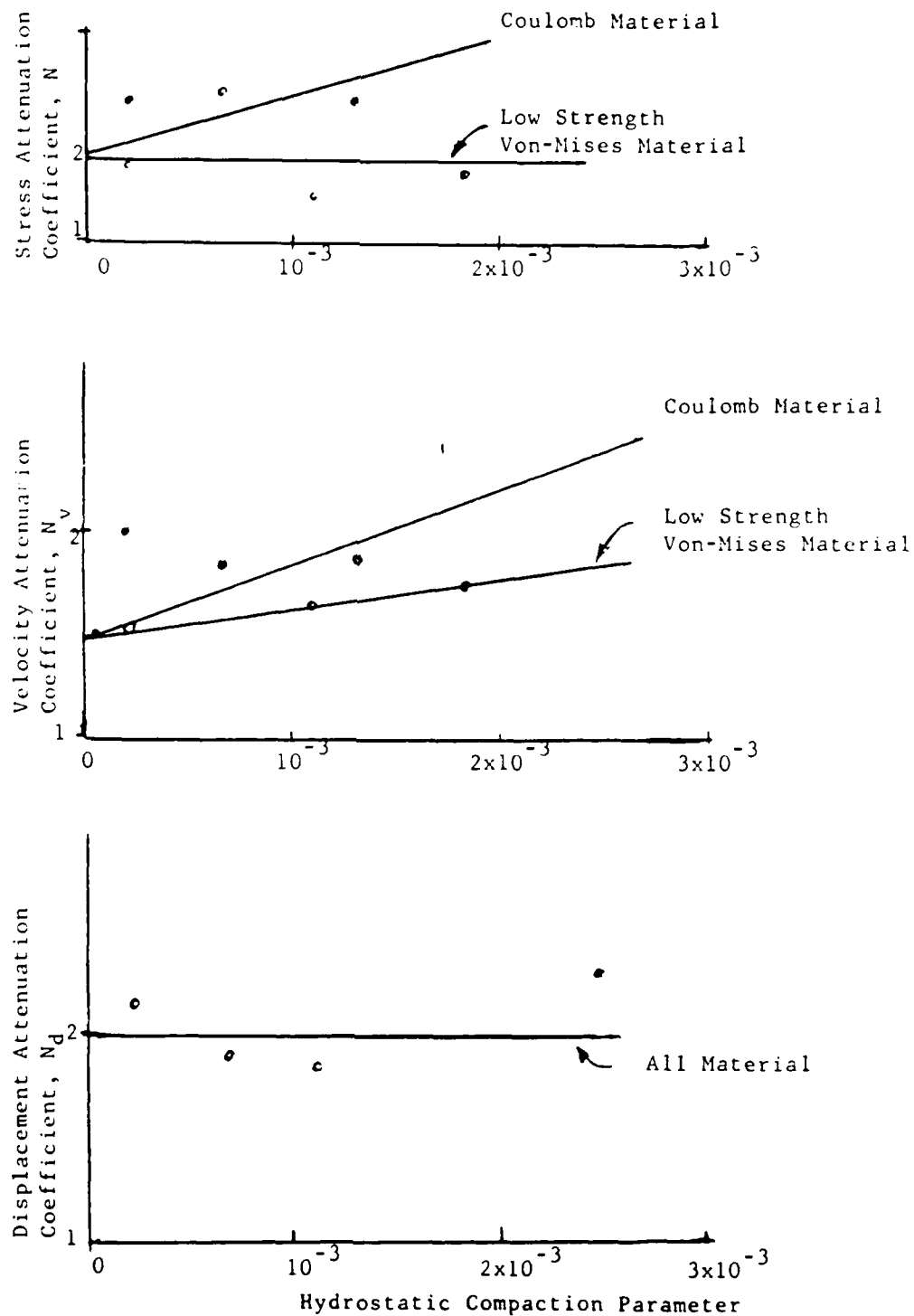


Figure 8. Attenuation Coefficient Calculated in Reference 31

the structure. In general, the size of a protective structure is relatively large in comparison with the relative closeness of the structure to the detonation source in a close-in blast. This indicates that the ground shock-induced loads on a close-in structure will be localized. As described before, these loads are nonuniform (in time and space) and three dimensional in nature. Thus, soil-structural interaction of nonnuclear weapons blast for close-in structures is extremely complex. Figure 9 shows some of the experimental data on interface stress measurements in the literature (References 33 and 34) to illustrate the nonuniform nature of the loadings on protective structure.

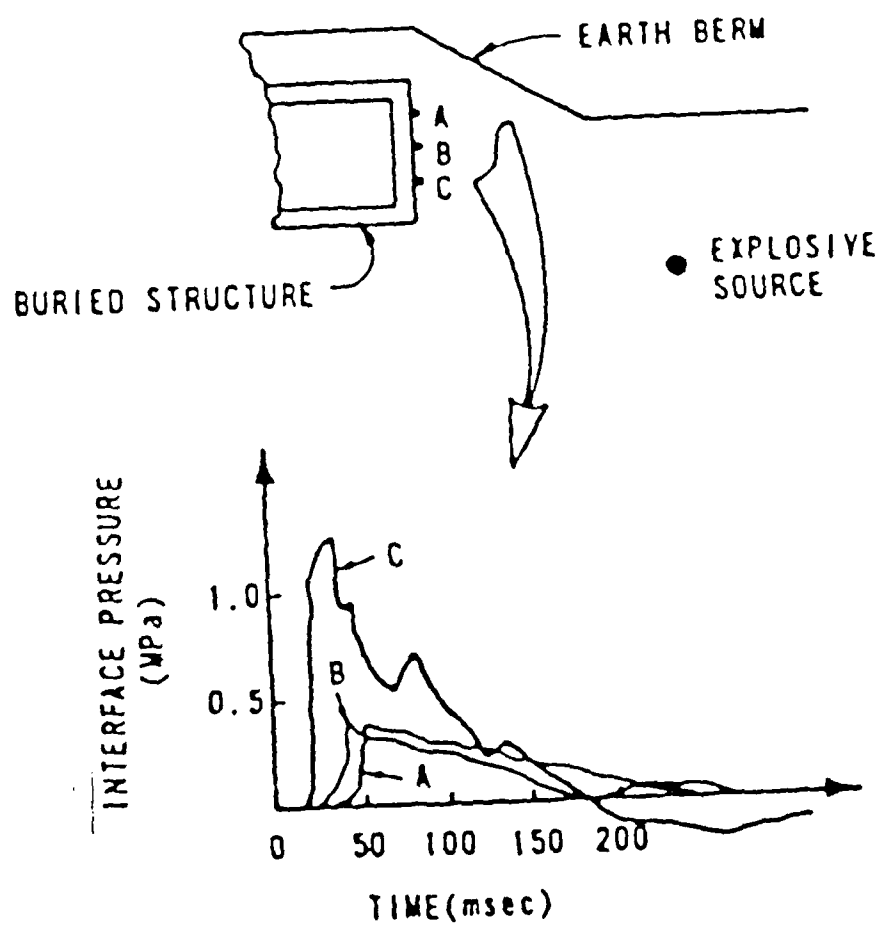
Current design methods (Reference 4) generally involve simplified and conservative assumptions (e.g., the use of a conservative uniform load on a structure with a magnitude on the order of 1.5 to 2 times the calculated free field peak stresses) to account for soil-structure interaction effects. These assumptions result in overly conservative designs.

E. ENGINEERING CHARACTERISTICS OF GEOLOGIC MATERIALS

As described in previous sections, the deformation and strength characteristics of geologic materials will affect the ground shock propagation and its interaction with the protective structure. As noted by various investigators (References 26, 1, and 27) these important engineering characteristics include:

- o Stress-strain (volumetric strain) behavior under hydrostatic loading
- o Stress-strain behavior under deviatoric (shear) stresses
- o Shear stress-induced volumetric strain (shear-dilatancy) behavior
- o Shear strength.

Other material properties such as Poisson's ratio or hysteretic material damping are implicit byproducts of above deformation characteristics. The deformation characteristics of geologic materials are generally stress and strain history and temperature-dependent (Reference 28). Thus, stress-strain behavior of geologic materials are nonlinear in nature. Figures 6 and 7 schematically show general stress-strain patterns of geologic materials.



Reference 34

Figure 9. Interface Pressure from Point Source

Identification and simplification of such complex relationships are necessary for analytical or experimental simulation of geologic material responses under blast loadings. As described previously, a linear elastic model is not able to simulate the essence of the ground shock problem. The use of simple nonlinear models (Reference 31) without considering stress-dependency of the material and shear-induced dilatancy is also unsatisfactory (Section II.C). Various other constitutive models have also been used for numerical analyses. These include an elastic-plastic model with an associated flow rule in accordance with theory of plasticity (Reference 35), a hypoelasticity model (Reference 36), a cap model (Reference 37), an elasto-plastic model with non-associated flow rule (References 38 and 39), and a critical state soil model (Reference 40). The adequacy of these models for blast loading problems has not been verified by well-documented laboratory or field ground shock experimental data.

The shear strength of geologic materials is also stress dependent. Although various shear strength models (Reference 28) exist, including Tresca, von Mises, Mohr-Coulomb models, and others (Reference 41), the modified Mohr-Coulomb model is still the most appropriate and widely used in practice. The modified Mohr-Coulomb model, which includes the effect of pore pressure, is expressed as

$$S = C + (\sigma_{ff} - u) \tan \phi$$

where

- S = shear strength (maximum shear stress possible on a failure plane)
- σ_{ff} = total stress normal to the failure plane
- u = pore pressure
- ϕ = effective friction angle
- C = cohesion intercept

In this study, the shear strength equation above is utilized to serve as a basis for discussing the role of shear strength in one-g physical scale modeling to simulate nonnuclear weapons effects.

As pointed out (Reference 27), there are several fundamental concerns in applying geologic material models to analytical simulation of ground shock

problems. These concerns are equally applicable to experimental simulations and include:

- (1) Our understanding of geologic material behavior is mostly based on laboratory testing conducted under idealized stress conditions (uniaxial, biaxial, and triaxial) during quasistatic loading or at a rate of loading significantly dissimilar to the nonuniform intense and rapidly varying loading conditions in blast loading problems.
- (2) Even if reliable material behavior data commensurate with blast problems were obtainable, the problems of capturing all the relevant and salient features of material behavior would still remain a formidable task.

F. SUMMARY OF TECHNOLOGY GAPS

Base on the results of literature review, Table 2 provides a summary of the obvious technology gaps and uncertainties in current state-of-knowledge in simulating structural responses under nonnuclear weapons blasts. Further experimental and analytical studies are needed to solve these technology gaps and uncertainties.

TABLE 2. SUMMARY OF TECHNOLOGY GAPS AND UNCERTAINTIES IN
CURRENT STATE-OF-KNOWLEDGE IN SIMULATING STRUCTURAL
RESPONSE UNDER NONNUCLEAR WEAPONS BLASTS

1. Material Properties of Geologic Materials

- o Properties based on laboratory testing conducted under quasi-static or at a rate of loading significantly dissimilar to the nonuniform high intensity and rapidly varying loading conditions in blast problems
- o Use of simple properties which do not reflect the nonlinear, stress-strain dependent behavior of geologic materials
- o Adequacy of available constitutive models for blast loading problems has not been verified by experimental data.

2. Experimental Studies

- o Uncertainties associated with properties of geologic materials as those summarized in Item 1
- o Insufficient documentation with respect to detailed characterization of geologic materials
- o Site-specific and problem-specific nature (i.e., not intended for general application)
- o Little contribution to general understanding of the problems
- o Insufficient instrumentation and monitoring
- o Lack of well-documented, small-scale, or prototype experiment data
- o Use of inappropriate modeling materials and scaling relations to simulate prototype.

3. Analytical Model

- o Uncertainties associated with geologic material properties as summarized in Item 1 above
 - o Lack of verification by well-documented, small-scale or prototype experimental data
 - o Use of simple constitutive models which do not reflect the relevant and salient features of geologic material behavior
 - o Inability of handling strain-softening effects.
-

SECTION III

ENGINEERING ANALYSIS FOR 1-G MODELS NEGLECTING GRAVITY EFFECTS

A. ASSUMPTIONS

As in any model testing, performing one-g small-scale model tests to simulate nonnuclear weapons effects generally involves several steps: (1) defining the problem and identifying important parameters that affect the problem; (2) establishing the conditions of similarity; (3) selecting an appropriate scale and then choosing materials that satisfy the similarity conditions; (4) constructing the model; (5) performing the tests; and (6) observing and evaluating the model responses. The last three steps will not generally present insurmountable difficulties except that the scale of the model and instrumentation details will affect technical completeness and cost.

In this study, emphasis was placed on ground shock propagation and soil-structure interaction for close-in blasts. The following assumptions were made:

- (1) The source of blast can be modeled as a spherical explosion.
- (2) The effects of a blast on surrounding geologic materials and nearby structures can be simulated by modeling the impact (explosive) energy at the source of blast.
- (3) The magnitude of impact energy at the source of blast is proportional to the weapons yield (weight).

In model testing, the materials used in the model can either be the same materials as those in the prototype system or other equivalent materials that satisfy similarity conditions to be established. However, in view of the complexity of the properties and behavior of geologic materials, it will not always be possible to rigidly adhere to every similarity condition if equivalent dissimilar materials are used. Under such a situation, certain assumptions and simplifications may be necessary as long as they do not significantly affect the accuracy of the results. These simplifications and assumptions will be eliminated if the prototype materials that satisfy the established similarity conditions can be used in the model. Thus, emphasis in

this study should be placed on investigating the feasibility of using prototype materials in small-scale, 1-g model(s).

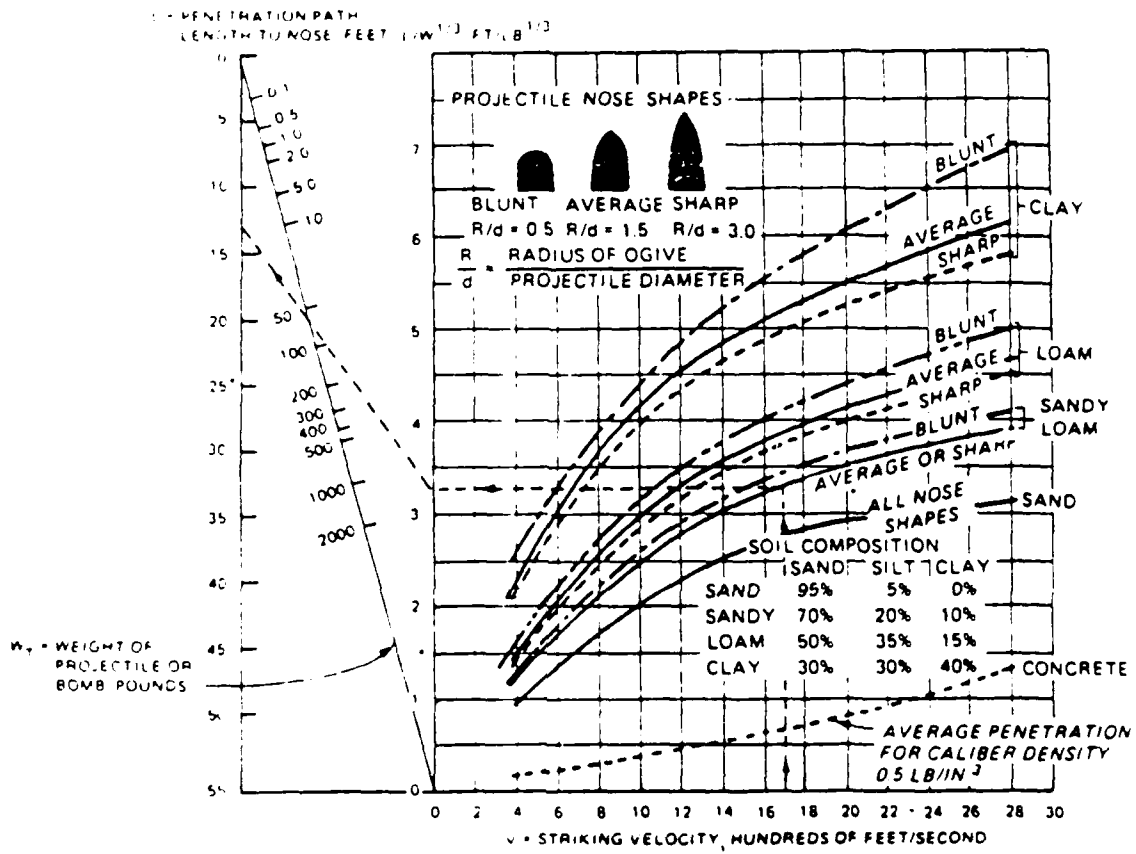
B. GRAVITY EFFECTS

This section presents an approximate comparison of the potential range of blast-induced stresses with gravity stresses using available design graphs (Figures 3 and 10) to qualitatively illustrate potential effects of gravity stresses for discussion purposes only. Available peak stress measurement data shown in Figure 3 can be interpreted for various scaled distances of interest as follows:

Scale Distance R (ft)/ $[W(\text{lbs})]^{1/3}$	Range of Peak Stress (psi)
0.2	300,000
0.5	25,000 to 200,000
1	2,000 to 30,000
2	250 to 10,000

Based on the available nomogram shown in Figure 10 (Reference 4) and assuming a 2,000-pound bomb with a striking velocity of 1700 ft/sec, the penetration depth will range from about 35 to 55 feet for sand and clay/clayey shale, respectively. The stresses because of gravity deadweight were calculated assuming a soil unit weight of about 120 pcf and a Poisson's ratio of 0.3. The calculated peak vertical and horizontal stresses from a 2000-pound weapon blast at various scaled distances are shown in Table 3. These data are approximate in nature since the effects of geologic material yielding (shear failure), the potential effects of reflected waves from the ground surface, material layering, and the soil-structure interaction were not considered.

As shown in this table, if a 2000-pound bomb detonated 35 feet below the ground surface, the estimated ground shock-induced mean confining stresses within the scaled distances of interest, range from 10 to 10,000 times more than the corresponding stresses due to gravity deadweight. It can be postulated that the gravity deadweight would have little effect on the stress-strain behavior on the geologic materials.



Reference 4

Figure 10. Penetration of Bombs and Projectiles into Soil

TABLE 3. COMPARISON BETWEEN CALCULATED PEAK GROUND SHOCK-INDUCED STRESSES AND GRAVITY (DEADWEIGHT) STRESSES* BASED ON DATA SHOWN IN FIGURE 3 (REFERENCE 3)

Depth (ft)	Calculated Peak Stresses (psi) *** at Horizontal Scaled Distance (from blast source)				Gravity Stresses (psi)
	0.2 ft/W-1/3	0.5 ft/W-1/3	1.0 ft/W-1/3	2.0 ft/W-1/3	
0	(V)** 7.5 to 6,500 (H)** 5.4 to 4.66	69 to 5,900 12 to 1,060	53 to 5,360 19 to 2,510	28 to 3,490 21 to 3,280	0 0
5	(V) 140 to 8,000 (H) 12 to 670	98 to 72,000 21 to 1,520	78 to 5,990 33 to 2,510	36 to 3,910 30 to 4,250	4.2 1.8
10	(V) 225 to 10,000 (H) 23 to 1,000	194 to 9,700 49 to 2,440	134 to 7,590 45 to 3,600	49 to 4,230 70 to 5,250	8.3 3.6
15	(V) 397 to 13,890 (H) 50 to 1,750	324 to 13,360 102 to 4,200	245 to 10,100 155 to 6,400	50 to 4,070 70 to 5,250	12.5 5.4
20	(V) 1,480 to 24,650 (H) 249 to 4,140	940 to 17,500 310 to 7,350	383 to 11,500 320 to 9,600	67 to 3,890 163 to 8,360	16.7 7.2
25	(V) 4,460 to 31,000 (H) 1,120 to 7,820	2,290 to 28,800 1,440 to 18,000	532 to 12,500 670 to 15,600	64 to 3,310 163 to 8,360	20.8 8.9
30	(V) 26,800 to 89,300 (H) 13,500 to 45,000	6,220 to 37,200 7,830 to 47,000	555 to 10,000 1,400 to 25,000	40 to 1,990 196 to 9,800	25 10.7
35	(V) -0 (H) 300,000	-0 25,000 to 200,000	-0 2,000 to 30,000	-0 210 to 11,000	29.2 12.5

Notes:

*Depth of Burst = 35 feet, Weapons Yield W = 2,000 lbs.

** (V) = normal stress in vertical direction, (H) = normal stress in horizontal direction

***Lower bound and upper bound values for dry loose sand and saturated clay/clay shale, respectively.

The following section (Section III.C) presents the 1-g small-scale model concept and procedures that are applicable where gravity effects are insignificant. However, since the current state-of-knowledge cannot determine exact significance, this concept is intended for illustration purposes only.

C. ONE-G MODEL USING PROTOTYPE MATERIALS

1. Concept

The previous section demonstrates that the potential gravity effects may not be significant for experimental simulations of nonnuclear weapons effects on a close-in structure. Under such a condition, 1-g small-scale models can be developed using the same materials as those associated with the prototype systems. This concept was first utilized (Reference 43) in modeling the elastic structural response to a blast wave. The concept has since been extended for scaling large deformation and elastic-plastic response of structures-to-blast loading (References 44 and 10). Various experimental verifications of this concept have also been reported (Reference 10).

The concept is based on the "replica" modeling procedure (Reference 10) where any geometric dimension of a model is a scaled-down version of the prototype system and the same materials (geologic materials, weapon charge type, and structure materials) are employed in the model and prototype. Stress, velocity, and mass density-per-unit-volume, under such conditions, are identical at homologous locations. The time scale, times, and the lengths scale are the same.

In summary, the following relations are applicable:

$$l_m = \lambda l_p \quad (1)$$

$$(\sigma_{ij})_m = (\sigma_{ij})_p \quad (2)$$

$$(u_i)_m = (u_i)_p \quad (3)$$

$$t_m = \lambda t_p \quad (4)$$

$$\rho_m = \rho_p \quad (5)$$

where λ = geometric scaling factor

l = length

σ_{ij} = stress tensor (nine components) on the j th face in the i th direction ($i = 1, 2, 3$ and $j = 1, 2, 3$)

u_i = particle velocity in the i th direction

t = time

ρ = mass density per unit volume.

Subscripts "m" and "p" represent the model and the prototype, respectively.

The relations above also apply to

$$(\epsilon_{ij})_m = (\epsilon_{ij})_p \quad (6)$$

$$(u_i)_m = \lambda(u_i)_p \quad (7)$$

$$(u_i)_m = \frac{1}{\lambda} (\ddot{u}_i)_p \quad (8)$$

where ϵ_{ij} = strain tensor (nine components) on the j th face in the i th direction

u_i = particle displacement in the i th direction, $i = 1, 2, 3$

$\ddot{u}_i$ = particle acceleration in the i th direction, $i = 1, 2, 3$

Since stress and strain components for the model are identical to the corresponding components in the prototype, the deformation and strength characteristics of the model and prototype must also be identical. This condition is automatically satisfied since the same materials are used in both the prototype and the model.

The general equation of motion governing the dynamic response is

$$\sigma_{ij,j} + \rho f_i = \rho \ddot{u}_i \quad (9)$$

where f_i = body force per unit volume in the i th direction,
 $i = 1, 2, 3$

Since gravity effects for a close-in blast can be ignored, the equation of motion can be rewritten as

$$\sigma_{ij,j} = \rho \ddot{u}_i \quad (10)$$

Equations (1), (2), (4), (5), and (8) can be used to prove that Equation (10) is automatically satisfied.

2. Scaling of Weapons Yield

It is assumed that weapons weight is proportional to impact energy. Impact energy is a product of force and length. In this case, the scaling factor for impact energy will be equal to λ^3 . Thus, scaling of weapons yield (W) should be as follows:

$$(W_m/W_p)^{1/3} = \lambda \quad (11)$$

This scaling relation is exactly the same as the Hopkinson's rule stated in Section II.B.

3. Soil-Structure Interaction

The uncertainties in the constitutive modeling of geologic materials and structural elements (Section II) make the analytical evaluation of soil-structure interaction complex. However, for a scaled experiment, it is relatively straightforward. The ground shock waves (incident and reflected waves) will produce a generalized transient pressure (surface tractions) of P and a duration of T on the prototype structure, that will cause the structure to respond in its natural modes of vibration with modal frequencies of $f_1, f_2, \dots$ for corresponding modal displacements of $X_1, X_2, \dots, X_n$. If the entire system is scaled geometrically by a factor of λ and if the modal frequencies of the structural models are $1/\lambda$ of the corresponding frequencies in the prototype, then the model will predict the structural responses in accordance with the established scaling rules [Equations (1) to (8)]. This is graphically illustrated in Figure 11.

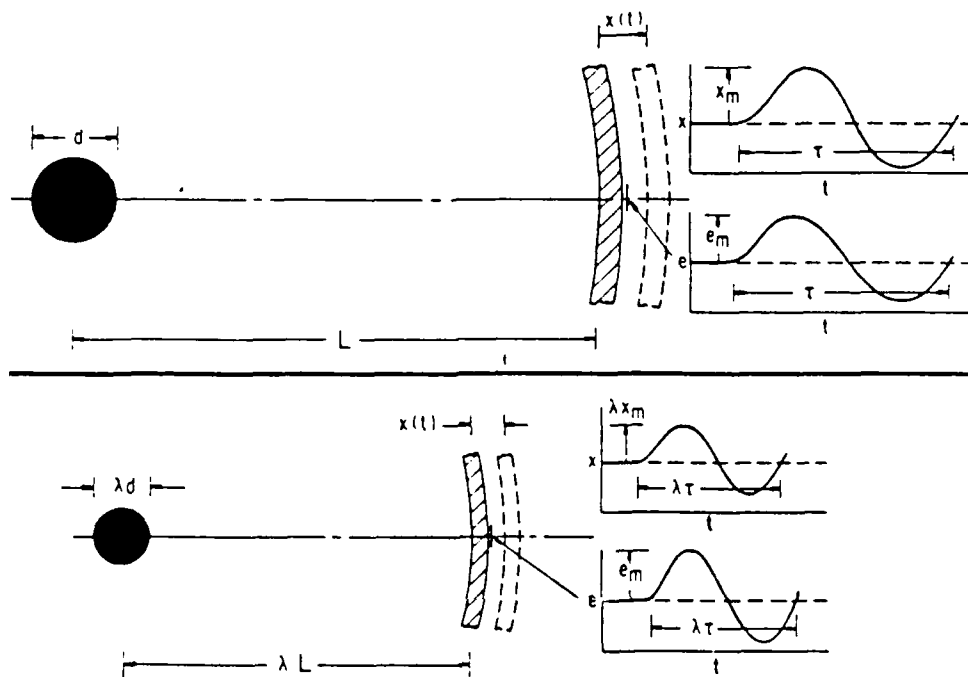


Figure 11. Replica Scaling of Structural Response to Blast Loading

Modeling the structure using prototype materials for testing and automatically satisfying the above modal frequency requirement, is relatively simple if the structural dimensions are geometrically scaled with the same scaling factor λ .

To illustrate this point, selected general modal frequency formulas compiled (Reference 45) for various common structural systems and members such as beam/column, plates, and shells are shown in Table 4. The formulas shown in Table 1 are general in nature and applicable to all varieties of boundary conditions and structural elements including elements with solid, cylindrical, tubular sections, curved, or nonuniform cross sections, and with or without concentrated masses. All the conceivable variations documented (Reference 45) were examined in this study. The results indicate that the structural scaling relationships derived in this section and summarized in Table 5 and the modal frequency formulas shown in Table 4 can satisfy the modal frequency scaling requirements $[(f_i)_m = (f_i)_p/\lambda$ or $(f_{ij})_m = (f_{ij})_p/\lambda]$ without exception.

4. Remarks

The 1-g scale model described in this section assumes that the effects of gravity are insignificant. While this assumption sometimes limits the general applicability of the developed modeling concept. Instead, a more general 1-g scale model concept which can compensate for gravity effects, whether they are significant or not, will be more appropriate. The concept and associated model material requirements of such a general purpose 1-g scale model are presented in Section IV.

TABLE 4. GENERAL MODEL FREQUENCY FORMULA FOR STRUCTURAL SYSTEM AND ELEMENTS
(REFERENCE 45)

Structural Element	Mode of Vibration	Modal Frequency Formulas $f_1, i = 1, 2, 3 \dots$ or $f_{ij}, j = 1, 2, 3$	Comments
Beam/Column	Transverse Vibration of Flexural Beam	$f_1 = \frac{(k_t)_1}{2\pi L^2} \left(\frac{EI}{m} \right)^{1/4}$	1. Dimensionless Coefficients $(k_t)_1, (k_s)_1, (k_0)_1, (K_0)_1, (k_{s1})_1$ $(k_2)_1, \alpha_{ij}, (k_s)_1, (k_{s3})_1, C,$ and K are functions of boundary conditions (end constraints) and geometry.
	Vibration	$f_1 = \frac{(k_s)_1}{2\pi L^2} \left(\frac{EI}{m} \right)^{1/4}$	
	Shear Beam/Shear Vibration	$f_1 = \frac{(k_s)_1}{2\pi L} \left(\frac{KG}{\rho} \right)^{1/4}$	
	Torsional Vibration	$f_1 = \frac{(k_0)_1}{2\pi L} \left(\frac{CG}{\rho I_p} \right)^{1/4}$	
Plate/Slab	All Modes	$f_{ij} = \frac{(k_p)_{ij}^2}{2\pi a^2} \left[\frac{ER^3}{12\nu(1-\nu)^2} \right]$	2. The above coefficients are the same for prototype and geometrically scaled models in this study.
Shell	Cylindrical Shell of Infinite Length	$f_1 = \frac{(k_{s1})}{2\pi Q} \left[\frac{E}{\rho(1-\nu^2)} \right]^{1/4}$	3. Descriptions of involved properties and dimensions as well as associated scaling relationships are shown in Table 4.
	Cylindrical Shell of Finite Segment	$f_{ij} = \frac{(k_{s2})_{ij}}{2\pi Q} \left[\frac{E}{\rho(1-\nu^2)} \right]$	
	Cylindrically curved panel	$f_{ij} = \left[(f_{ij})_p + \frac{\alpha_{ij} E h}{a^2 \nu (1-\nu)} \right]$	
	Spherical Shell segments	$f_{ij} = \left[(f_{ij})_p + \frac{E}{\rho a^2} \right]^{1/4}$	
	Torsional Mode of Spherical Caps	$f_1 = \frac{(k_{s3})_1}{2\pi a} \left[\frac{E}{\rho(1-\nu^2)} \right]^{1/4}$	

TABLE 5. SCALING RELATIONS FOR PARAMETERS INVOLVED IN TABLE 3

Symbol in Table 4	Description	Scaling Relation for Model Described in Section III	Scaling Relation for Model Described in Section IV
E	Young's Modulus	$E_m = E_p$	$E_m = \rho^* \lambda E_p$
L	Length of Segment	$L_m = \lambda L_p$	$L_m = \lambda L_p$
a	Radius of a cylinder or sphere, or length of one of the rec- tangular or square plate	$a_m = \lambda a_p$	$a_m = \lambda a_p$
I	Moment of inertia	$I_m = \lambda^4 I_p$	$I_m = \lambda^4 I_p$
R	Thickness of tubular section, or plate or sheet	$h_m = \lambda h_p$	$h_m = \lambda h_p$
M	Mass density per unit length	$M_m = \lambda^2 M_p$	$M_m = \rho^* \lambda^2 M_p$
Y	Mass density per unit area	$\gamma_m = \lambda \gamma_p$	$\gamma_m = \rho^* \lambda^2 \gamma_p$
G	Shear Modulus	$G_m = G_p$	$G_m = \rho^* \lambda G_p$
ρ	Mass density per unit volume	$\rho_m = \rho_p$	$\rho_m = \rho^* \rho_p$
I_p	Polar area moment of Inertia about axis of torsion	$(I_p)_m = \lambda^4 (I_p)_p$	$(I_p)_m = \lambda^4 (I_p)_p$

SECTION IV GENERAL PURPOSE 1-G MODELING CONCEPT CAPABLE OF COMPENSATING FOR GRAVITY EFFECTS

A. GENERAL

The model developed in Section III is applicable only if gravity has little or no effects on the results. If gravity effects are significant, the model scaling relationships generated in Section III will be unsatisfactory. This section presents a general purpose one-g small-scale model concept that can compensate for gravity effects, significant or not.

B. DERIVATION OF SCALING RELATIONS

1. Geometric Scaling

In this concept, the conditions of geometric scaling are still valid. Thus,

$$\frac{l_m}{l_p} = \lambda \quad (12)$$

To satisfy geometric scaling during and after blasting, the strain, ϵ_{ij} , in the prototype and the model must be the same, i.e.,

$$(\epsilon_{ij})_m = (\epsilon_{ij})_p \quad (13)$$

This indicates that the displacement (u_i), velocity ($\dot{u}_i$) and acceleration ($\ddot{u}_i$) should have the following scaling relationships:

$$(u_i)_m = \lambda(u_i)_p \quad (14)$$

$$(\dot{u}_i)_m = \lambda(\dot{u}_i)_p/t^* \quad (15)$$

$$(\ddot{u}_i)_m = \lambda(\ddot{u}_i)_p/(t^*)^2 \quad (16)$$

$$\text{and } t_m = t^* t_p \quad (17)$$

where t^* = time scaling factor.

2. Scaling of Time and Stress

The equation of motion shown in Equation (9) is used for the purpose of scaling the time and stresses. The scaling relations for stress (σ_{ij}) , mass density per unit volume (ρ) , and body force (f_i) can be expressed as:

$$(\sigma_{ij})_m = \sigma^* (\sigma_{ij})_p \quad (18)$$

$$\rho_m = \rho^* \rho_p \quad (19)$$

$$(f_i)_m = f^* (f_i)_p \quad (20)$$

Where σ^* , ρ^* , and f^* are scaling factors for stress, mass density per unit volume, and body force, respectively.

For a 1-g model, the body force per unit volume is equal to the gravity (g). Thus, $f^* = 1$ (21)

Substituting Equations (17), (18), (19), and (21) into the general equation of motion [Equation (10)] for the model and prototype we obtain the following relationship:

$$(\sigma_{ij,j})_p + \frac{\rho^* \lambda}{\sigma^*} (\rho g)_p = \frac{\rho^* \lambda^2}{\sigma^* (t^*)^2} (\rho \ddot{u}_i)_p \quad (22)$$

Equation (22) implies

$$\sigma^* = \rho^* \lambda \quad (23)$$

$$t^* = \sqrt{\lambda} \quad (24)$$

The mass densities per unit volume of geologic materials do not differ appreciably. For all practical purposes, if geologic materials are used as simulants in the model the mass density scaling factor can be expressed as

$$\rho^* = 1 \quad (25)$$

Thus, if geologic materials are used as simulants, Equations (23) to (25) give

$$\sigma^* = \lambda \quad (26)$$

3. Constitutive Similarity Scaling

If dissimilar materials are used in the model, constitutive similarity conditions require that the model and prototype materials have homologous stress-strain curves and strength properties. Since the stresses in the model are scaled with a factor of σ^* and the model strains are unscaled (i.e., same as the prototype strain), the stiffness properties in terms of hydrostatic, deviation and shear-dilatancy behavior will need a scale factor of σ^* . This is shown graphically in Figure 12.

Similarly the shear strength in terms of Mohr-Coulomb parameters (C and ϕ) should have the same scaling factor σ^* , i.e.,

$$C_m + (\sigma_n')_m \tan \phi_m = \sigma^* [C_p + (\sigma_n')_p \tan \phi_p] \quad (27)$$

where σ_n' = effective normal stress on the failure surface

Since $(\sigma_n')_m = \sigma^*(\sigma_n')_p$, Equation (27) indicates that the following relations should be maintained:

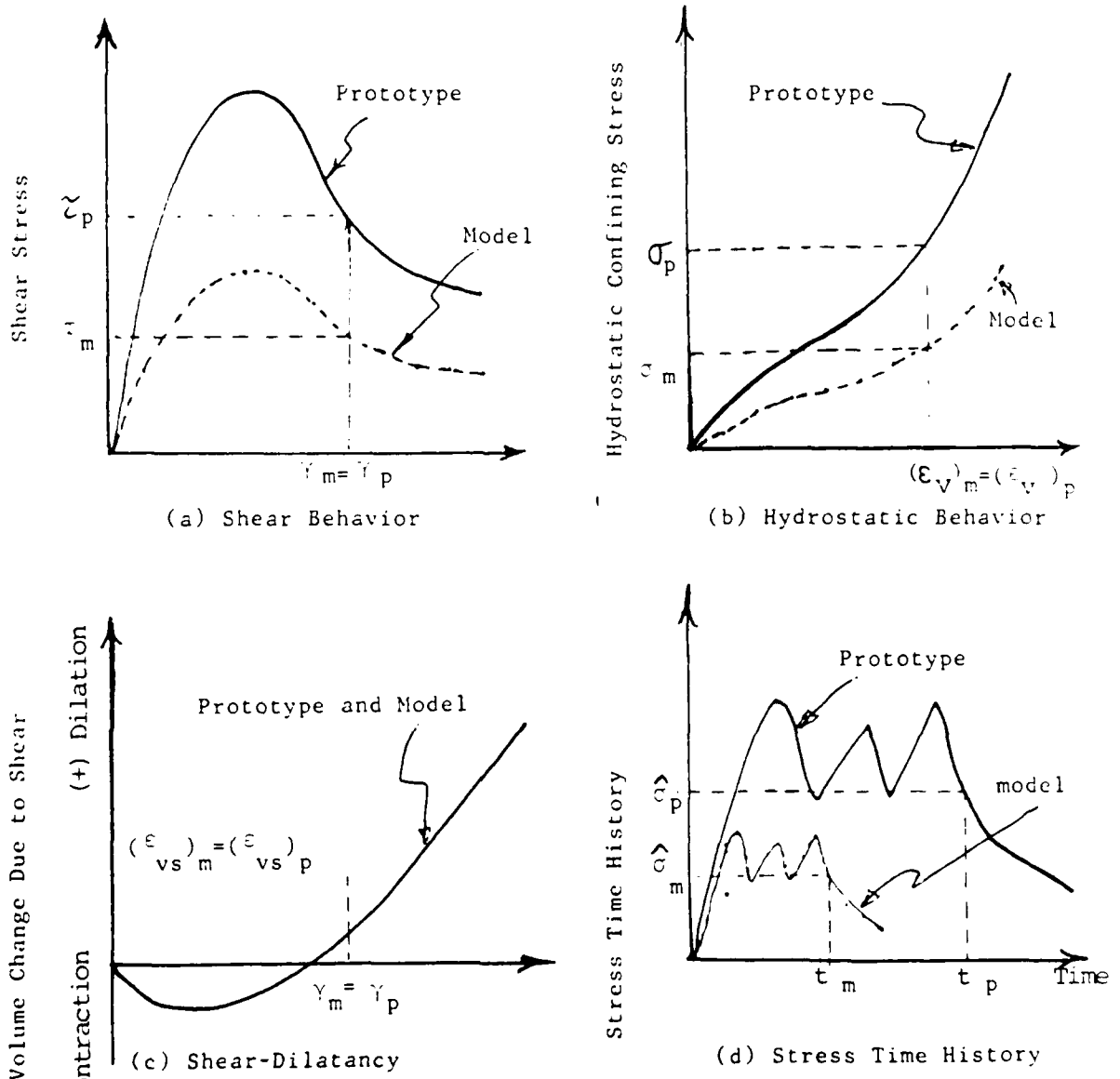
$$C_m = \sigma^* C_p \quad (28)$$

$$\phi_m = \phi_p \quad (29)$$

4. Scaling of Weapons Yield

The impact energy is a product of force (stress times area) and length. According to the above developed scaling relations, the scaling factor for impact energy will be equal to $\rho^* \lambda^4$. Since impact energy is assumed proportional to weapons yield (W), the following scaling relation for weapons yield will be valid:

$$W_m = \rho^* \lambda^4 W_p \quad (30)$$



$$\frac{\gamma_m}{\gamma_p} = \frac{(\epsilon_v)_m}{(\epsilon_v)_p} = \frac{(\epsilon_{vs})_m}{(\epsilon_{vs})_p} = 1$$

$$\frac{\tau_m}{\tau_p} = \frac{\sigma_m}{\sigma_p} = \frac{\hat{\sigma}_m}{\hat{\sigma}_p} = \sigma^* = \text{Stress Scaling Factor}$$

$$t_m/t_p = N^\lambda \quad \text{where } \lambda = \text{Geometric Scaling Factor}$$

Figure 12. Constitutive Similarity Requirement for Geologic Materials

5. Structural Model and Soil-Structure Interaction

For structural materials, appropriate constitutive relations can be represented by Young's Modulus E , yield stress σ_y , ultimate stress σ_u , or other properties. These properties all have to be scaled by a factor of σ^* for the model. This scaling is shown in Figure 13 in dimensionless and dimensional forms.

For the soil-structure interaction scaling, modeling concepts similar to those detailed in Section III.C can be followed. This essentially follows the concept that modal frequencies of the model should be $1/\sqrt{\lambda}$ of the corresponding prototype modal frequencies (since the time scale is $\sqrt{\lambda}$). Again, formulas detailed in Table 3 and the above developed scaling relationships (summarized in Table 4) were utilized to evaluate this soil-structure interaction requirement. The results show that such a requirement is automatically satisfied.

C. SIMULANT MATERIALS FOR MODEL

The scaling relationships derived in Section IV.B require the model materials to have significantly (σ^* times) less stiffness and strength characteristics than the prototype materials. The means of finding such equivalent materials (simulants), especially for geologic materials, to satisfy the constitutive scaling shown in Figures 12 and 13 are described in this section.

The ability to obtain suitable simulants for 1-g small-scale model tests depends, to a large extent, on material types and the selected geometric scaling factor λ . An arbitrary range for λ of 0.05 (1/20) to 0.1 (1/10) is selected as a target for this study for the following reasons:

- (1) If the scaling factor λ is larger than 0.1, model tests may become too expensive.
- (2) If the scaling factor λ is less than 0.05, it may be difficult to model the structure in sufficient detail for a reliable structural response study.

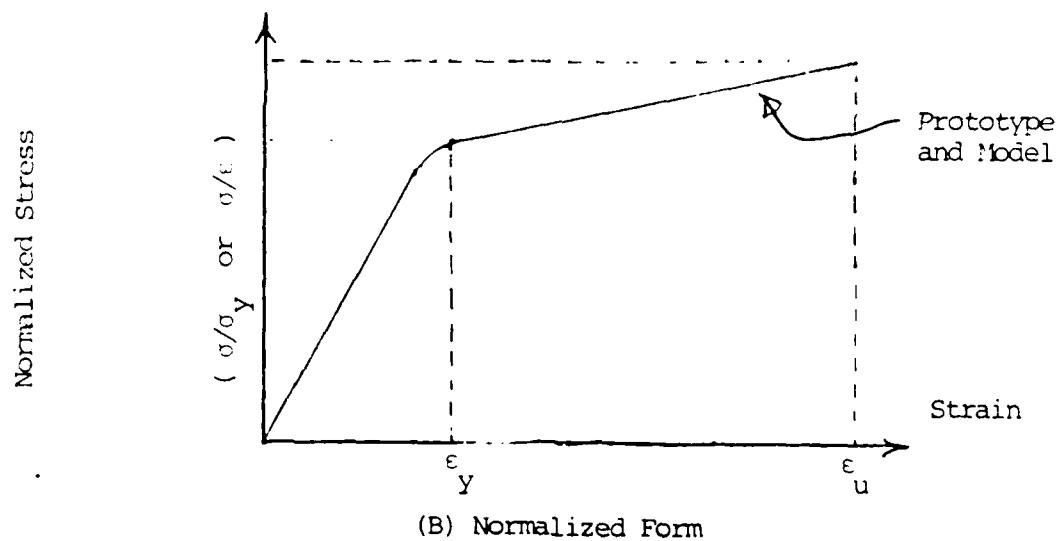
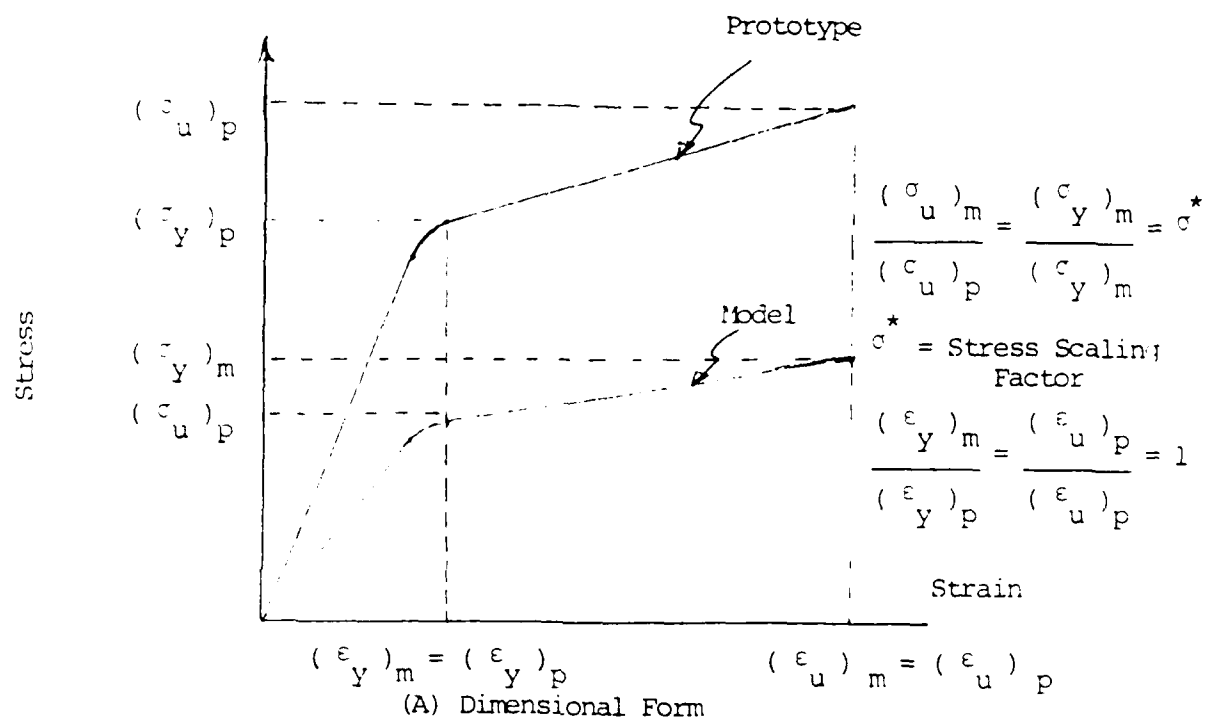


Figure 13. Constitutive Similarity Requirement for Structural Materials

The above λ range may not always be possible since suitable simulants may not exist within such a scaling range. Potential means and difficulties of obtaining suitable model simulants are presented in the following subsections.

1. Cohesionless Soils

The strength scaling relation shown in Equation (29) indicates that prototype soils can be utilized as model materials. However, they should also satisfy the stress-strain relationship shown in Figure 12. This can be accomplished by the provision stated in the subsequent paragraphs.

As suggested (Reference 46), the state parameters of a cohesionless soil can be prescribed within a specific steady state line (SSL) and parallel lines above or below the SSL. At any point along the SSL or any parallel line, the sand will exhibit similar normalized stress-strain behavior when subjected to the same normalized loading path. This is illustrated in Figure 14. This means that model sand should have lower density (i.e., higher void ratio) than the prototype sand in order to achieve similar normalized stress-strain behavior.

In past model tests, it has been incorrectly assumed that the density of the model soil be the same as that of the prototype. As pointed out (Reference 47), various examples exist in the literature (References 48 and 49) that describe soil as "loose," "dense," etc., with the implication that the observed behavior will be representative of a "loose," "dense," etc., prototype soil. This may be the reason why some of the 1-g model tests failed to duplicate prototype behavior (Reference 50).

The applicability of this modeling concept for cohesionless soils (Figure 14) has been verified (Reference 47) by conducting 1/100 scale 1-g tests following the same modeling concept to simulate the lateral load-deflection behavior of a prototype pile in sand. The results of model tests and corresponding prototype tests are practically identical. The same concept can apply to blast loading effects on structural response.

Recent experiments (Reference 47) indicate that for dense prototype sands a size scaling factor as small as 1/100 is achievable. For looser

sands, this scaling factor will be increased. However, it is quite reasonable to anticipate a scaling factor of 0.05 or less being achievable, even for very loose sand.

A supplementary concept for producing appropriate model materials for cohesionless soils is to use heavier materials such as lead shot which can increase the mass density by a factor of about 4 (i.e., $\rho^* = 4$)^{*}. Based on Equation (23), the stress scaling factor would become 4λ instead of λ , if lead shot material is used as a simulant for cohesionless soils. For example, for $\lambda = 0.05$ (1/20 scale), the stress scaling factor would be only 0.2 (1/5 scale). If this supplementary concept is utilized, a scaling factor of about 0.0125 (i.e., 0.05 divided by 4) or less can be achieved to simulate the behavior of very loose sand.

2. Cohesive Soils (Clays)

a. Saturated Clay

As suggested by Scott (Reference 47), the modeling concept considered for cohesionless soils (described above) can also be applied to saturated clays. The same considerations of critical state line and stress-strain similarity apply. In this case, modeling soils along the critical state line or its parallel lines can be achieved by varying void ratio, moisture content, or over consolidation ratio (OCR).

For saturated cohesive soils during blast loading, the relevant shear strength will be in terms of consolidated undrained shear strength, S_u , since the blast loading will last a very short time (a small fraction of a second). Thus, the relevant shear strength of saturated cohesive soils can be considered to have a single strength parameter in terms of S_u (similar to the cohesion component).

* The specific gravity of lead is about 11.32 and the specific gravity of soil grain (e.g., quartz) is generally about 2.7.

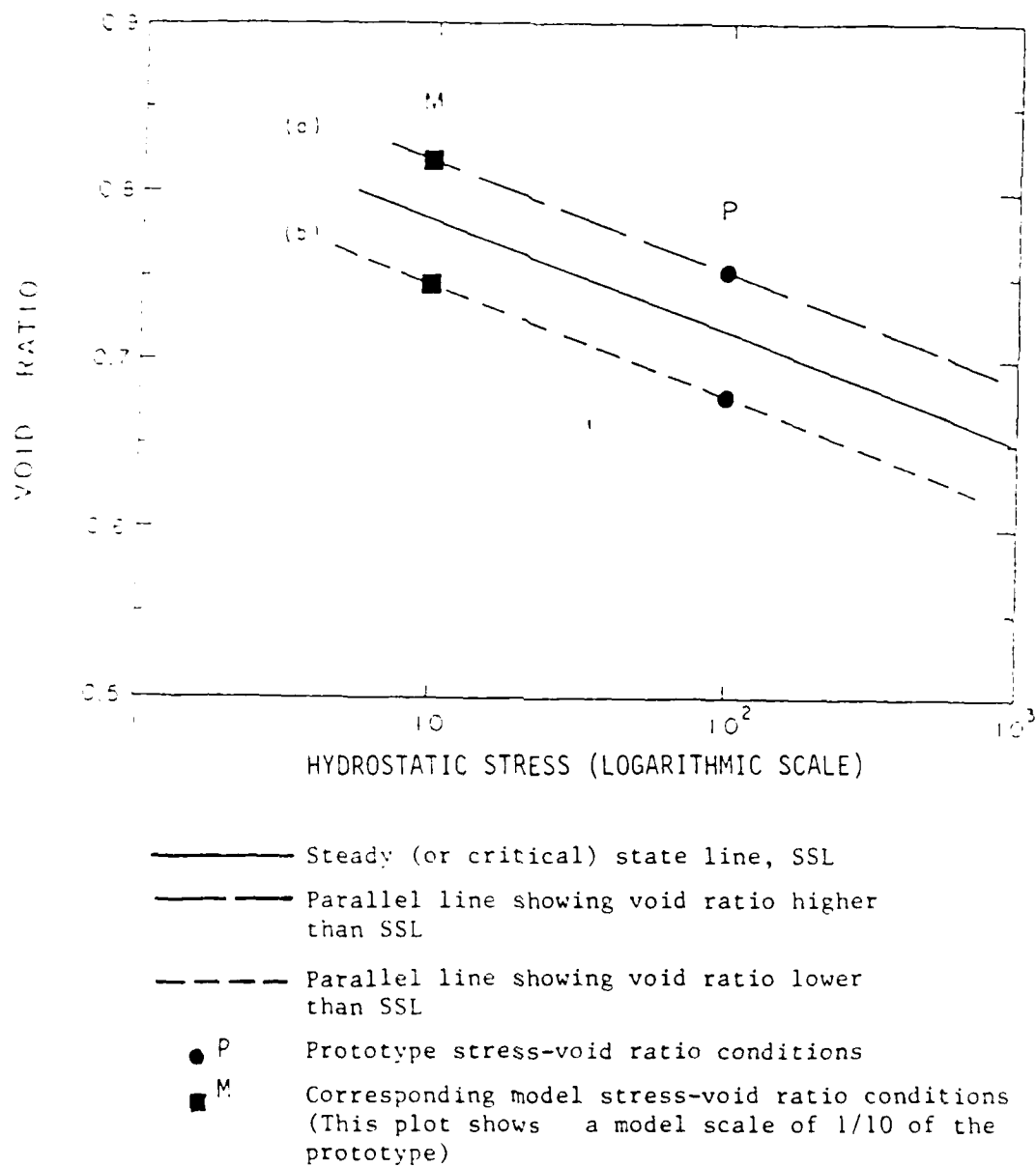


Figure 14. Conceptual Diagram Showing Relationship Between Model and Prototype Cohesionless Soils

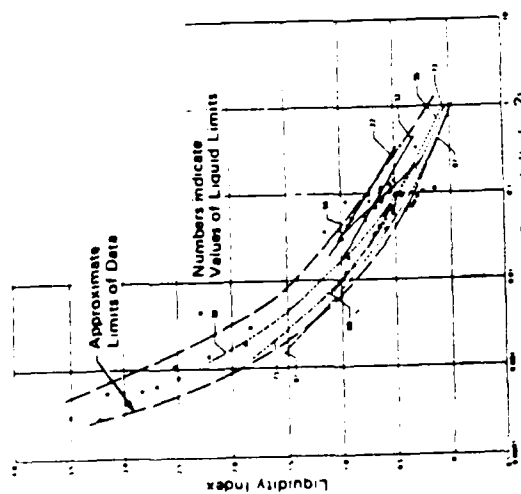
Supplementary concepts for producing soil simulants for saturated clays are available. In geotechnical engineering practice several methods exist to reduce stiffness and strength properties of cohesive materials. These include one or a combination of the following:

- o Remold the soil (i.e., disturb and destroy the soil fabric structure)
- o Increase moisture content
- o Partly or completely replace the soils with clay minerals, especially montmorillonites (calcium or sodium bentonites)
- o Make a soil slurry and let the moisture content dissipate to the desired moisture content level
- o Subject the soil to different consolidation stresses significantly lower than those experienced by the prototype materials.

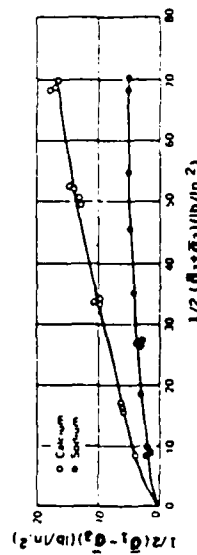
If a soil simulant, obtained by one or a combination of the above supplementary methods, is found too soft to satisfy the constitutive requirements, granular materials can be added to increase its stiffness and strength to the desired levels. Selected data to illustrate the feasibility of using the above methods to achieve the desired scaling requirements are shown in Figure 15.

Another supplementary concept, same as the one developed for cohesionless soils, is to add lead shot to the clay to increase ρ^* (i.e. increasing the required scaling factor σ^* for constitutive similarity). In other words, lead shot can be added to cohesive soils to increase their ρ^* and increase the constitutive scaling requirements.

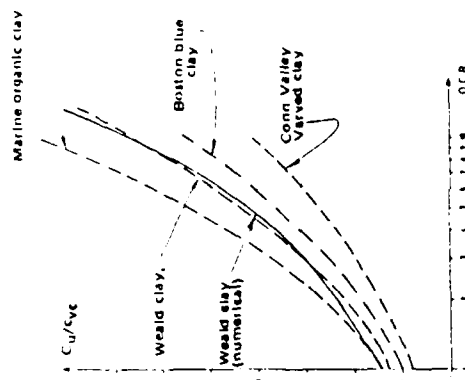
Although additional work is needed to develop supplementary simulants for different cohesive soils at different geometric scales, we believe the above methods can produce satisfactory simulants for saturated cohesive soils. Such simulants will satisfy the constitutive similarity requirements for a 1-g model capable of incorporating gravity effects and evaluating structural response under nonnuclear weapons blasts.



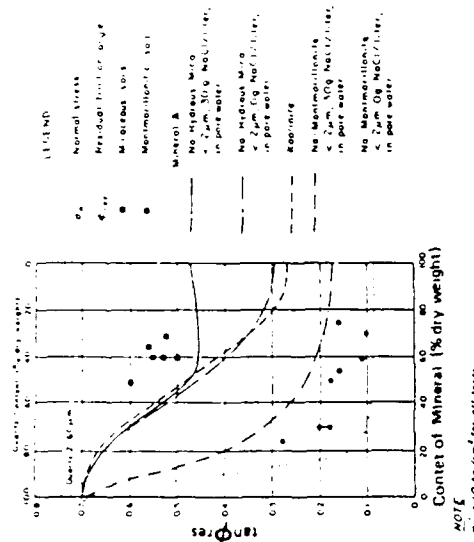
(a) Remold Shear Strength



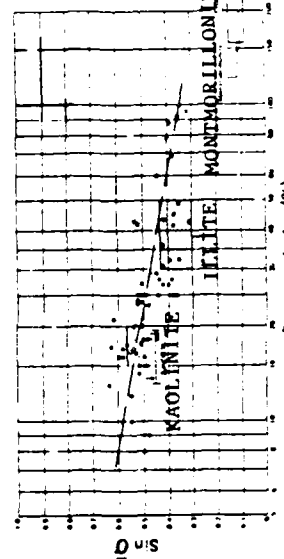
(d) Mohr-Coulomb Failure Envelopes of Calcium and Sodium Montmorillonites



(b) Variation of C_u Vs. OCR



(c) Residual Shear Strength Vs. Clay Mineral Content



(e) Effective Friction Angles of Various Clay Minerals

$\bar{\sigma}_1$ = Effective major principal stress
 $\bar{\sigma}_3$ = Effective minor principal stress
 ϕ = Effective friction angle
 C_u = Undrained shear strength
 $\bar{\sigma}_{vc}$ = Effective vertical stress
 σ_{OCR} = Overconsolidation Ratio

REFS: 52 (a) & (c)
 39 (b)
 53 (d)
 54 (e)

Figure 15. Examples of strength Behavior of Clay and Clay Minerals

b. Moist or Partially Saturated Clays

For moist or partially saturated (i.e., above the groundwater table) cohesive materials, the shear strength parameters include c and ϕ components. Our understanding of moist or partially saturated clays is less defined than that of saturated clays. However, it is reasonable to anticipate that a critical state and stress-strain similarity for cohesionless soils and saturated clays can apply to moist and partially saturated clays. In this case, void ratio, moisture content, and OCR are again the parameters that require adjustment to satisfy the critical state and similarity requirements.

The supplementary concepts developed for the saturated clays are equally applicable for moist and partially saturated clays.

c. Range of Scaling Factors

For either saturated or partially saturated clays, we anticipate that a scaling factor of 0.05 or less can be achieved.

3. Rock

Natural rock deposits have a wide variety of strength and stiffness characteristics. Detailed modeling of rock behavior requires the knowledge of strength and stress-strain behavior of intact rock and discontinuities in the rock mass which are difficult to define. Orientation, frequencies of occurrence, and surface roughness of the discontinuities have a significant influence on the in situ rock mass behavior. In general, the friction angle along a discontinuity is 25° to 40° (Table 6-after Reference 55). These friction angles do not require scaling [Equation (29)]. Such discontinuities are easily simulated by varying the roughness of surfaces.

One of the logical choices for rock simulants would be the use of cement or gypsum grouts by changing water ratios to adjust the consistency of

TABLE 6. APPROXIMATE FRICTION ANGLE ALONG DISCONTINUITIES
FOR DIFFERENT ROCKS (REFERENCE 55)

Rock	ϕ -degrees
Amphibolite	32
Basalt	31 - 38
Conglomerate	35
Chalk	30
Dolomite	27 - 31
Gneiss (schistose)	23 - 29
Granite (fine grain)	29 - 35
Granite (coarse grain)	31 - 35
Limestone	33 - 40
Porphyry	31
Sandstone	25 - 35
Shale	27
Siltstone	27 - 31
Slate	25 - 30

Lower value is generally given by tests on wet rock surfaces.

the grout. Rimer (Reference 56) reported using a low density LD2C4 grout in a laboratory small scale explosive experiment and claimed to be able to simulate particle velocity in high strength and saturated tuffs calculated by two different analytical models. Unfortunately, neither the composition of the grout nor the material properties of the prototype tuff materials were given. Some of the potential approaches to obtain rock simulants have been described (Reference 57). The concepts essentially involve the use of cement or gypsum grouts with or without one or a combination of the following additives:

- o Bentonites
- o Barites
- o Glass beads
- o Air entraining agent.

Some of the typical shear strength properties of rock (References 58 and 59) are shown in Table 7. Some of the available literature data on cement grouts (References 60 and 61) and plaster/celite grouts (Reference 62) are shown in Figures 16 and 17, respectively. A close examination of these data would indicate that there exist various means to produce rock simulants from these grout mixes to practically an unlimited geometric scaling range for rock properties covered in Table 7. In addition, various methods to fine-tune these strength and stiffness properties are also possible by the presence of additives such as:

- o Flyash
- o Sulfur
- o Brine

Temperature, moisture conditioning, and curing time, can be varied to fine-tune these properties to satisfy the similarity scaling requirements.

In summary, it is clearly possible to produce simulants to model a wide spectrum of natural rock deposits to the required geometric scaling range for this study.

TABLE 7. SUMMARY OF TYPICAL SHEAR STRENGTH AND YOUNG'S MODULUS VALUES OF INTACT ROCK (REFERENCES 58 AND 59)

Rock Type	Typical Shear Strength Parameters of Intact Rock Ranges/(Average value)			Ratio of Initial* Young's Modulus to Uniaxial Strength
	Uniaxial Strength Ksi	Cohesion, c, Ksi	Friction Angle, ϕ Degree	
Granite	10 to 40/(25)	1.4 to 5.8/(3.6)	51 to 58/(55)	32 to 500
Limestone	3 to 30/(15 to 20)	0.5 to 5/(2.5 to 3.3)	37 to 58/(50)	200 to 1,000
Sandstone	3 to 30/(8 to 20)	0.6 to 6/(1.6 to 4.1)	48 to 50/(48)	125 to 500
Shale*	1 to 27/(?)	?	?	100 to 275
Quartzite*	17 to 55/(?)	?	?	250 to 600
Diabase*	30 to 52/(?)	?	?	250 to 350
Basalt*	3 to 55/(?)	?	?	200 to 580

Notes:

* Data estimated (Reference 59)

? Data not included in Reference 58

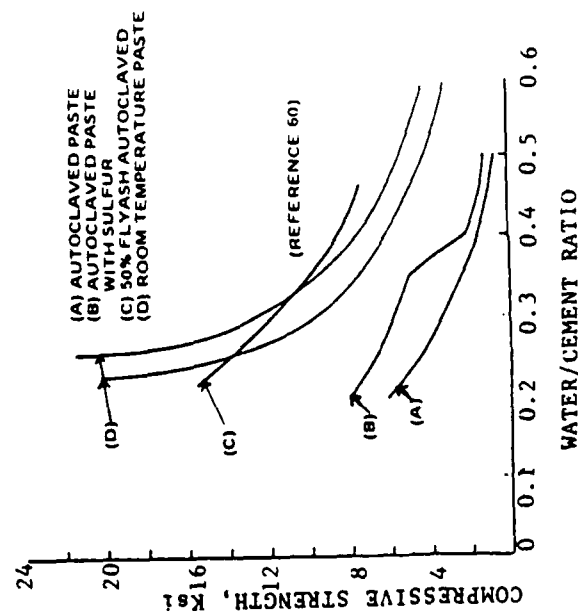
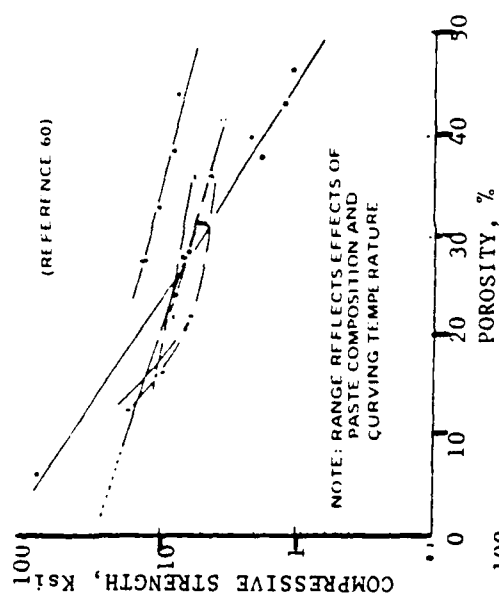
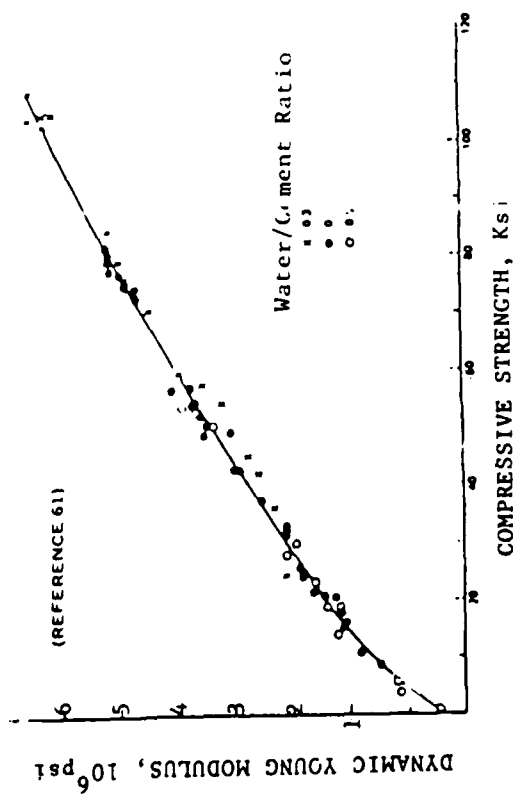
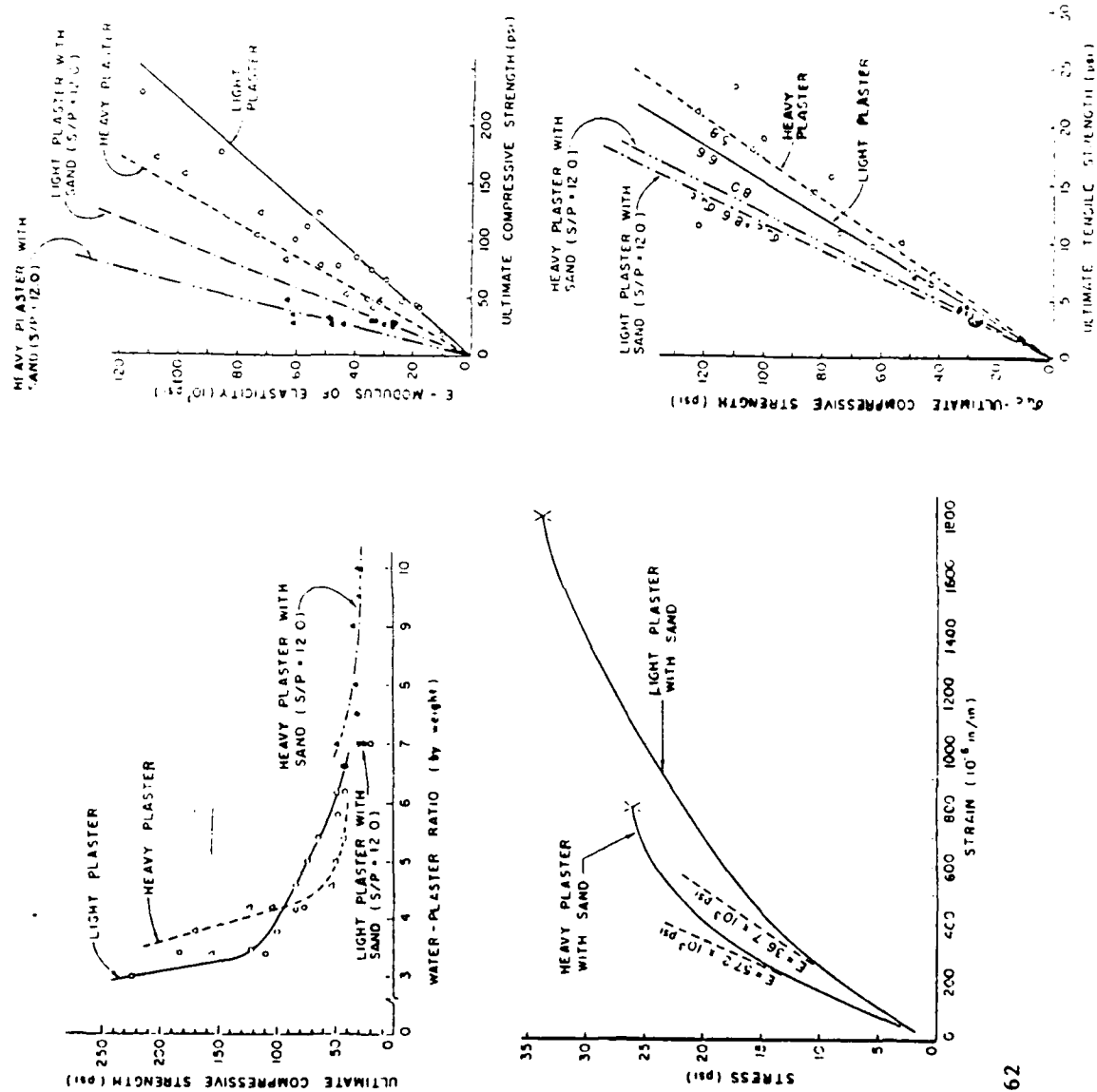


Figure 16. Example Cement Grout Behavior Range



Reference 62

Figure 17. Example Plaster Grout Behavior Range

4. Concrete and Reinforcement

The strength and stiffness of concrete are within the ranges of those anticipated for natural rock deposits. Simulating concrete behavior, using the above concepts for modeling rock properties, is entirely feasible.

Steel reinforcement in the concrete is primarily used for the purpose of providing tensile strength of the structural members. Simulation of such tensile strength in accordance with the required similarity relationships is a relatively easy task since one or a combination of the following two provisions can be easily utilized:

- (1) Changing the reinforcement in terms of number and cross-sectional area
- (2) Use of other materials such as aluminum, aluminum alloy, plastic fibers, etc., with tensile strengths lower than that of the reinforcement steel.

5. Steel Structural Elements

Modeling the strength and stiffness behavior of steel structural components to the required range of 0.05 to 0.1 will require further work. Some researchers (References 10 and 63) have attempted using 6061-T6 aluminum alloy and tin alloy (white metal-92 percent Sn, 8 percent Sb) to scale the steel behavior. The 6061-T6 aluminum alloy can provide a scale factor for Young's Modulus and yield stress of about 0.33. However, the mass density scale factor (ρ^*) of 0.31 [i.e., λ is about 1 based on Equation (23)] is unacceptable. The tin alloy (Reference 63) is capable of achieving a geometric scale of about 1/6, but this is still too large in comparison with the range of interest (0.05 to 0.1).

Other alternatives will be required. Potentially viable materials might include lead alloys, steel reinforced fiberglass, and steel-reinforced synthetic rubbers. The Metals Handbook (Reference 64) has listed the following ranges of properties for lead alloys (lead contents 99 percent or more):

- o Ultimate Tensile Strengths: 2300 to 10,300 psi
- o Yield Strength: 808 to 9570 psi
- o Elongation: 25 to 60 percent.

It is quite reasonable to expect that a geometric scaling factor of 0.05 to 0.1 can be obtained by using certain lead alloys to simulate prototype structural steel by comparing the above properties with the following properties of structural steel (AISI No. 1020):

- o Ultimate Tensile Strength: 57,300 to 65,000 psi
- o Yield Strength: 42,800 to 50,300 psi
- o Elongation: 35.8 to 36.5 percent.

Although further work is necessary, it can be concluded that materials for model testing to satisfy a geometric scaling factor ranging from 0.05 to 0.1 can be obtained.

SECTION V
PRELIMINARY PLANNING FOR PHASE II STUDY

A. GENERAL

The developed 1-g small-scale concepts to simulate structural response for close-in nonnuclear weapons blasts (no gravity effects) and far-away blasts (where significant gravity effects may be present) are described in Sections III and IV, respectively. These concepts are applicable to any buried blasts in a wide variety of geologic materials and protective structural types. These concepts and procedures have been developed on the basis of theoretical and experimental evidence (Hopkinson's scaling rule), theoretical requirements (i.e., equations of motion, soil-structure interaction requirements), constitutive similarity, and known behavior of other potential materials for use in the model. Although Phase II work is necessary to experimentally demonstrate the viability of the developed concepts, no major obstacles to the success of these concepts are apparent.

A successful completion of the Phase II program could culminate in the development of a powerful and economical means of experimentally and analytically simulating structural response under a wide spectrum of blast loading conditions. Through these simulations, an economical and safe design/upgrade of a wide variety of blast resistant facilities would be possible.

B. TASK 5 SCOPE

The preliminary planning for the Phase II study consists of:

- (1) Identifying needs and making recommendations for the Phase II study
- (2) Developing a planning strategy to address needs, critical factors, and technology gaps
- (3) Developing a preliminary plan for scope, methodology, schedule, and cost (rough order of magnitude - ROM) for the Phase II study.

C. NEEDED PHASE II EFFORTS

The concept developed in Section III assumes that gravity effects are insignificant. Such a concept is too restrictive for general applications. The concepts generated in Section IV can compensate for gravity effects without any restriction and should be targeted for further efforts in the Phase II study. The Phase II efforts are aimed to:

- (1) Verify and modify, if needed, the assumptions and the developed scaling relations
- (2) Resolve technology gaps to ensure that Phase II work is optimal and that the developed concept can obtain reliable results
- (3) Verify the results by closely simulating well-documented prototype testing case histories.

Although 1-g scale model tests will be much less expensive than the prototype tests, it is neither practical nor economically feasible to perform 1-g scale tests for every protective structure design in so many possible variations of geologic materials. Thus, it is important to have a parallel development of appropriate analytical models which are capable of modeling the effects of nonnuclear weapon blasts on protective structures. The analytical model can also be used for the following purposes:

- (1) Provide guidance for experiments to design and fabricate appropriate instrumentation schemes and types.
- (2) Check the appropriateness of scaling relationships developed in this study.
- (3) Provide an economic means of evaluating the responses of various structure types and configurations leading to development of improved structural design concepts and methodology once the analytical model is verified by a 1-g scale model and/or prototype tests.

Thus, a parallel development of 1-g scale experiments and analytical modeling techniques will be most appropriate for Phase II work.

In general, the recommended work for Phase II work consists of the following items:

- (1) Develop laboratory test procedures and equipment to appropriately characterize the selected geologic materials to be utilized in the experiments. The procedures should be performed to characterize the developed scaling relationships with stress-strain behavior determined under test conditions that are commensurate with the anticipated stress and loading rate conditions in nonnuclear weapons blasts.
- (2) Develop an appropriate analytical model and perform preliminary analyses of the scheduled 1-g experiments under nonexplosive and explosive loadings (Items 4 and 5).
- (3) On the basis of the results of Item 2, develop instrumentation and data acquisition systems for the planned 1-g experiments (Items 4 and 5).
- (4) Perform a number of 1-g scale model tests using non-explosive means (such as impacts by a hammer or using a gas gun) to check the scaling relations under dynamic loading conditions as well as checking the overall instrumentation and data acquisition systems.
- (5) Perform 1-g scale model tests simulating the phenomena of detonation, free field shock propagation, and soil-structure interaction under a close-in blast in selected geologic materials.
- (6) Use the experimental results to check the analytical model and modify the analytical model, if appropriate.
- (7) Perform 1-g small-scale experiments to simulate a selected well-documented prototype testing program for further verification of the developed 1-g scale model concept as well as the analytical model.

D. STRATEGY FOR PHASE II

Although 1-g scale model tests are much less expensive than the prototype model, the cost for each test is still relatively substantial. Thus, one of the strategies for Phase II places emphasis on performing a limited amount of tests supplemented by parallel analytical development to maximize the results. The Phase II work should lead to the development of well-verified, 1-g scale model test procedures and an appropriate analytical model that can inexpensively and confidently evaluate the response of structures in any geologic materials under nonnuclear weapons blasts.

The experiments should be systematically performed in an increasing order of complexity to minimize cost and yet be sufficient to serve Phase II needs.

These experiments should start with a combination of simple geologic materials and structures with simple configurations and uncomplicated dynamic loading conditions. They should then be performed with a more complex combination of conditions with results that have been verified by well-documented prototype tests (e.g., the MUST or BDCC projects, Section II) to ensure the 1-g scale model concept is applicable to the project purpose.

The Phase II needs, described in Section V.C, have been based on the above strategies. A wide variety of geologic materials exists for potential one-g scale model tests. These include:

- (1) Dry cohesionless soils
- (2) Saturated cohesionless soils
- (3) Saturated cohesive soils
- (4) Moist or partially saturated soils
- (5) Rocks.

Economic and time constraints for the Phase II program require limited efforts. The types of geologic materials will be limited by setting priorities as described below.

Saturated cohesionless soils should not be considered due to the potential of blast-induced liquefaction which will render the protective structure and equipment useless. It has been suggested (Reference 4) that the material modeling concept developed for cohesionless soils is equally applicable to the case of saturated clays. Various supplementary concepts exist (Section IV.C.2) which are capable of producing model simulants for saturated clayey soils to satisfy the developed scaling relationships. The possibility of success is extremely high. Thus, saturated clays are not recommended at this time, but they should be considered in a Phase III program for technical completeness.

Moist and partially saturated soils frequently prevail in shallow depths where the protective structures are most likely located. These conditions are anticipated in NATO installations in Europe and DOD installations in Korea. It is important that these soil conditions be incorporated into the Phase II

program to prove the technical feasibility of the development 1-g scale model for protective construction applications.

Rocks have a wide variety of properties and discontinuities. The results shown in Section IV.C indicate that once the rock type and discontinuity characteristics in the prototype conditions are known, proven methods of using various cement grouts and additives to produce appropriate model simulants for 1-g model tests are available. The potential for a successful simulation is extremely high. They should be considered in a Phase III program for technical completeness.

In summary, only the following two soil types are proposed for the Phase II study:

- o Dry cohesionless soil
- o Moist or partially saturated soil.

Another strategy is to maximize test results for each 1-g scale model test so that free-field experiments and the response of several structures buried at different locations can be performed under one test setup and under one explosion source. Such a strategy has been utilized with success (Reference 8) in centrifuge testing.

E. PRELIMINARY PLANNING FOR PHASE II

The preliminary planning for Phase II scope, methodology, and rationale has been described above. This section provides a rough-order-of-magnitude (ROM) estimate of potential cost and an anticipated schedule for the recommended Phase II work.

For schedule and cost estimate purposes, the Phase II work can be divided into nine tasks, as follows:

<u>Task No.</u>	<u>Description</u>
1	Project management and quality assurance
2	Experiment planning
3	Material testing and characterization
4	Analytical model development and verification
5	1-g scale model tests in cohesionless soil using explosive and nonexplosive sources to check test systems and scaling relationships, and to evaluate blast effects on protective structures
6	1-g scale model tests to simulate prototype tests for verification purposes
7	1-g scale model tests in moist or partially saturated soils
8	Instrumentation and data acquisition system - design, acquisition, and calibration
9	Report preparation

1. Cost Estimate

Our ROM cost estimate follows:

<u>Task</u>	<u>Direct Labor</u>	<u>Other Direct Labor</u>
1	\$ 20,000	\$ 7,000
2	20,000	15,000
3	30,000	25,000
4	40,000	7,000
5	70,000	42,000
6	30,000	11,000
7	50,000	16,000
8	20,000	80,000
9	<u>20,000</u>	<u>13,000</u>
Subtotal	\$300,000	\$216,000

Thus, the total ROM estimate cost is about \$516,000. With further fine-tuning, the cost can be reduced to below \$500,000 which is the limit set for Phase II work.

2. Schedule Estimate

It is estimated that the needed Phase II work can be accomplished within 22 months. A detailed schedule breakdown follows:

<u>Task</u>	<u>Starting Date</u>	<u>Completion Date</u>
1	Beginning of 1st month	End of 22th month
2	Beginning of 1st month	End of 6th month
3	Beginning of 3rd month	End of 6th month
4	Beginning of 3rd month	End of 20th month
5	Beginning of 7th month	End of 12th month
6	Beginning of 13th month	Middle of 15th month
7	Middle of 16th month	End of 20th month
8	Beginning of 1st month	End of 8th month
9 (draft) report	Beginning of 20th month	End of 21st month
(final) report	Middle of 22nd month	End of 22nd month

SECTION VI

CONCLUSIONS

The objective of this Phase I study has been successfully accomplished. We have developed two concepts and associated procedures that can compensate for gravity effects on 1-g small-scale model tests to simulate the effects of nonnuclear weapons blasts on protective structures.

The first concept detailed in Section III is applicable to the case where gravity effects are insignificant. This concept is potentially applicable to a close-in (near-miss) blast where gravity effects are likely to be insignificant. However, this concept has limited application since the current state-of-knowledge is incapable of determining exactly where and when gravity effects become significant. Thus, this concept is too restrictive for general application and should not be considered in Phase II work.

The second concept, as detailed in Section IV, can compensate for gravity effects whether they are significant or not. This concept is capable of simulating structural response under either close-in or far away nonnuclear weapons blasts. This concept is applicable to a wide variety of geologic materials and protective structure types and configurations. Proven ways and means of establishing appropriate modeling materials for a wide variety of geologic and structural materials are also developed for this concept. Although a Phase II program is necessary to demonstrate the viability of this concept, no major technical or practical obstacles exist to prevent the successful simulation of the effects of nonnuclear weapons blasts on protective structures in 1-g small-scale model tests.

As detailed in Section V, preliminary planning for the Phase II study has been developed to achieve optimal results. It is imperative that the Phase II work encompass parallel development of experimental and analytical efforts, so that analyses can guide the experimental work that, in turn, can provide needed data to verify and refine the analytical model. To verify the applicability and increase the confidence level of the developed experimental and analytical models, it is also important that well-documented prototype test results be utilized. Various strategies have been incorporated in our recommended Phase II program to ensure that the objectives of Phase II program can be systematically and economically accomplished.

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