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**EARTHQUAKE ENGINEERING SUPPORT
PHASE 5**

Final Technical Report

by

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SUMMARY

This report summarizes the findings of an experimental study supported by the U.S. Army Centrifuge Research Center and Engineer Earthquake Engineering Research Program (EQEN) into the behavior of saturated sands under high initial effective confining stresses subjected to strong ground shaking. The research was conducted using the Army Centrifuge at the U.S. Army Engineering Research and Development Center (ERDC), located in Vicksburg, MS. A large dataset of the response of saturated sand to dynamic shaking under 'level ground' conditions has been compiled and a series of verification models have been conducted. Several techniques were used to investigate the response of deep soil sites (in excess of 70m) including surcharges, lowered water table and higher acceleration (gravities). The most effective approach was to test specimens at higher gravity, as the interpretation of data from specimens tested using a heavy surcharge on the ground surface, or a deep water table has proved difficult. Many deep samples showed a limit to the excess pore pressure generated during shaking at a level much less than 100% of the initial vertical effective stress. A range of explanations has been proposed, including container effects, saturation, compression of the soil, redistribution of pore pressure and dynamic response of the surcharge. The verification tests eliminated container effects, and parallel research by others has shown that there are several reasons for pore pressure generation at depth to be limited. However, as postulated in earlier stages of this research, there is no absolute limit: in a fully saturated specimen of broadly uniform permeability, liquefaction was observed within a few cycles of strong shaking throughout (to an equivalent field depth of around 65m). A second key finding indicates that dense layers overlying loose layers may still be readily liquefied as a consequence of the high excess pore pressures generated below. These findings are highly significant for designers.

LIST OF KEYWORDS

liquefaction
centrifuge
earthquake
model
experiment
sand
dam safety

TABLE OF CONTENTS

<i>Summary</i>	<i>i</i>
<i>List of Keywords</i>	<i>ii</i>
<i>Table of Contents</i>	<i>iii</i>
1 Background	1
2 Introduction	1
3 The ERDC centrifuge facility	3
4 Research Program	4
5 Results	7
6 Determination of shear stress-strain histories	12
7 Conclusions	16
8 References and bibliography	16
Appendix A Earthquake dataset	A-1
Appendix B Summary of data	B-1

1.0 BACKGROUND

This research contract addressed a further phase in the completion of an experimental and analytical research programme in support of the Earthquake Engineering Research Program under the direction of the USAE ERDC (formerly the Waterways Experiment Station), Vicksburg, Mississippi. The phase was entitled Earthquake Induced Liquefaction in Deep Sand Deposits. This study was a continuation of earlier research under Contract Nos. N68171-98-C-9014, N68171-97-M-5710, N68171-97-C-9012, N68171-99-C-9021 and N68171-00-M-5505. The research involved further interpretation of the early experimental data, design of verification experiments, interpretation and analysis of new experimental data and preparation of technical papers for publication. The work was completed in September 2001.

2.0 INTRODUCTION

The current state-of-practice for the evaluation of liquefaction potential and for remediation design and analysis depends on empirical correlations of in-situ measurements of strength versus field experience of liquefaction at shallow depth and laboratory data of the behavior of confined elements under cyclic loading. (Liquefaction is defined here to mean the development of pore pressure equal to 100% of the initial vertical effective stress.) This approach is known as the "simplified procedure". Opinions vary as to the maximum depth in the field at which liquefaction has been observed, but there is no established field evidence from historic earthquakes of liquefaction at depths greater than a few tens of meters. The NCEER Workshop in 1996 on the Evaluation of Liquefaction Resistance of Soils noted that the simplified procedure was developed from evaluations of field observations and field and laboratory test data, Youd and Idriss (1997). The report notes, "These data were collected mostly from sites ... at shallow depths (less than 15m). The original procedure was verified for and is applicable only to these site conditions".

Hence, in design practice the assessment of liquefaction under high initial effective confining stress, such as might relate to the foundations of large earth dams, is based on the extrapolation of observed behavior and correlations at shallow depths. In practice, the behavior of saturated soil under these conditions is not well understood. Based on the results of laboratory tests, researchers have postulated that there is a reduction in the liquefaction resistance of such soil compared to shallow depths. This reduction is accounted for in standard approaches by a ratio known as K_σ , a "correction factor" developed by Seed (1983) in the simplified procedure. This strength ratio is postulated to reduce with increasing initial effective confining stress, which has a large impact potentially on the extent and method (hence cost) of remedial construction required to assure adequate seismic performance of large dams. For example, it may reduce the cyclic shear stress ratio predicted to cause liquefaction in a soil layer under a typical large dam (of the order of 30m high) to about 50% of its value in the absence of the dam. The predicted deformations and resistance and the remedial strength required are a direct function of the reduced shear strength. The K_σ strength reduction therefore

has a strong influence on the decision to remediate a large dam and on the costs of that remediation.

The factor K_σ quantifies the curvature in the cyclic shear strength envelope (cyclic shear stress required to cause liquefaction versus confining stress) for a soil as observed in laboratory tests on discrete specimens. Although some curvature may be expected, such large reductions in cyclic shear strength ratios are counter-intuitive. It is generally accepted that increased confining stress should broadly improve the capacity of a soil to resist applied loads, not reduce it. Clearly the volume of soil that requires to be treated and the difficulty and expense of that treatment are highly dependent on an accurate assessment of the potential for and consequences of liquefaction.

There is therefore strong motivation for owners of large dams to investigate the behavior of saturated sands subject to strong ground shaking under high initial effective confining stresses. In the absence of field data, the use of a centrifuge was considered to be the only practical option to realistically represent a deep soil deposit subjected to earthquake shaking. The experiments reported herein relate exclusively to level ground initial stress conditions in a single layer (loose) or two-layer (dense over loose) deposit of clean, fine sand.

Liquefaction of a level sand bed has previously been the subject of research by many others. Experiments using Nevada sand were conducted at many centrifuge centers under the VELACS project, Arulanandan and Scott (1994). The objective of the ERDC study is to investigate the onset of liquefaction under much higher initial effective overburden stresses than used in the VELACS experiments. Nevada sand, which was used in the VELACS research and has been extensively studied in the laboratory, was adopted for the series of experiments under the ERDC centrifuge test program.

3.0 THE ERDC CENTRIFUGE FACILITY

The design specification for the ERDC centrifuge followed a review of the Army's research needs and a study of the available academic facilities, Ledbetter (1991). Many of the field problems with which the U.S. Army Corps of Engineers is concerned are physically large, such as earth dams, locks and river control structures, environmental problems and military research. It was determined that a new facility with a high payload capacity and high g capability was required to meet future Army needs. A large beam centrifuge was commissioned, Figure 1, termed the Acutronic 684, based on the French designed Acutronic 661, 665 and 680 series of geotechnical centrifuges, Ledbetter et al. (1994a). The capacity of the ERDC centrifuge is a payload of 8 tonnes at up to 143 g, reducing to 2 tonnes at 350 g, with a platform area of 1.3m square. This high capacity enables field problems of the order of up to 300m in breadth, 300m in depth, and 1000m in length to be simulated under a wide variety of loading conditions. The facility is equipped with a large range of equipment and appurtenances.

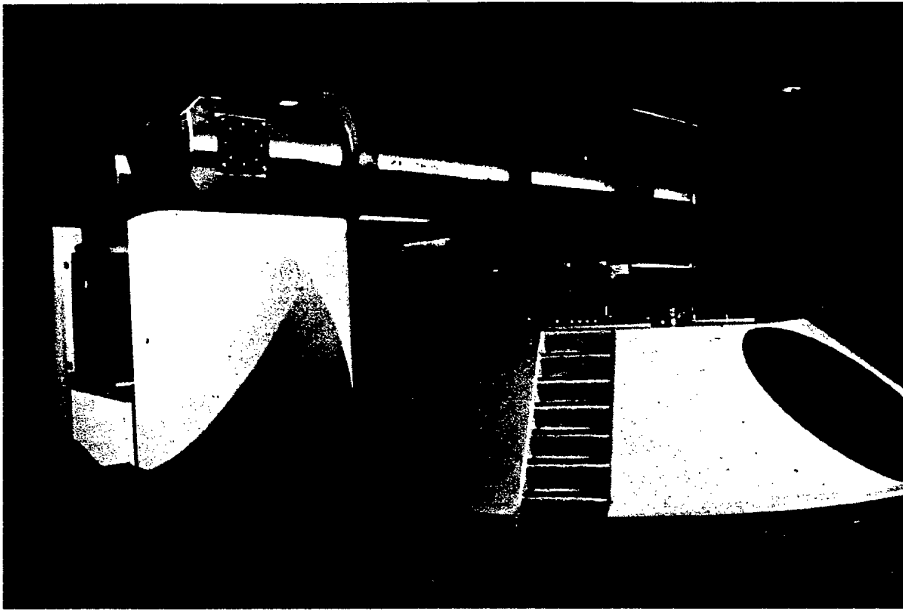


Figure 1. The WES centrifuge

The research approach for this high confining stress liquefaction study uses the large capacity of the WES centrifuge to investigate the generation of excess pore pressure and liquefaction under conditions that much more closely resemble those at depth in the field, Ledbetter et al. (1999). To do this required the design and construction of a large dynamic actuator. The history, design and characteristics of the actuator and specimen container have been discussed in a previous Technical Report, Steedman (2000) and are not repeated here.

4.0 RESEARCH PROGRAM

Table 1 summarises the experiments conducted during 1998 and 2001. The models are grouped in series, where each series corresponds to a different target range of vertical effective overburden stress in the loose layer.

Model series	Models in series	Effective overburden stress near bottom	Equivalent field depth (approx)	Depth of specimen	Notes (all specimens constructed from Nevada Sand, tested at 50g unless specified)
2	a, b, c, d, e, f	110 KPa (1 tsf)	15 m	300 mm	Fully submerged
3	a, b, c, d, e, f	210 KPa (2 tsf)	26 m	525 mm	Fully submerged (3f at 100g)
4	a, b, c, d	320 – 540 KPa (3 – 5 tsf)	26 – 40 m	525 mm	Lowered phreatic surface or surcharge (weights)
	e, f, g, h, i, j	420 – 1040 KPa (3.9 – 9.7 tsf)	30 – 60 m	525 mm	Surcharge (weights) and fully submerged, tested up to 125g
	k	200 – 510 KPa (1.9 – 4.8 tsf)	25 – 39 m	525 mm	No surcharge, fully submerged, tested up to 125g
5	a, b, c, d, e	750 – 1070 KPa (7 – 10 tsf)	54 – 63 m	525 mm	Surcharge (weights), fully submerged
	f, g	740 KPa (6.9 tsf)	41 m	525 mm	Surcharge (weights), fully submerged (5g reused Model 3e)
	h	610 KPa (5.7 tsf)	41 m	525 mm	No surcharge, fully submerged, tested up to 125g
	i	730 KPa (6.8 tsf)	41 m	460 mm	No surcharge, lowered phreatic surface, tested at 125g

Table 1. Outline summary of centrifuge model test program

Model Code	Overall depth (mm)	Relative Density (D _r)*	σ_v near base of specimen (tsf)	OCR	Number of earthquakes	Comments (all models constructed from Nevada Sand and tested at 50g unless specified)
2a	300	44% loose, 83% dense	1	1	3	Fully submerged
2b	300	50% loose, 75% dense	1	1	2	Fully submerged
2c	300	49% loose, 74% dense	1	1	5	Fully submerged
2d	300	50% loose, 75% dense	1	1	4	Fully submerged
2e	300	49% loose, 73% dense	1	2.5	4	Fully submerged
2f	300	50% loose, 75% dense	1	2.5	4	Fully submerged
3a	525	34% loose, 73% dense	2	1	2	Fully submerged
3b	525	49% loose, 77% dense	2	1	3	Fully submerged
3c	525	49% loose, 79% dense	2	1	3	Fully submerged
3d	525	54% loose, 80% dense	2	2.5	4	Fully submerged
3e	525	50% loose, 75% dense	2	1	1	Fully submerged
3f	262	50% loose, 75% dense	2	1	1	182 mm dense layer overlying 80 mm loose layer, fully submerged, no surcharge, 100g
4a	525	49% loose, 80% dense	3	1	4	Saturated to top of loose layer only.
4b	525	56% loose, 74% dense	3	2.5	4	Saturated to top of loose layer only.
4c	525	50% loose, 75% dense	4.7	1	4	Fully submerged, surcharge (weights)
4d	525	50% loose, 68% dense	4.7	2.5	4	Fully submerged, surcharge (weights)
4e	525	47% uniform	3.9 – 7.8	1	2,1,1	Fully submerged, surcharge (weights), Shaking at 50, 80, 100g
4f	525	55% uniform	3.9 – 9.7	1	1,1, 2,1	Fully submerged, surcharge (weights), Shaking at 50, 80, 100, 125g
4g	525	50% uniform	3.9 – 9.7	1	1,1, 1,2	Fully submerged, surcharge (weights), Shaking at 50, 80, 100, 125g
4h	525	50% uniform	3.9 – 9.7	1	1,1, 1,1	Fully submerged, surcharge (weights), Shaking at 50, 80, 100, 125g
4i	525	50% uniform	3.9 – 9.7	1	1,1, 1,1	Fully submerged, surcharge (weights), Shaking at 50, 80, 100, 125g
4j	525	50% uniform	3.9 – 9.7	1	1,1, 1,2	Fully submerged, surcharge (weights), Shaking at 50, 80, 100, 125g.
4k	525	50% uniform	1.9 – 4.8	1	1,1, 1,2	Fully submerged, no surcharge, Shaking at 50, 80, 100, 125g.
4l	525	Densities uncertain	4.8	1	1	Fully submerged, surcharge (weights)
5a	525	51% loose, 72% dense	7.4	1	4	Fully submerged, surcharge (weights)
5b	525	49% loose, 76% dense	7.4	2.5	4	Fully submerged, surcharge (weights)
5c	525	52% loose, 75% dense	9.2	1	3	Fully submerged, surcharge (weights)
5d	525	57% loose, 80% dense	9.2	1	1	Fully submerged, surcharge (weights)
5e	525	50% uniform	8.4	1	7	Fully submerged, surcharge (weights)
5f	525	50% loose, 75% dense	6.9	1	1	Fully submerged, surcharge (weights)
5g	525	50% loose, 75% dense	6.9	1	1	Fully submerged, surcharge (same model as 3e with surcharge added)
5h	525	49% loose, 74% dense	5.7	1	1	Fully submerged, no surcharge, 125g
5i	460	50% loose, 75% dense	6.8	1	1	396 mm dense layer, saturated to depth of 250mm only, overlying 64 mm loose layer, no surcharge, 125g

*Relative density of the portion of the model termed 'loose', generally refers to a 160 mm thick layer placed at the bottom of the model. For the 'model of the model' experiments, this loose layer was reduced in depth. Relative density of the portion of the model termed 'dense', refers to that portion of the model above the 'loose' layer (ranged in thickness from 140 to 365 mm). Model 4l was understood to have been built to the standard specification, i.e. 75% dense over 50% loose.

Table 2. Summary description of centrifuge model test program

Generally, specimens were up to 525mm deep with the bottom 160mm placed at around 50% Relative Density (RD) and the upper portion at around 75% RD. The 'early' models were shaken at 50g; later models were shaken at up to 125g. During the verification phase modelling of models was carried out at 100g and 125g. Some models were overconsolidated by a factor of 2.5 prior to shaking (achieved by running the centrifuge up to 125g and then dropping back to 50g). The size of the dataset and number of repetitions provided the opportunity to characterise the data on the basis of the quality of the output. This is seen in Appendix A, where the summary data for each transducer and each earthquake analysed is presented. A quality rating of low/medium/high and * was assigned to each time history based on the consistency and reliability of the data and the quality of the experiment itself. For example, higher 'quality ratings' would be assigned to transducers which showed internal consistency in terms of static pore pressures, physical location in the model, response during shaking etc.

The Nevada sand used in the models was characterized by standard laboratory tests to determine parameters such as dry density and gradation. Table 3 presents key material parameters for this sand.

Specific gravity	2.64
Maximum void ratio	0.757 (density 93.8 pcf)
Minimum void ratio	0.516 (density 108.7 pcf)
D ₅₀	0.18 mm (approx)
D ₁₀	0.11 mm (approx)

Table 3. Nevada Sand (parameters as measured)

The pore fluid comprised a mixture of glycerine and water, 80% by weight for experiments conducted at 50g. Measurements of the viscosity of glycerine-water mixes at a range of temperatures and proportions show that the viscosity is sensitive to both parameters.

The density of a glycerine-water mix was calculated from:

$$\rho_m = \rho_g(m_g + m_w) / (m_g + \rho_g m_w)$$

where ρ_m is the density of the mix, ρ_g is the density of glycerine, m_g is the mass of glycerine, and m_w is the mass of water. Table 4. summarizes the properties of the glycerine-water solution used as the pore fluid.

Density	1200 kg/m ³
Viscosity	50 cs
Specific Gravity	1.26
Composition	80% glycerine-water mix (by weight)

Table 4. Parameters for pore fluid (as measured)

The models were poured dry from a hopper and saturated under vacuum, or slowly under gravity. Instrumentation was placed in the model as it was being constructed.

The typical arrangement of the model specimens for the different test series is shown in Figure 2. Instrumentation was positioned through the depth of the models, and comprised pore pressure transducers and accelerometers. The location of the instrumentation for Model 5b is shown in Figure 3.

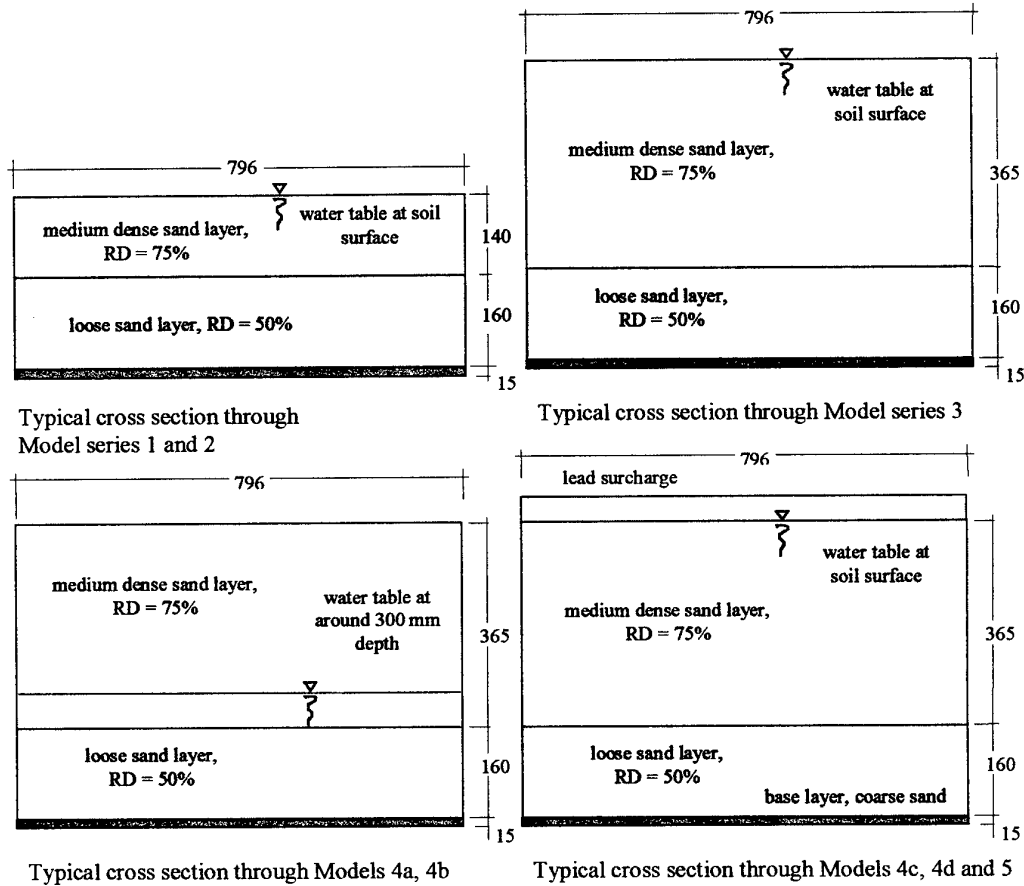


Figure 2. Cross sections through the different model configurations

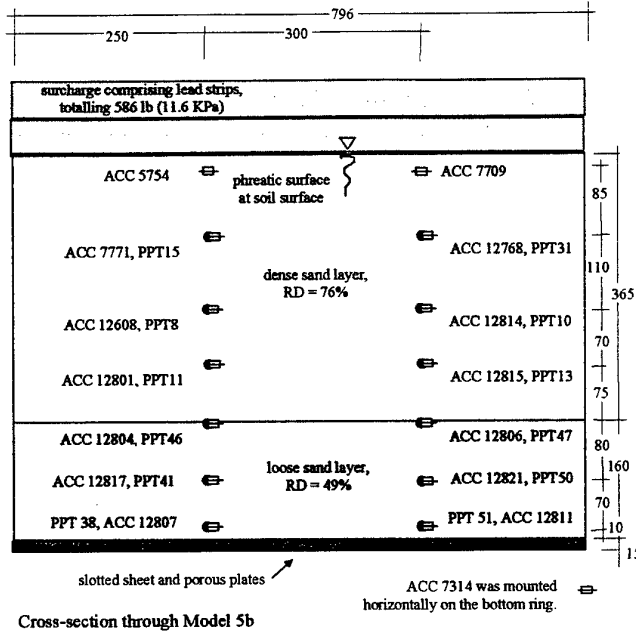


Figure 3. Instrumentation for Model 5b

5.0 RESULTS

Earlier reports, Steedman (1999), (2000) have presented analysis of the data using a range of approaches. In this report, the data from the verification models is summarized alongside the earlier experimental results, and in the same format.

Appendix A presents the dataset of limiting excess pore pressures, by model and by transducer. Comments are added concerning the quality of each record, and the experiment in general.

From this set a number of time histories were selected as of particularly high quality for possible future interpretation. This selection was made in part based on the internal consistency of the experimental results, and in part using subjective judgment based on past experience. These data are presented in Figures 4a and 4b, and 5a and 5b, below. In each case, the model reference number and earthquake is given, which can be checked against the commentary in Appendix A. Figures 4a and 5a present the pore pressure records; Figures 4b and 5b present the (matching) base input acceleration time history from the same model test.

A summary of selected data and recommendations for future centrifuge testing of level ground conditions under high effective confining stress has been prepared, Sharp and Steedman (2002).

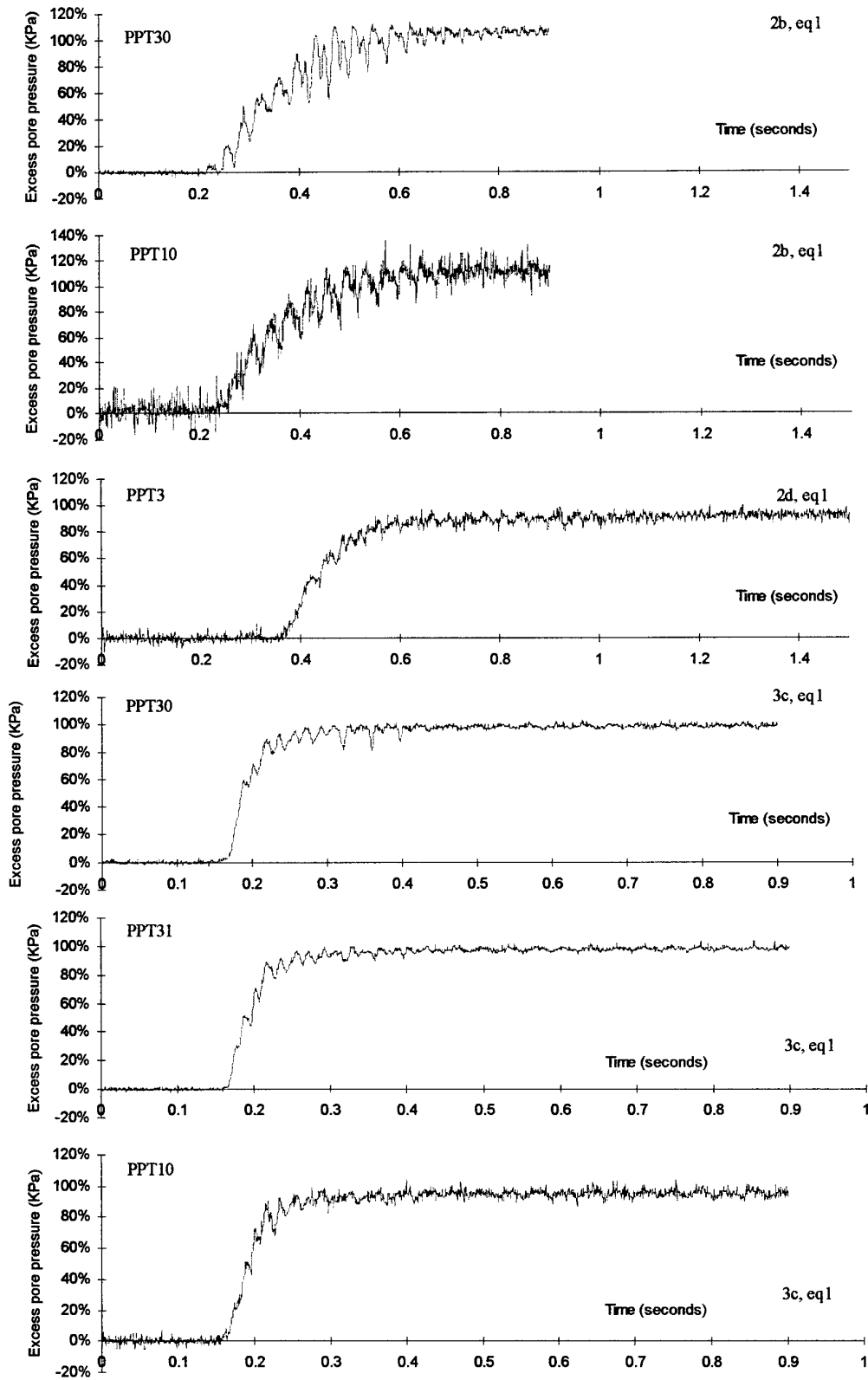


Figure 4a. Selected pore pressure time histories (I)

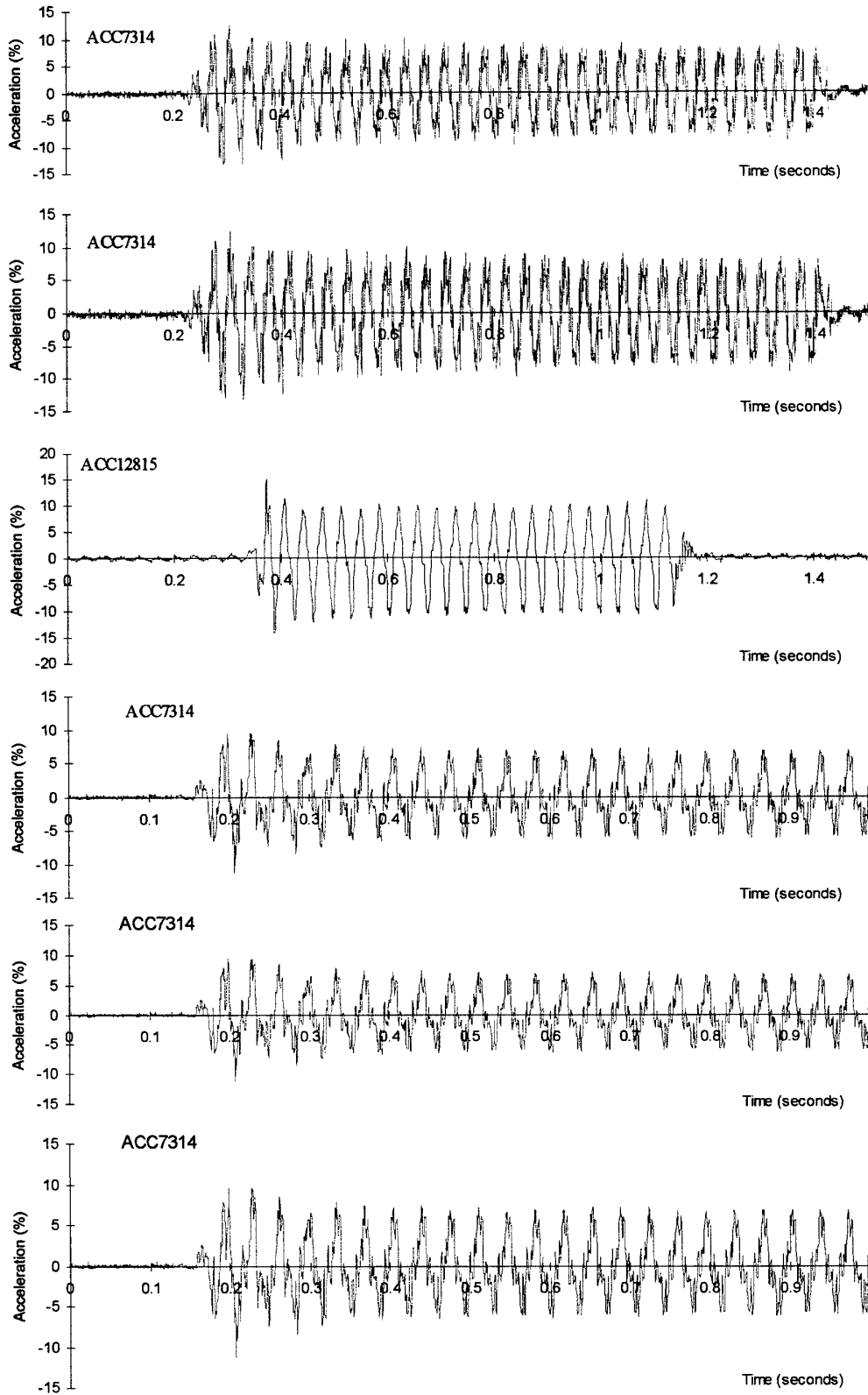


Figure 4b. Matching acceleration (base input) time histories (I)

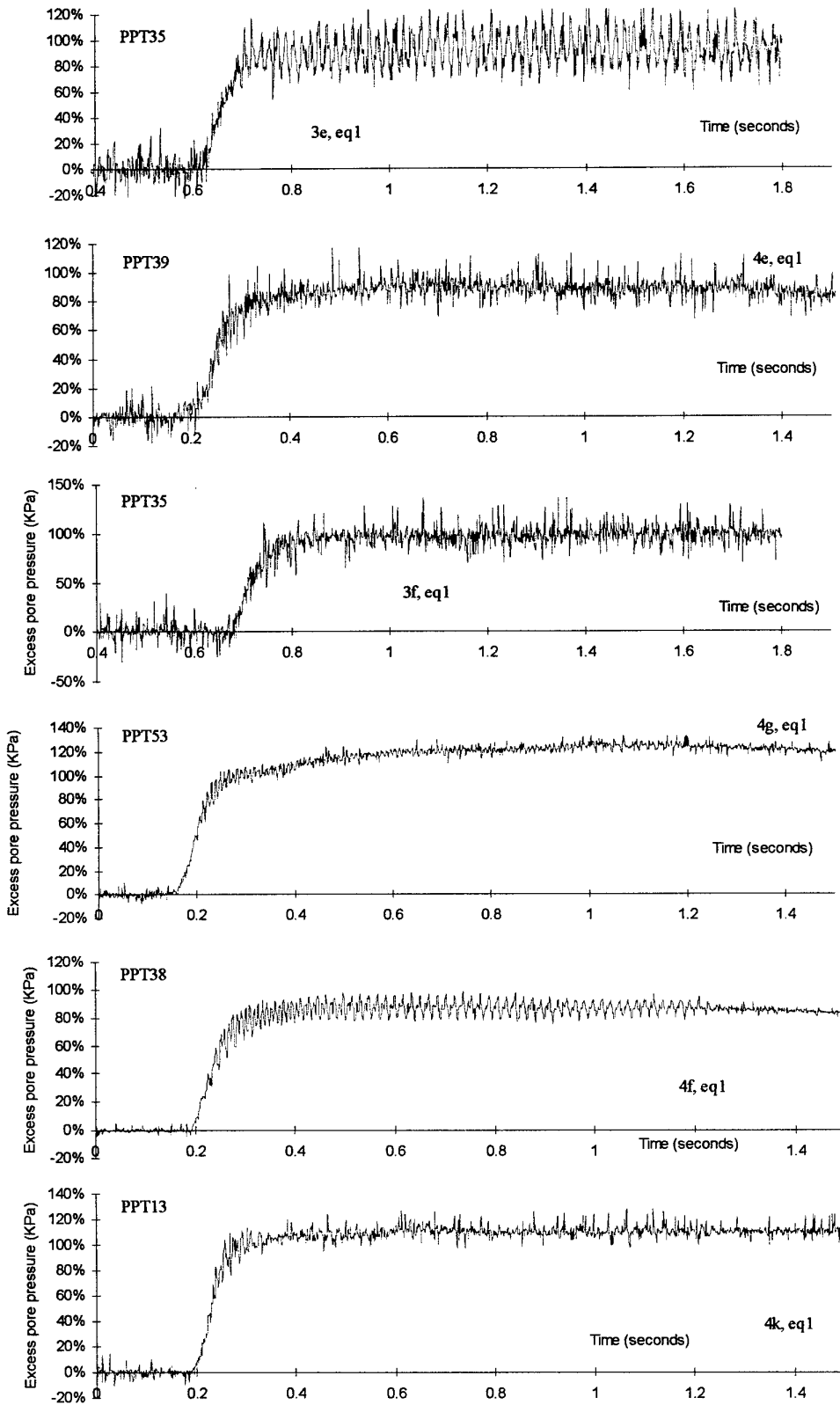


Figure 5a. Selected pore pressure time histories (II)

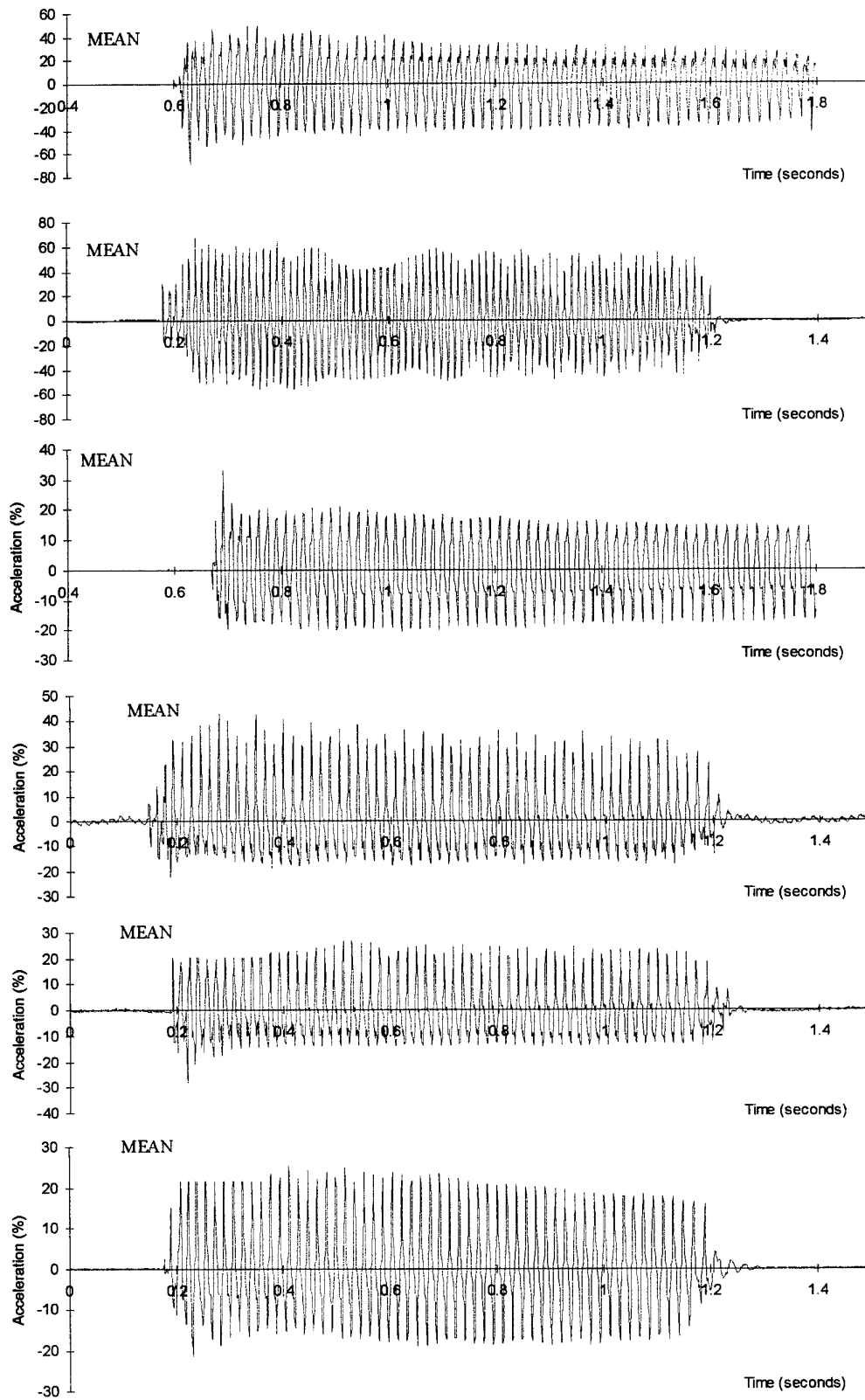


Figure 5b. Matching acceleration (base input) time histories (II)

6.0 DETERMINATION OF SHEAR STRESS-STRAIN HISTORIES

All of the experiments undertaken in this study addressed level ground conditions, with no initial static shear stress. The only shear stress and subsequent shear strain was that imposed by the loading. Level ground liquefaction is therefore a special case of the cyclic mobility phenomenon that occurs when the static shear stress is less than the shear strength of the liquefied soil. Level ground liquefaction failures are caused by the upward flow of water that occurs when seismically induced excess pore pressures dissipate. Depending on the length of time required to reach hydraulic equilibrium, level ground liquefaction failure may occur well after ground shaking has ceased and this was seen in a number of the experiments. References in Appendix A to transducers 'still climbing at the end of shaking' are evidence of pore pressure redistribution affecting the pore pressure generation caused by shaking.

A critical aspect in the assessment of these model experiments was to compute the stress strain time histories for comparison with laboratory element and field experience. This was done in collaboration with researchers at WES and RPI.

The method adopted to compute the stress and strain time histories was known as System Identification or SI. The method is described in a paper by Zeghal et. al. (1995), where the authors proposed that accelerometer and pore pressure time histories could offer a direct and effective means of evaluating seismic soil properties, in particular, a second order accurate estimation of shear stress and shear strain. This SI technique was utilized for analysis of the earthquake data.

Stress strain figures are shown here for Models 4k (Figure 6) and 5b (Figure 7), windowed during similar stages of shaking, Steedman and Sharp (2001).

The left column of plots are the traditional stress-strain loops computed for the early time data, as the excess pore pressures are developing strongly. This may be seen by comparison with the time history of vertical effective stress below the stress strain figures. For Model 4k this shows the largest amount of straining near the surface at nearly 1%, decreasing to a strain of 0.6% at a depth of 24 m. The remaining columns of figures show how the stress strain loops are altered by the development of excess pore pressure. In the case of Model 4k, the specimen reaches close to 100% excess pore pressure, and the upper layers become isolated from the straining at the base. In the case of Model 5b, the excess pore pressure is limited and the response of the soil column becomes nearly linear. The marked contrast in response between the two specimens confirm the observation that the stabilization of the excess pore pressure development in the deeper specimens is a genuine phenomenon associated with a stable cycling of applied load at a level significantly below 100% excess pore pressure, and with the soil retaining considerable reserves of strength and stiffness.

One explanation for the limiting level of excess pore pressure may be associated with upward drainage of the excess pore pressures.

Appendix B presents isochrones of stress and strain levels from each experiment, based on this method.

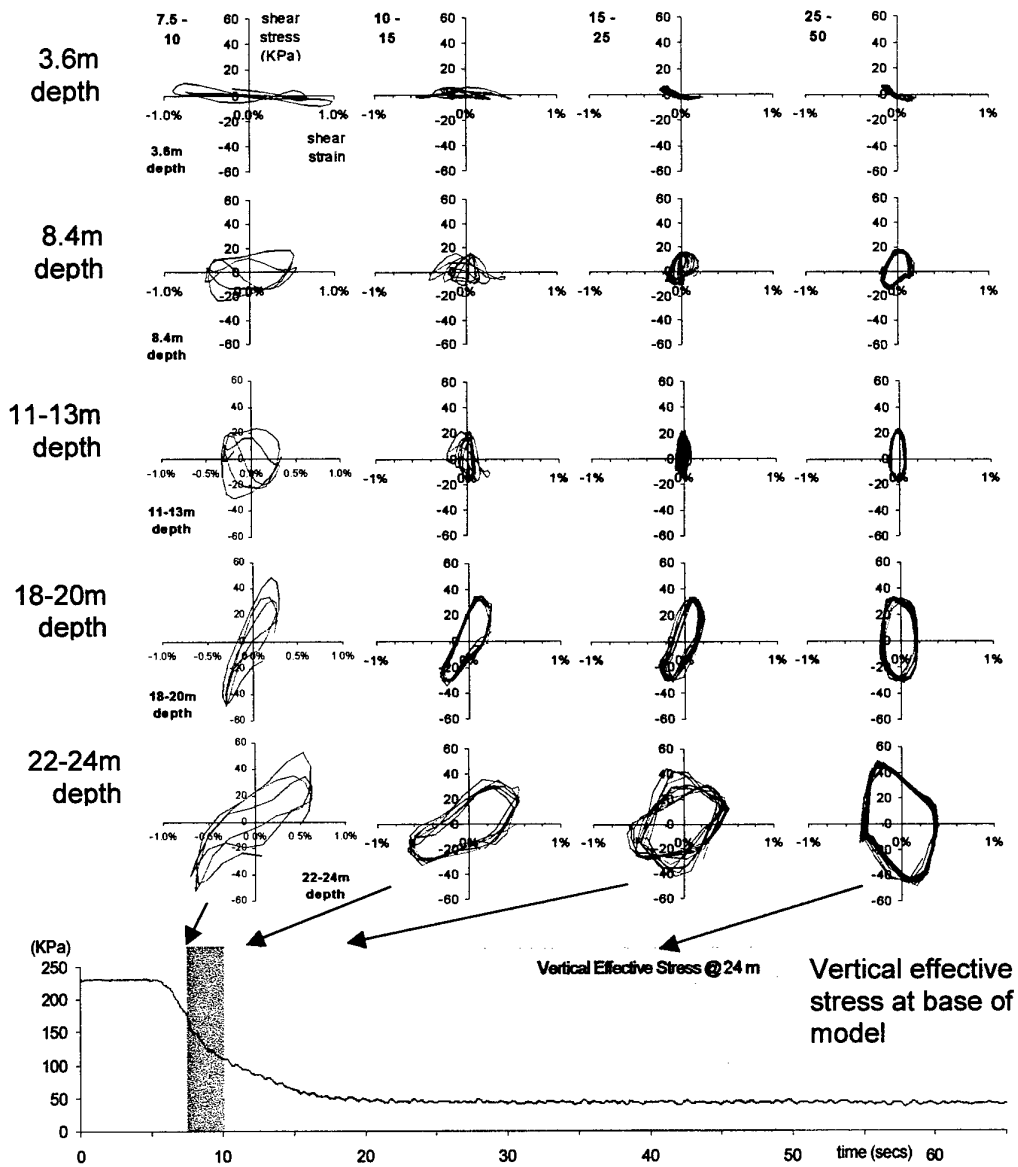


Figure 6. Stress strain time histories, Model 4k

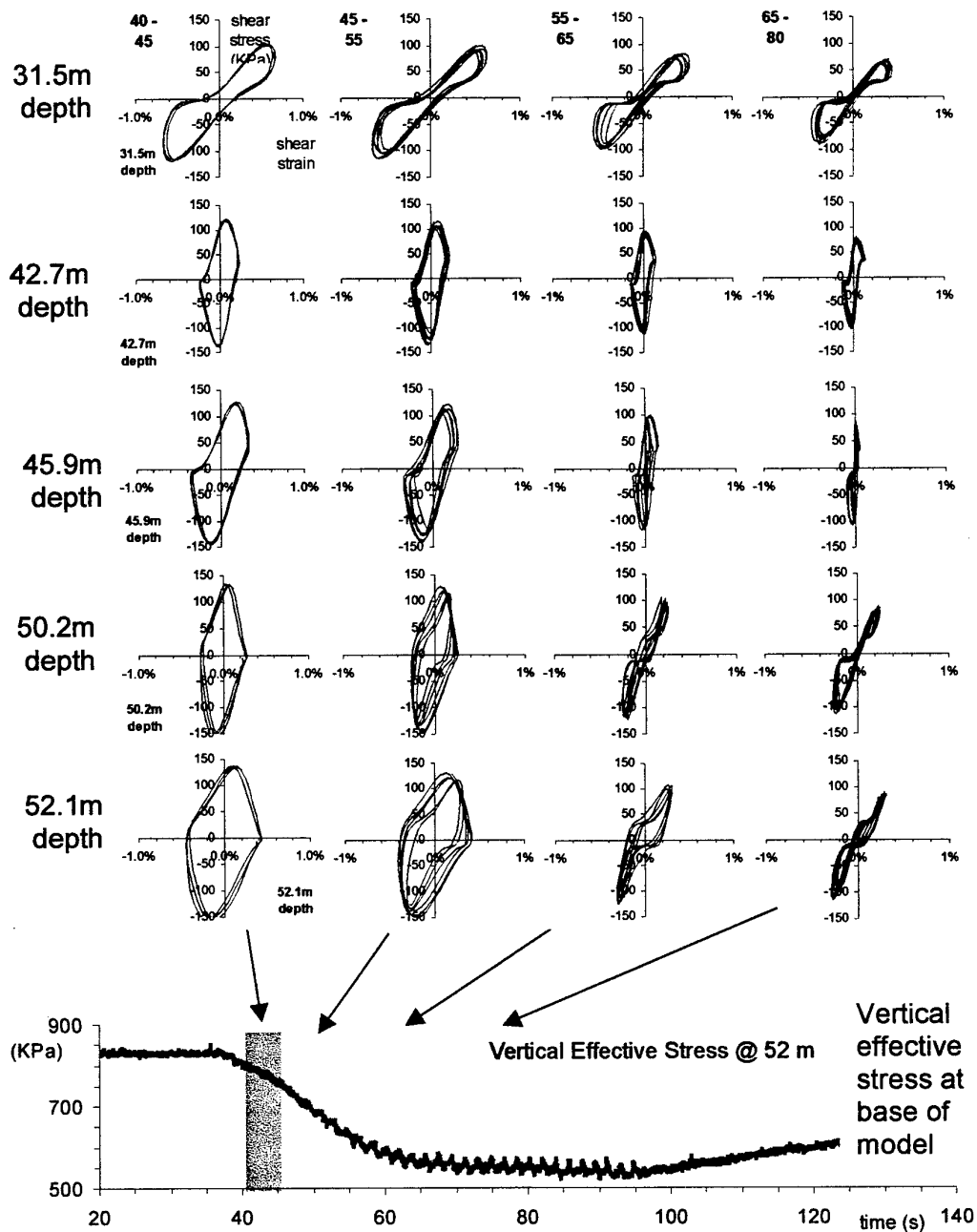


Figure 7. Stress strain time histories, Model 5b

A very large dataset of the behavior of Nevada sand subject to shaking under level ground conditions has been accumulated as a result of this work. Review of the stress-strain data alongside the time histories of excess pore pressure provided considerable additional insight into the explanation of the pore pressure response in many cases. The verification models that were tested during 2000-2001 were successful in validating the performance of the specimen chamber and shaker in many respects. The verification models showed that the use of surcharges may indeed be having an effect on the response of the soil column, although exactly how the surcharge affects the soil column has not yet been conclusively

determined; many other factors, including soil density, compression and saturation may also be influencing the 'true' response under cyclic loading at high effective confining stress. It is clear that the most effective method of investigating the influence of very high effective confining stress is to use the centrifuge at high g, with or without dry sand surcharging, as for example was achieved with the final experiments in the series, Models 5h and 5i.

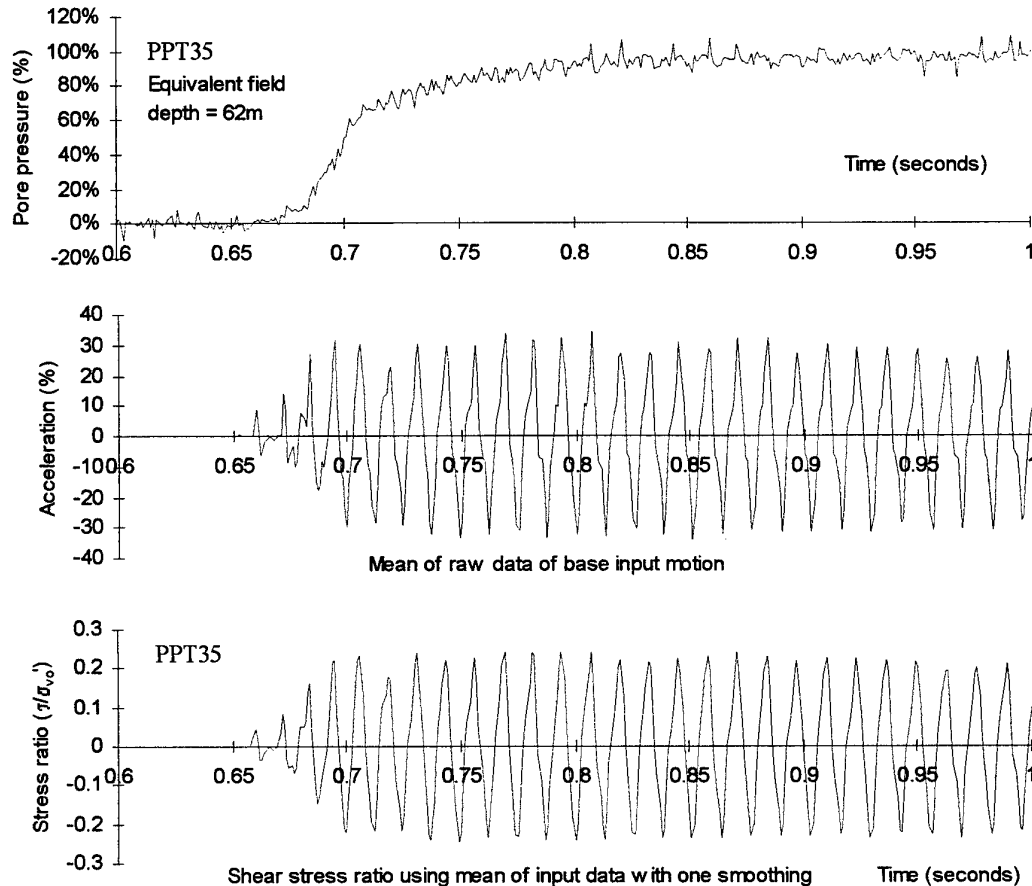


Figure 8. Liquefaction at 62m equivalent depth, Model 5h

Figure 8 presents data from PPT35, Model 5h, which shows 100% excess pore pressure reached after a few cycles of strong shaking in a fully saturated deep specimen without surcharge, at 125g. The shear stress ratio time history shown here was calculated using the simplified method, Steedman (2000) and may be compared to the isochrones of stress ratio calculated using the SI method, Appendix B. Appendix B also shows the long term response after the end of shaking, where consolidation effects and pore pressure redistribution last for a very long period after the end of the earthquake.

7.0 CONCLUSIONS

1. A large data-set of the behavior of loose saturated sands under high initial effective confining stresses and subject to earthquake-like shaking has been collected during an extensive experimental program on the ERDC Centrifuge, Vicksburg MS.
2. Early findings from the centrifuge experiments showed that under high effective confining stress, the potential to generate excess pore pressures was limited, and this may be of considerable importance if verified.
3. Detailed investigation into the early findings has provided a range of explanations for the limiting values, including experimental problems such as specimen saturation, chamber effects or the distorting effects of large surcharges on the soil surface. Of these possible effects, detailed investigation of the response of the chamber effectively eliminated movement, or distortion of the ESB container as an explanation.
4. The effect of surcharging was investigated by comparison with changing g level and using different methods of surcharging, or no surcharges at all. The use of dry sand appeared preferable to lead or steel weights; this method was used in early experiments as well as in later models.
5. In the final experiments, which were carried out at high g without the use of surcharges, liquefaction occurred throughout the entire depth within a few cycles. This experiment confirmed that with sufficient input shaking, large excess pore pressures are generated in a saturated soil column of broadly uniform permeability.
6. A key finding of the study has been to recognise the importance of pore pressure redistribution in deep soil columns, which can cause an 'up-welling' of excess pore pressure from lower layers leading to liquefaction of upper layers some time after shaking has ceased. This is an effect not widely considered in standard design methods.

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APPENDIX A

EARTHQUAKE DATASET

Data of limiting pore pressures, Models and cycles (1998-2001)

EARTHQUAKE DATASET

Data of limiting pore pressures, Models and cycles

Model, Earthquake	Eq	Centrifg acc'n	Total vertical stress (KPa)	Effective Overburden Pressure (KPa)	Cycles to upper limit	Cycles to 50% excess	Pore pressure Upper limit (%)	Upper value (KPa)	Peak Cyclic stress ratio	Stress ratio	0.65 Relative Density (%)	Quality low/med/high/*	PPT	Comments	Summary details and WES Model Ref
Model 1a, 1	1	50	67.6	34	10.8			59	20.06	0.105	0.068	70 low		31 Uncertain measured depth of transducers, showed double frequency	
Model 1a, 1	1													10 Still climbing at end of datacapture	
Model 1a, 1	1													9 Still climbing at end of datacapture	
Model 1a, 2	2	50	67.6	35	12.4			100	35		0.0511	70 low		31 Ottawa sand, Second eq showed slow rise to final limit	
Model 1a, 2	2													10 Still climbing at end of datacapture	
Model 1a, 2	2													9 Still climbing at end of datacapture	
Model 2a, 1	1	50	70.3	30	2.51			100	30	0.318	0.207	83 low		Near surface acceleration clearly shows liquefaction	20/2/1998, Ref 2
Model 2a, 2	2	50	70.3	30	2.48			100	30	0.25	0.162	83 low		Estimated as no ppts functioning	300mm depth
Model 2a, 3	3													Probably did not liquefy	44% loose, 83% dense
Model 2b, 1	1	50	221	106	10.719	2.187		110	116.6	0.18	0.117	50 *		10 Clearly over 100%, large cycles affect 50% point	30/4/1998, Ref 5
Model 2b, 1	1	50	223	106	11.529	2.349		105	111.3	0.181	0.118	50 *		30 Double frequency just over 100%, large cycles affect 50% point	300mm depth
Model 2b, 1	1	50	68.9	27	10.611	2.16		110	29.7	0.292	0.19	75 *		31 Clearly over 100%, large cycles affect 50% point	50% loose, 75% dense
Model 2b, 2	2	50	230	111	5.4			104	115.44	0.221	0.143	50 *		10 Very clearly 100%	
Model 2b, 2	2	50	236	115	4.59			98	112.7	0.216	0.141	50 *		30 Rapid rise to 100%	
Model 2b, 2	2	50	76.4	32	5.4			100	32	0.33	0.214	75 *		31 Clear 100%, rapid rise	
Model 2c, 1	1	50	240	98	27.5	13.095		100	98	0.092	0.059	49 high		46 Possibly just reached limit before being cut off	6/6/98, Ref 8
Model 2c, 1	1	50	256	98	27.5	8.343		103	100.94	0.097	0.063	49 high		41 Seems to be very close to limit at the end of the eq	300mm depth
Model 2c, 1	1	50		99		21.978				0.0899	0.0585	49 high		49 Still climbing when data cut off	48% loose, 74% dense
Model 2c, 1	1													Reached upper limit early, unlike other depths, high freq rapid rise affects 37 50% point	
Model 2c, 1	1	50	69.2	30	8.59	5.238		70	21	0.114	0.074	74 high		42 Erratic response, still climbing at end	
Model 2c, 1	1													39 Erratic response, still climbing at end	
Model 2c, 1	1													41 Very close to limit at end	
Model 2c, 1	1													49 Still climbing at end of shaking	
Model 2c, 2	2	50	240	98	46			96	94.08	0.094	0.061	49 high		37 Reached upper limit early, unlike other depths	
Model 2c, 2	2	50	256	98	46			100	98	0.1	0.065	49 high		42 Erratic response, still climbing at end	
Model 2c, 2	2	50	70.8	27.6	6.6			75	20.7	0.132	0.085	74 med		39 Reached upper limit early, like pp37	
Model 2c, 2	2													46 Still climbing at end of shaking	
Model 2c, 2	2	50	74.1	30.3	12.8			90	27.27	0.123	0.08	74 med		41 Still climbing at end of shaking	
Model 2c, 3	3													49 Still climbing at end of shaking	
Model 2c, 3	3													37 Reached upper limit early, very noisy response	
Model 2c, 3	3	50	70.8	27.6	7.7			70	19.32	0.127	0.083	74 med		42 Erratic response, still climbing at end	
Model 2c, 3	3													39 Reached upper limit later than pp37, very noisy	
Model 2c, 3	3	50	74.1	30.3	15.4			80	24.24	0.069	0.045	74 med		46 Still climbing at end of shaking	
Model 2c, 4	4													41 Still climbing at end of shaking	
Model 2c, 4	4													49 Still climbing at end of shaking	
Model 2c, 4	4													37 Reached upper limit early, very noisy response	
Model 2c, 4	4	50	70.8	27.6	5.4			70	19.32	0.107	0.07	74 med		42 Erratic response, still climbing at end	
Model 2c, 4	4													39 Possibly reached limit, very noisy	
Model 2c, 4	4	50	74.1	30.3	36.5			75	22.725	0.1	0.085	74 med		46 No excess pore pressure	
Model 2c, 5	5													41 No excess pore pressure	

50% loose, 75% dense

Model 2f, 1	1	125	320	136	7.34	3.1	85	115.6	0.207	0.134	50 *	46 Excellent
Model 2f, 1	1	125	104	32.2	5.21	1.7	101	37.03	0.395	0.257	75 *	38 Excellent
Model 2f, 1	1	125	102	31.7	5.4	2.4	115	36.455	0.397	0.258	75 *	51 Clear limit, very rapid rise with one or two big cycles, affecting 50%
Model 2f, 1	1	125	172	62.6	13.5	7.5	93	58.218	0.293	0.191	50 *	15 Good record, loose/dense interface
Model 2f, 1	1	125	337	138	10.8	3.9	90	124.2	0.213	0.138	50 *	41 Bottom of loose layer, rapid rise to limit, with cycles which may affect 50%
Model 2f, 2	2	125	177	69	8.6		88	60.72	0.287	0.187	50 *	31 Excellent
Model 2f, 2	2	125	254	103.5	14		79	81.765	0.248	0.161	50 *	47 Good record
Model 2f, 2	2	125	320	136	2.2		85	115.6	0.222	0.144	50 *	46 Very rapid rise to limit
Model 2f, 2	2	125	113	41.4	3.2		80	33.12	0.341	0.222	75 *	38 Clear limit, slightly noisy
Model 2f, 2	2	125	112	41.9	4.1		82	34.356	0.336	0.218	75 *	51 Clear limit, again noisy
Model 2f, 2	2	125	177	67.6	20.3		85	57.46	0.294	0.191	50 *	15 Two stage rise to final limit
Model 2f, 2	2	125	339	140.3	6.8		86	120.658	0.225	0.146	50 *	41 Bottom of model, rapid rise to limit
Model 2f, 3	3	125	177	69	19.7		92	63.48	0.328	0.247	50 high	31 Reached limit near end of shaking, loose/dense interface
Model 2f, 3	3	125	254	103.5	34.8		92	95.22	0.328	0.213	50 high	47 Just reached limit near end
Model 2f, 3	3	125	320	136	4.3		92	125.12	0.293	0.191	50 *	46 Bottom of model, very rapid rise to limit
Model 2f, 3	3	125	113	41.4	6.2		100	41.4	0.452	0.293	75 *	38 Clear limit, slightly noisy
Model 2f, 3	3	125	112	41.9	4.9		93	38.967	0.444	0.288	75 *	51 Clear limit, again noisy
Model 2f, 3	3	125	339	140.3	15.4		82	115.046	0.305	0.199	50 *	15 Still rising at end of shaking
Model 2f, 3	3	125	474	181	4.2	1.9	102	184.62	0.314	0.204	34 high	41 Bottom of model, rapid rise to limit
Model 2f, 4	4	125	177	69	26.2		83	57.27	0.39	0.254	50 high	31 Reached limit near end of shaking, cyclic response
Model 2f, 4	4	125	254	103.5	23.5		84	86.94	0.337	0.219	50 high	47 Reached limit near end
Model 2f, 4	4	125	320	135.7	4.6		86	116.702	0.301	0.196	50 *	46 Bottom of model, very rapid rise to limit
Model 2f, 4	4	125	113	41.4	7.3		78	32.292	0.463	0.301	75 *	38 Clear limit, slightly noisy
Model 2f, 4	4	125	112	41.9	4.6		77	32.263	0.455	0.296	75 *	51 Clear limit, again noisy
Model 2f, 4	4	125	339	140.3	15.4		82	115.046	0.305	0.199	50 *	15 Still rising at end of shaking
Model 2f, 4	4	125	474	181	4.2	1.9	102	184.62	0.314	0.204	34 high	41 Bottom of model, slower rise to limit
Model 3a, 1	1	50	474	181	4.2	1.9	102	184.62	0.314	0.204	34 high	9 affects 50%
Model 3a, 1	1	50	429	182	3.8	1.8	110	200.2	0.281	0.183	34 high	Low static pore pressure value, good dynamic response, rapid rise affects
Model 3a, 2	2	50	477	186	7.9		98	182.28	0.288	0.187	34 high	10 50%
Model 3a, 2	2	50	432	184	3.6		102	187.68	0.258	0.168	34 high	9 Slow rise contrasts with pp410
Model 3b, 2	2	50	466	198	5.4		90	178.2	0.124	0.081	49 med	10 Good limit, spiky acceleration on sgs 1 and 2
Model 3b, 2	2	50	469	200	5.7		90	180	0.124	0.081	49 high	16 Calibration adjusted to bring into line with pp42
Model 3b, 2	2	50	528	228	4.5		82	186.96	0.117	0.076	49 high	2 Good record
Model 3b, 2	2	50	385	164	25.1		90	147.6	0.132	0.086	49 high	11 Clearly reached limit
Model 3b, 3	3	50	466	190	5.2		85	161.5	0.135	0.088	50 med	1 Just reached limit
Model 3b, 3	3	50	469	197	4.9		90	177.3	0.135	0.088	50 high	16 Calibration adjusted to bring into line with pp42
Model 3b, 3	3	50	528	220	6.5		86	145.2	0.127	0.083	50 high	2 Good record
Model 3b, 3	3	50	385	164	19.7		90	147.6	0.144	0.093	50 high	11 Clearly reached limit
Model 3c, 1	1	50	457	194	4.3	1.0	100	194	0.225	0.146	50 *	1 Just reached limit
Model 3c, 1	1	50	468	196	4.1	1.2	100	196	0.228	0.148	50 *	30 Excellent, exactly 100%, less than 1 cycle to 50% query amplitude
Model 3c, 1	1	50	524	222	4.2	1.2	95	210.9	0.216	0.141	50 *	31 Excellent, again exactly 100%
Model 3c, 1	1	50	296	130	17.6	2.2	87	113.1	0.247	0.161	75 high	10 Excellent
Model 3c, 1	1	50	320	129	14.9	1.9	90	116.1	0.268	0.174	75 high	11 Limit rises slowly
Model 3c, 1	1	50	382	160	7.5	1.2	100	160	0.243	0.158	75 high	16 Limit rises slowly
Model 3c, 1	1	50	115	53.5	5.4	2.1	84	44.94	0.3	0.195	75 high	15 Rapid rise time, liquefaction could be affected by loose layer below
Model 3c, 1	1	50	123	54	6.8	1.9	96	51.84	0.315	0.205	75 high	5 Clear limit, noisy record affects 50%
Model 3c, 1	1	50	252	100	9.5	1.7	96	96	0.296	0.192	75 high	2 Clear limit, noisy record affects 50%
Model 3c, 2	2	50	457	194	6.5		98	190.12	0.218	0.142	50 high	30 Rapid rise to 80% +
Model 3c, 2	2	50	468	196	5.7		96	188.16	0.221	0.143	50 high	31 Very rapid rise to 90% +
Model 3c, 2	2	50	524	222	12.0		92	204.24	0.209	0.136	50 med	10 First limit reached at 82%, then rose to 92%

Model 3c, 2	2	50	296	130	37.8	4.9	8.6	226	235	0.156	0.239	117	90	76 low	11 Still climbing slowly at end of shaking
Model 3c, 2	2	50	320	129	36.8	4.9	17.6	245	118.68	0.169	0.26	118.68	92	75 low	16 Still climbing slowly at end of shaking
Model 3c, 2	2	50	382	160	21.6	4.9	17.6	245	180	0.153	0.235	180	100	75 high	15 Reached limit, probably influenced by loose layer below
Model 3c, 2	2	50	115	53.5	24.3	3.4	12.4	243	41.195	0.189	0.29	41.195	77	75 high	5 Clear limit, noisy record
Model 3c, 2	2	50	123	54	32.4	4.2	7.9	223	44.82	0.198	0.305	44.82	83	75 high	2 Clear limit, noisy record
Model 3c, 2	2	50	252	100	31.1	4.2	23.0	54	95	0.186	0.286	95	95	75 high	1 Close to 100% at end of shaking
Model 3c, 2	2	50	457	194	8.1	7.9	23.0	54	97	0.134	0.207	188.18	97	50 high	30 Rapid rise to 90% +
Model 3c, 3	3	50	468	196	7.6	7.9	23.0	54	98	0.136	0.209	192.08	98	50 high	31 Very rapid rise to 90% +
Model 3c, 3	3	50	524	222	15.3	4.9	17.6	245	210.9	0.129	0.199	210.9	95	50 med	10 Again, double stage rise, as eq2
Model 3c, 3	3	50	296	130	44.3	4.2	23.0	54	92	0.148	0.227	119.6	92	75 low	11 Still climbing slowly at end of shaking
Model 3c, 3	3	50	320	129	45.9	4.2	23.0	54	93	0.16	0.246	119.97	93	75 low	16 Still climbing slowly at end of shaking
Model 3c, 3	3	50	382	160	22.7	4.2	23.0	54	100	0.175	0.223	160	100	75 high	15 Probably influenced by loose layer below
Model 3c, 3	3	50	115	53.5	24.3	4.2	23.0	54	76	0.179	0.275	40.66	76	75 high	5 Clear limit, noisy record
Model 3c, 3	3	50	123	54	23.0	4.2	23.0	54	82	0.188	0.29	44.28	82	75 high	2 Clear limit, noisy record
Model 3c, 3	3	50	123	54	23.0	4.2	23.0	54	82	0.188	0.29	44.28	82	75 high	1 Still rising at end of shaking
Model 3d, 1	1	125	434	226	8.6	4.9	8.6	226	142.38	0.09	0.147	142.38	63	54 *	48 Excellent
Model 3d, 1	1	125	515	245	17.6	4.9	17.6	245	191.1	0.095	0.147	191.1	78	54 med	37 Slow buildup makes definition of limit difficult
Model 3d, 1	1	125	522	243	12.4	3.4	12.4	243	182.25	0.097	0.149	182.25	75	54 high	35 Slow buildup makes definition of limit difficult
Model 3d, 1	1	125	434	223	7.9	4.2	23.0	54	65	0.092	0.141	144.95	65	54 *	40 Excellent, cycles affect 50%
Model 3d, 1	1	125	523	283	8.0	4.9	8.6	226	198.1	0.106	0.163	198.1	70	54 high	38 Still climbing at end of shaking
Model 3d, 1	1	125	522	273	8.5	4.9	8.6	226	199.29	0.11	0.169	199.29	73	54 high	44 Still climbing at end of shaking
Model 3d, 2	2	125	523	283	8.0	4.9	8.6	226	198.1	0.106	0.163	198.1	70	54 high	37 Rapid rise to 90%, then slow climb
Model 3d, 2	2	125	522	273	8.5	4.9	8.6	226	199.29	0.11	0.169	199.29	73	54 high	35 Rapid rise to 90%, then slow climb
Model 3d, 2	2	125	523	283	8.0	4.9	8.6	226	198.1	0.106	0.163	198.1	70	54 high	48 Still climbing slowly at end of shaking
Model 3d, 2	2	125	522	273	8.5	4.9	8.6	226	199.29	0.11	0.169	199.29	73	54 high	40 Still climbing at end of shaking
Model 3d, 2	2	125	523	283	8.0	4.9	8.6	226	198.1	0.106	0.163	198.1	70	54 high	38 Still climbing at end of shaking
Model 3d, 2	2	125	522	273	8.5	4.9	8.6	226	199.29	0.11	0.169	199.29	73	54 high	44 Still climbing at end of shaking
Model 3d, 3	3	125	523	283	8.0	4.9	8.6	226	198.1	0.106	0.163	198.1	70	54 high	37 Good record
Model 3d, 3	3	125	522	273	8.5	4.9	8.6	226	199.29	0.11	0.169	199.29	73	54 high	35 Good record
Model 3d, 3	3	125	523	283	8.0	4.9	8.6	226	198.1	0.106	0.163	198.1	70	54 high	48 Still climbing slowly at end of shaking
Model 3d, 3	3	125	522	273	8.5	4.9	8.6	226	199.29	0.11	0.169	199.29	73	54 high	40 Still climbing at end of shaking
Model 3d, 3	3	125	523	283	8.0	4.9	8.6	226	198.1	0.106	0.163	198.1	70	54 high	38 Still climbing at end of shaking
Model 3d, 3	3	125	522	273	8.5	4.9	8.6	226	199.29	0.11	0.169	199.29	73	54 high	44 Still climbing at end of shaking
Model 3d, 4	4	125	508	268	28.6	4.9	8.6	226	192.96	0.118	0.182	192.96	72	54 high	37 Two stage rise
Model 3d, 4	4	125	522	273	27.2	4.9	8.6	226	191.1	0.12	0.184	191.1	70	54 high	35 Two stage rise
Model 3d, 4	4	125	435	257	28.1	4.9	8.6	226	159.34	0.111	0.171	159.34	62	54 high	48 Clear limit
Model 3d, 4	4	125	438	257	25.9	4.9	8.6	226	156.77	0.112	0.172	156.77	61	54 high	40 Clear limit
Model 3d, 4	4	125	438	257	25.9	4.9	8.6	226	156.77	0.112	0.172	156.77	61	54 high	38 Still climbing at end of shaking
Model 3d, 4	4	125	438	257	25.9	4.9	8.6	226	156.77	0.112	0.172	156.77	61	54 high	44 Still climbing at end of shaking
Model 3e, 1	1	50	521	235	10.9	14.0	24.8	347	235	0.424	0.652	235	100	50 *	3/10/01, Ref 35
Model 3e, 1	1	50	369	170	10.9	14.0	24.8	347	235	0.424	0.652	235	100	50 *	525mm depth
Model 3e, 1	1	50	239	239	10.9	14.0	24.8	347	235	0.424	0.652	235	100	50 *	50% loose, 75% dense
Model 3e, 1	1	50	359	359	10.9	14.0	24.8	347	235	0.424	0.652	235	100	50 *	No surcharge on flight 1
Model 3e, 1	1	50	231	105	21.2	14.0	24.8	347	235	0.424	0.652	235	100	50 *	50g
Model 3e, 1	1	50	108	67	18.8	14.0	24.8	347	235	0.424	0.652	235	100	50 *	See also Model 5g
Model 3f, 1	1	100	471	191	9.4	14.0	24.8	347	235	0.424	0.652	235	100	50 *	16/10/01, Ref 37
Model 3f, 1	1	100	394	426	9.4	14.0	24.8	347	235	0.424	0.652	235	100	50 *	262mm depth
Model 3f, 1	1	100	316	131	4.1	14.0	24.8	347	235	0.424	0.652	235	100	50 *	50% loose, 75% dense
Model 3f, 1	1	100	375	169	4.1	14.0	24.8	347	235	0.424	0.652	235	100	50 *	No surcharge
Model 4a, 1	1	50	477	347	24.8	14.0	24.8	347	278	0.078	0.078	278	80	49 high	100g
Model 4a, 1	1	50	477	347	24.8	14.0	24.8	347	278	0.078	0.078	278	80	49 high	14/9/98, Ref 12

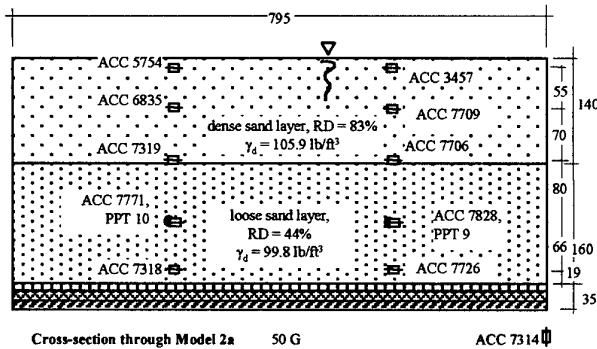
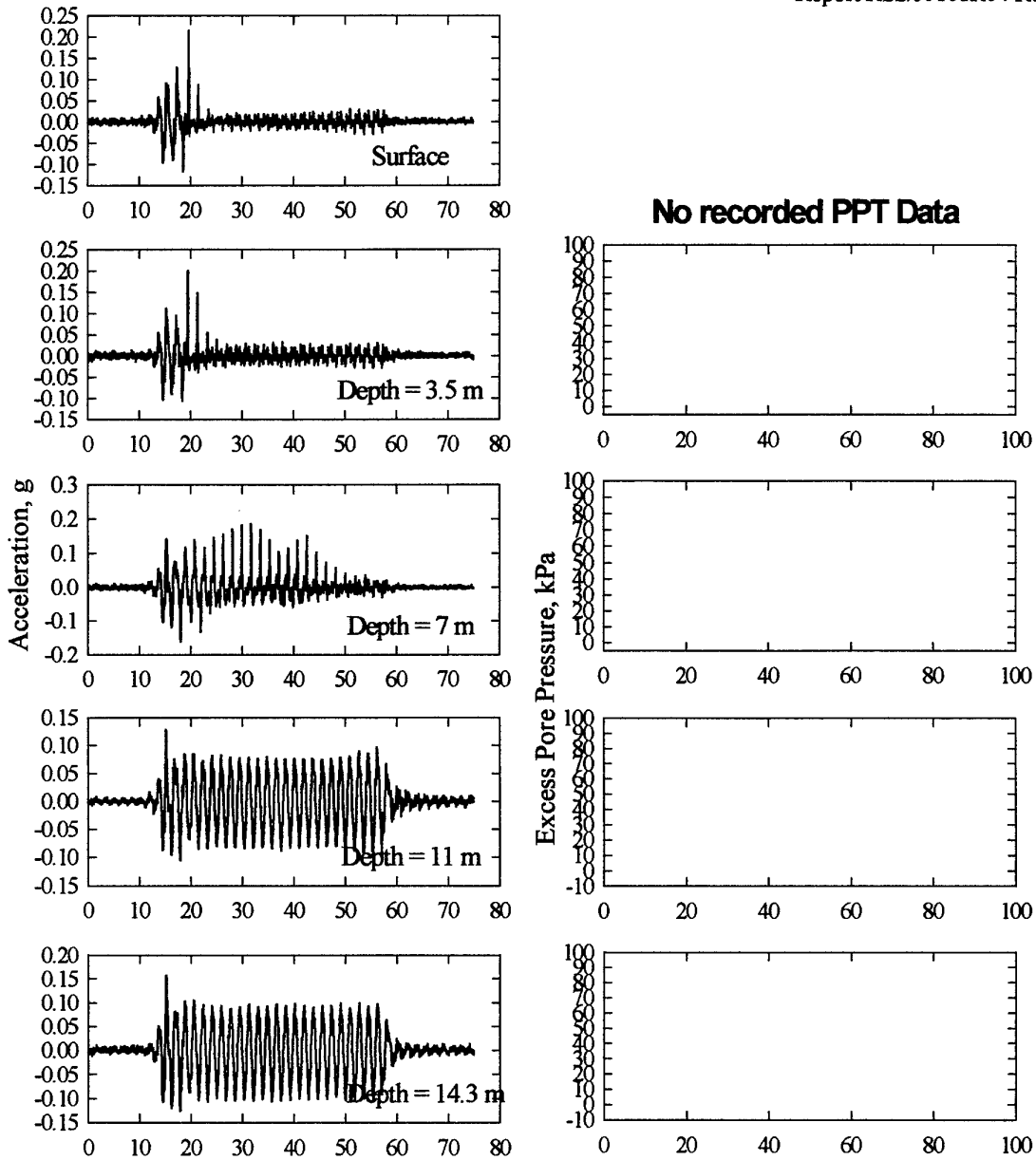
Model 4a, 1	1	50	483	348	26.7	22.1	75	261	0.078	0.051	49 high	35 Clearly reached upper limit	525mm depth
Model 4a, 1	1											52 Still climbing at end of shaking	49% loose, 80% dense
Model 4a, 1	1											43 Still climbing at end of shaking	
Model 4a, 2	2	50	469	339	40		27	91.53	0.098	0.064	49 med	45 Reached some sort of limit, much less than eq1	
Model 4a, 2	2	50	474	340	40		16	54.4	0.098	0.064	49 med	35 Reached some sort of limit, much less than eq1	
Model 4a, 2	2											52 Still climbing at end of shaking	
Model 4a, 2	2											43 Still climbing at end of shaking	
Model 4a, 3	3											45 Very little excess pore pressure generated	
Model 4a, 3	3											35 Very little excess pore pressure generated	
Model 4a, 3	3											52 Very little excess pore pressure generated	
Model 4a, 3	3											43 Very little excess pore pressure generated	
Model 4a, 4	4											45 No excess pore pressure at all	
Model 4a, 4	4											35 No excess pore pressure at all	
Model 4a, 4	4											52 No excess pore pressure at all	
Model 4a, 4	4											43 No excess pore pressure at all	
Model 4b, 1	1											39 Very noisy signal, minimal excess pore pressure	15/09/08, Ref 13
Model 4b, 1	1											40 Very noisy signal, minimal excess pore pressure	525mm depth
Model 4b, 1	1											44 Very noisy signal, minimal excess pore pressure	56% loose, 74% dense
Model 4b, 2	2	125	485	369	24.4		85	313.65	0.165	0.107	56 low	39 Clear limit, surprising after eq1	
Model 4b, 2	2											40 Climbing at end of earthquake	
Model 4b, 2	2											44 Climbing at end of earthquake	
Model 4b, 3	3											39 No excess pore pressure at all	
Model 4b, 3	3											40 Almost no excess pore pressure	
Model 4b, 3	3											44 Climbing at end of earthquake	
Model 4b, 4	4											39 No excess pore pressure at all	
Model 4b, 4	4											40 Almost no excess pore pressure	
Model 4b, 4	4											44 Almost no excess pore pressure	
Model 4c, 1	1	50	808	533	19.5	13.338	60	319.8	0.073	0.048	50 high	51 Good record : 6 other gpts in upper layer showed	22/10/08, Ref 17
Model 4c, 1	1	50	806	534	20.6	15.903	59	315.06	0.073	0.048	50 high	38 Good record : no response in any Model 4c eq)	525mm depth
Model 4c, 1	1											47 Still climbing at end of shaking	50% loose, 75% dense
Model 4c, 1	1											46 Still climbing at end of shaking	202 lb surcharge
Model 4c, 1	1											50 Still climbing at end of shaking	
Model 4c, 2	2											41 Still climbing at end of shaking	
Model 4c, 2	2											51 Still climbing at end of shaking	
Model 4c, 2	2											38 Still climbing at end of shaking	
Model 4c, 2	2											47 Still climbing at end of shaking	
Model 4c, 2	2											46 Still climbing at end of shaking	
Model 4c, 2	2											50 Still climbing at end of shaking	
Model 4c, 2	2											41 Still climbing at end of shaking	
Model 4c, 3	3											38 Still climbing at end of shaking	
Model 4c, 3	3											47 Still climbing at end of shaking	
Model 4c, 3	3											50 Still climbing at end of shaking	
Model 4c, 3	3											41 Still climbing at end of shaking	
Model 4c, 4	4											51 Almost no excess pore pressure	
Model 4c, 4	4											38 Almost no excess pore pressure	
Model 4c, 4	4											47 Almost no excess pore pressure	
Model 4c, 4	4											46 Almost no excess pore pressure	
Model 4c, 4	4											50 Almost no excess pore pressure	
Model 4c, 4	4											41 Almost no excess pore pressure	

Model 4d, 1	1	125	813	543	11.9	47	255.21	0.079	0.051	50 high	38 Excellent : (6 ppts in upper layer showed
Model 4d, 1	1	125	813	543	12.42	48	260.64	0.079	0.051	50 high	51 Excellent : almost no response in any 4d eq)
Model 4d, 1	1										47 Climbing at end of earthquake
Model 4d, 1	1										46 Climbing at end of earthquake
Model 4d, 1	1										50 Still climbing at end of shaking
Model 4d, 1	1										41 Still climbing at end of shaking
Model 4d, 2	2	125	813	543	12.4	44	238.92	0.085	0.055	50 high	38 Good record
Model 4d, 2	2	125	813	543	11.8	45	244.35	0.085	0.055	50 high	51 Good record
Model 4d, 2	2										47 Climbing at end of earthquake
Model 4d, 2	2										46 Climbing at end of earthquake
Model 4d, 2	2										50 Still climbing slowly at end of shaking
Model 4d, 2	2										41 Still climbing slowly at end of shaking
Model 4d, 3	3	125	813	543	47	37	200.91	0.083	0.054	50 med	38 Possible limit at end of shaking
Model 4d, 3	3	125	813	543	47	38	206.34	0.083	0.054	50 med	51 Possible limit at end of shaking
Model 4d, 3	3										47 Climbing at end of earthquake
Model 4d, 3	3										46 Climbing at end of earthquake
Model 4d, 3	3										50 Appears to reach limit near end of shaking
Model 4d, 3	3	125	739	515	37.9	41	211.15	0.083	0.054	50 high	41 Appears to reach limit near end of shaking
Model 4d, 3	3	125	741	512	36	41	209.92	0.083	0.054	50 high	38 Still climbing at end of shaking
Model 4d, 4	4										51 Still climbing at end of shaking
Model 4d, 4	4										47 Climbing at end of earthquake
Model 4d, 4	4										46 Climbing at end of earthquake
Model 4d, 4	4										50 Still climbing at end of shaking
Model 4d, 4	4										41 Still climbing at end of shaking
Model 4e, 1	1	50	738	430	20.2	87	374	0.439	0.285	50 *	39 Excellent early response
Model 4e, 1	1	50	648	415	30.6	77	320	0.416	0.270	50 high	38 Classic rise to near 100%
Model 4e, 1	1	50	505	337							50 Steady climb throughout duration
Model 4e, 1	1	50	586	353	13.1	74	261	0.464	0.302	50 high	46 Rapid rise to early limit, slight increase later
Model 4e, 1	1	50	439	310							6 Steady climb throughout duration
Model 4e, 1	1	50	500	346							54 Steady climb throughout duration
Model 4f, 1	1	50	313	267						low	1 No significant excess pore pressure
Model 4f, 1	1	50	220	220							8 u/s
Model 4f, 1	1	50	573	371	8.9	21	78	0.178	0.116	55 high	10 Quick rise to early limit, then flat
Model 4f, 1	1	50	555	555							16 u/s
Model 4f, 1	1	50	728	445	12.4	89	396	0.173	0.112	55 *	38 Excellent response, absolutely flat limit
Model 4f, 1	1	50	472	379	9.5	24	91	0.15	0.098	55 med	39 Quick rise to limit, very noisy
Model 4f, 1	1	50	431	431							14 u/s
Model 4f, 1	1	50	424	314	13.6	17	53	0.171	0.111	55 high	41 Quick rise to limit, then flat
Model 4f, 1	1	50	335	237						low	48 Very noisy
Model 4f, 1	1	50	647	407	8.3	17	69	0.176	0.114	55 high	54 Quick rise to limit, then steady climb
Model 4g, 1	1	50	698	342	8.1	101	345	0.273	0.177	50 *	53 Excellent early response, slight rise later
Model 4g, 1	1	50	562	383	4	19	73	0.206	0.134	50 high	43 Clear early limit, flat then long rise
Model 4g, 1	1	50	670	385	6.9	78	300	0.233	0.151	50 high	37 Good early rise to limit, then slow rise later
Model 4g, 1	1	50	508	336	6.9	15	50	0.221	0.144	50 high	6 Good early rise to limit, then steady rise later
Model 4g, 1	1	50	751	403	10.4	81	326	0.24	0.156	50 high	35 Good early rise to limit, then slow climb, noisy
Model 4g, 1	1	50	248	220						low	13 Rise, drop and rise
Model 4g, 1	1	50	505	338	7.5	14	47	0.219	0.142	50 high	42 Good early rise, flat then steady climb
Model 4g, 1	1	50	450	291	6.4	12	35	0.237	0.154	50 high	50 Good early rise, flat then steady climb
Model 4g, 1	1	50	330	247							46 No significant excess pore pressure
Model 4h, 1	1	50	631	446	31.5	81	361	0.183	0.119	48 high	43 Steady convex rise to limit
Model 4h, 1	1	50	511	335	6.7	20.6	69	0.216	0.140	51 high	53 Quick rise to early limit, drop and then steady rise to end

APPENDIX B

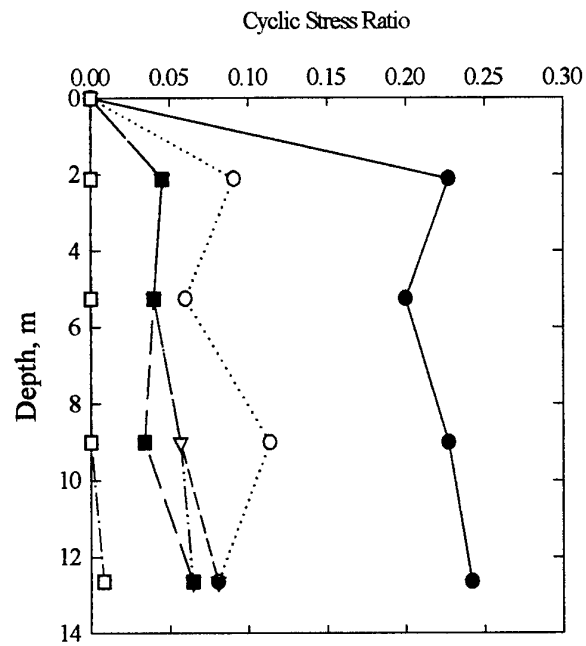
SUMMARY OF DATA

Time histories of acceleration, excess pore pressure and model configurations
Stress and strain histories

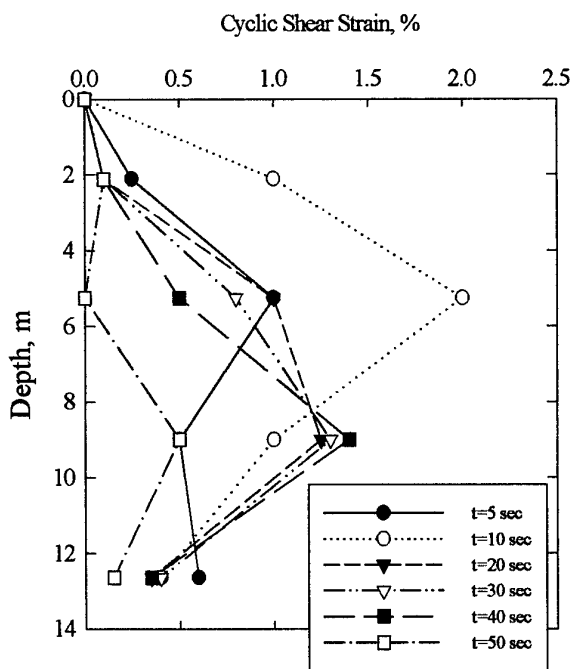


Model 2a

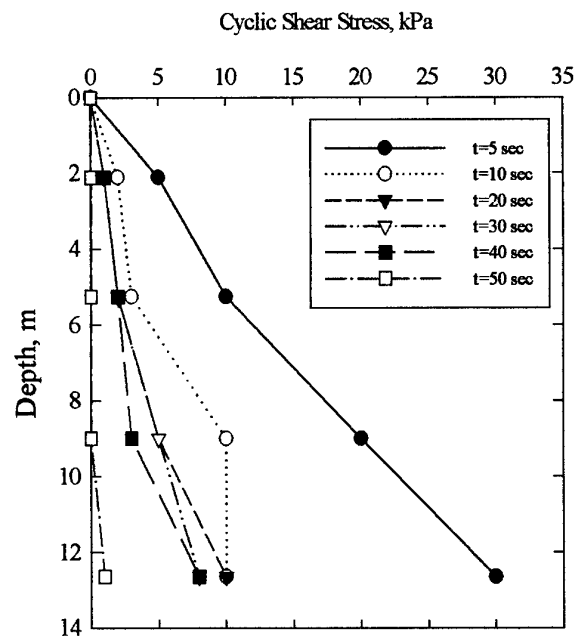
Model 2a-eq1



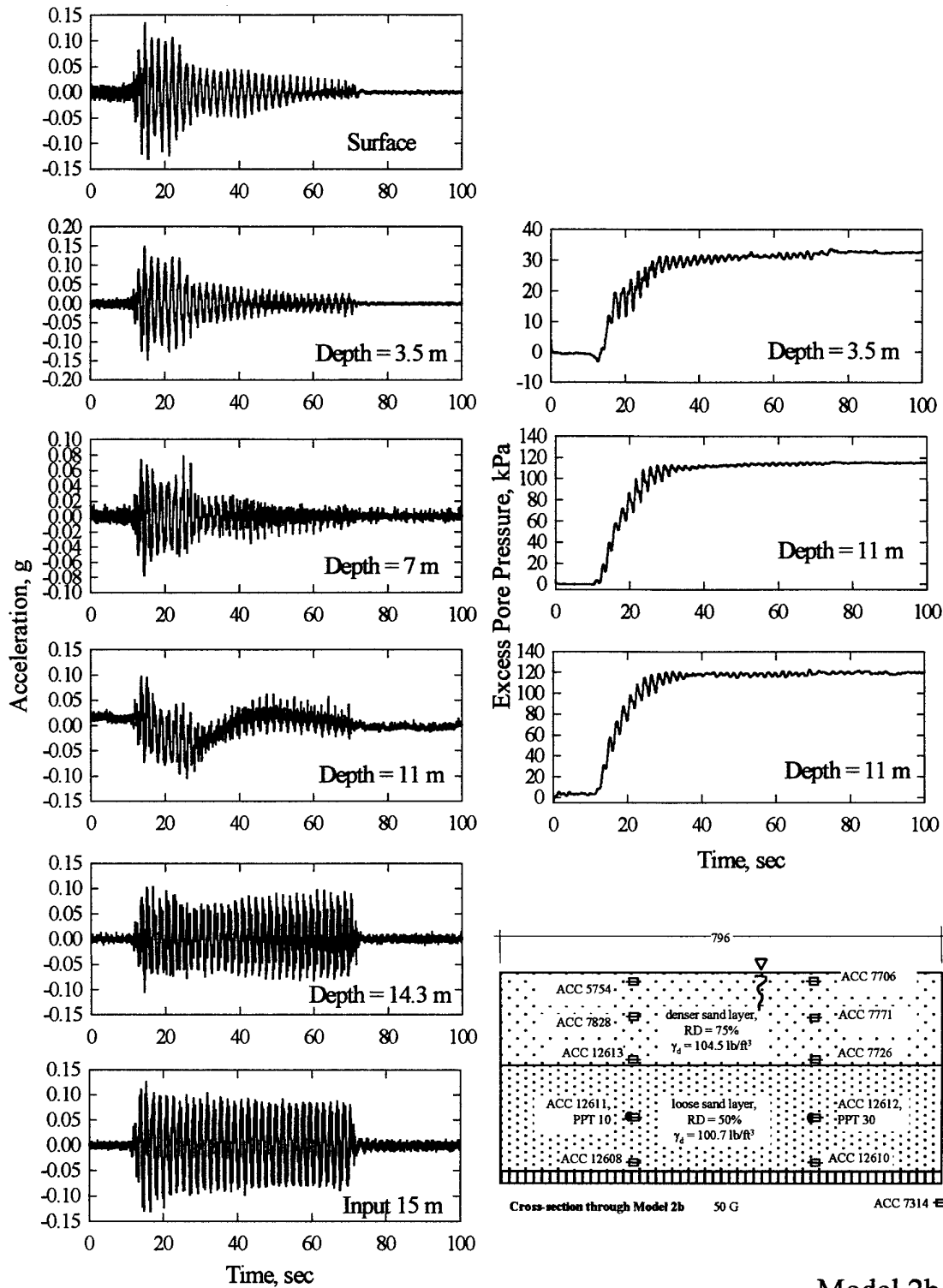
Model 2a-eq1



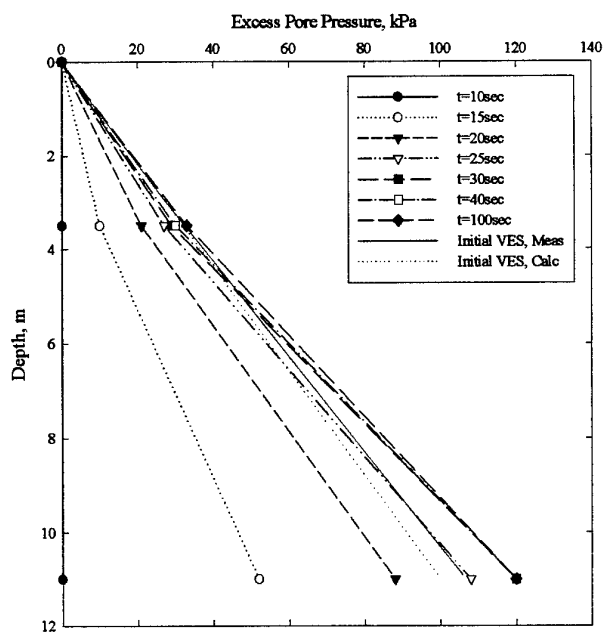
Model 2a-eq1



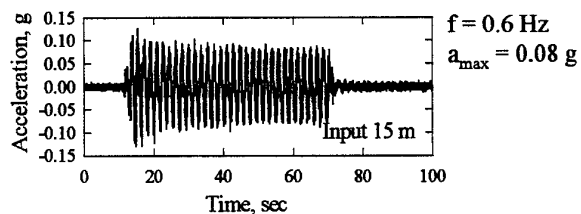
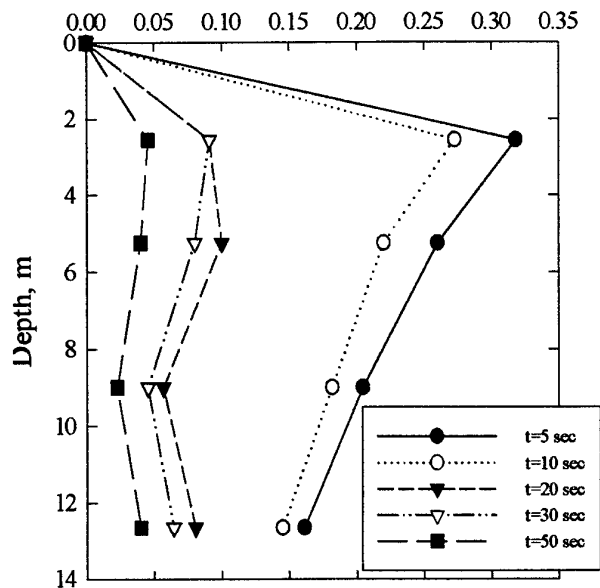
Model 2a Stress and strain isochrones



Model 2b-eq1

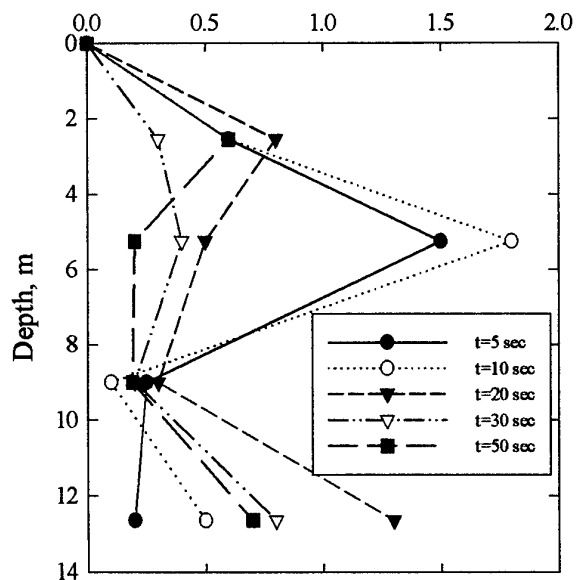


Cyclic Stress Ratio



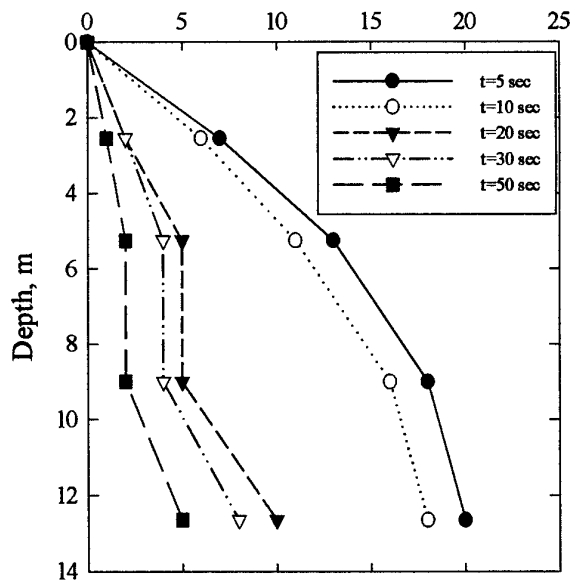
Model 2b-eq1

Cyclic Shear Strain, %

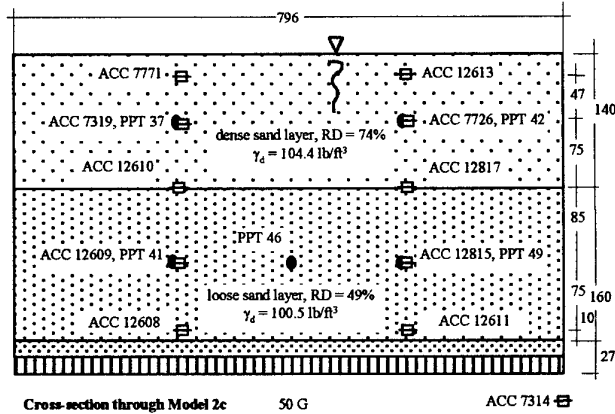
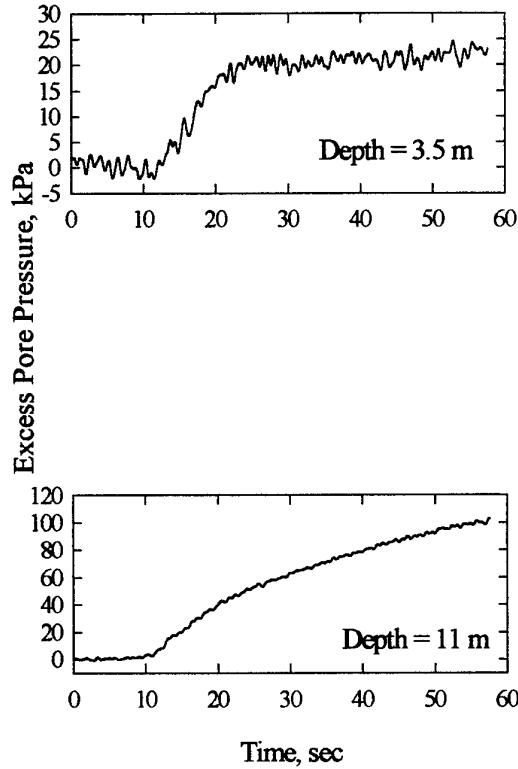
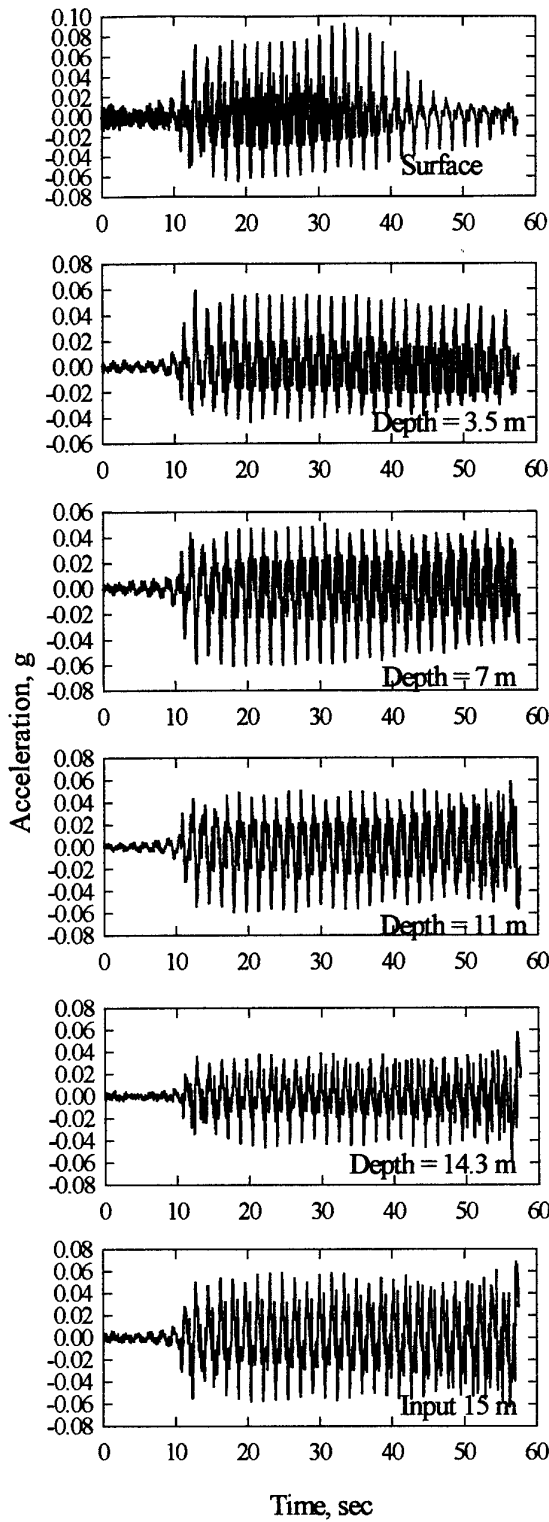


Model 2b-eq1

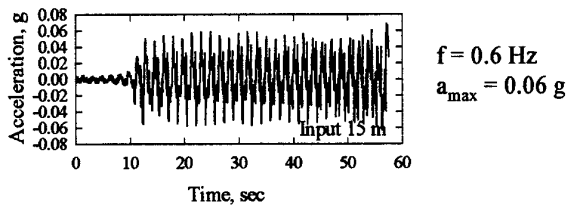
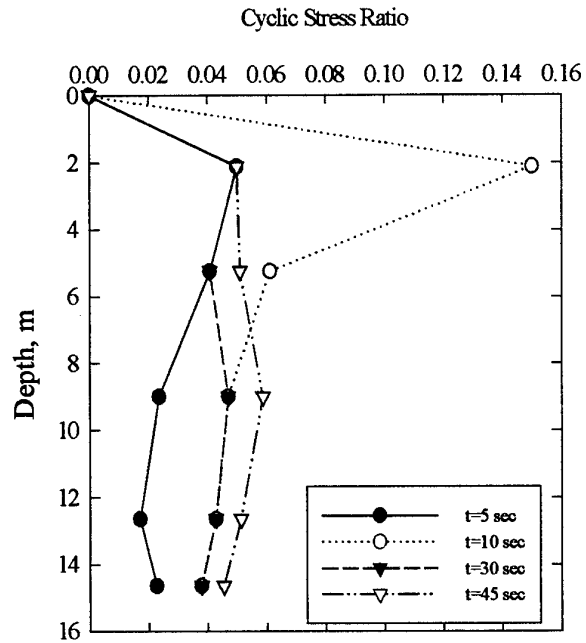
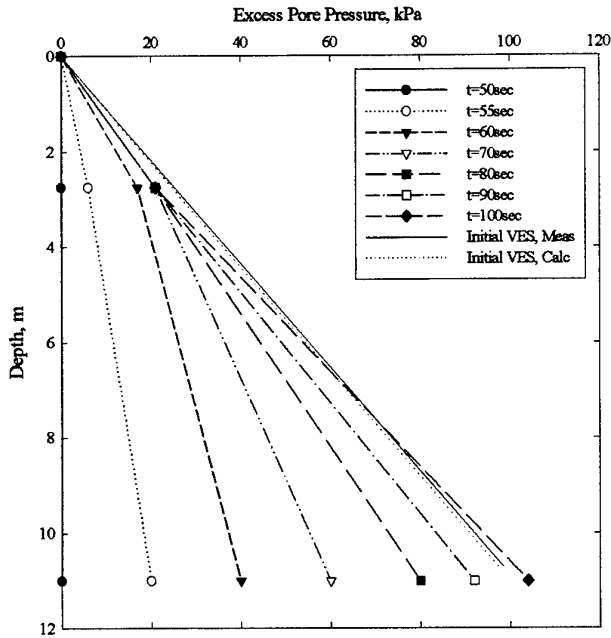
Cyclic Shear Stress, kPa



Model 2b Stress and strain isochrones

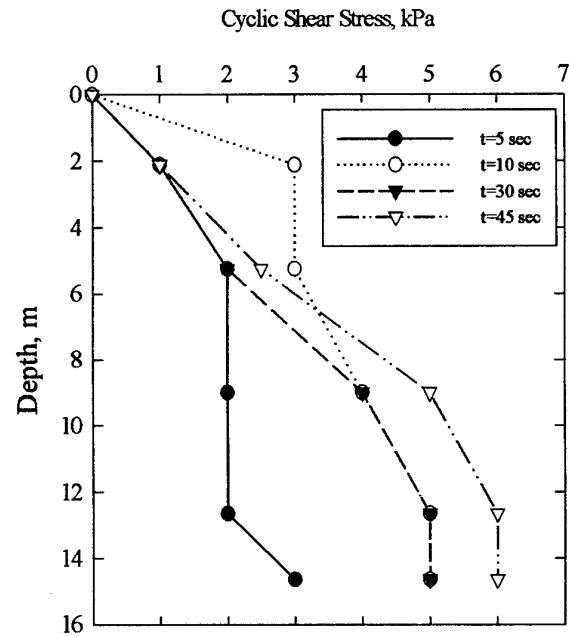
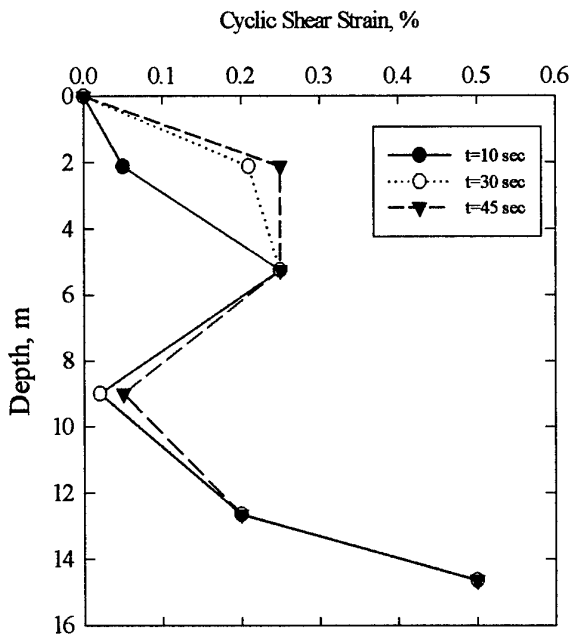


Model 2c

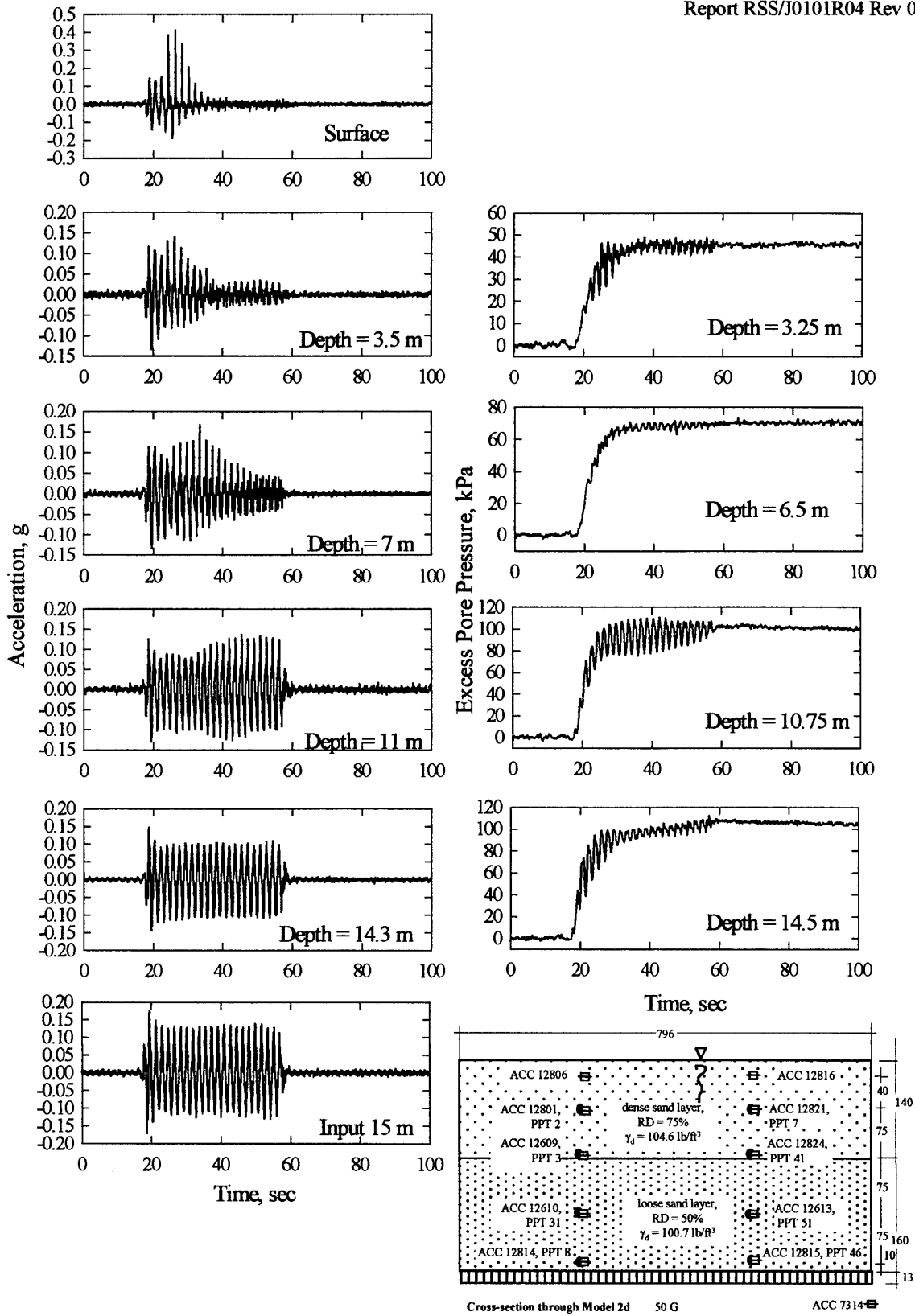


Model 2c-eq1

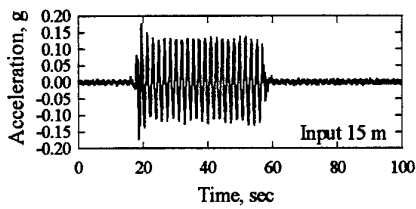
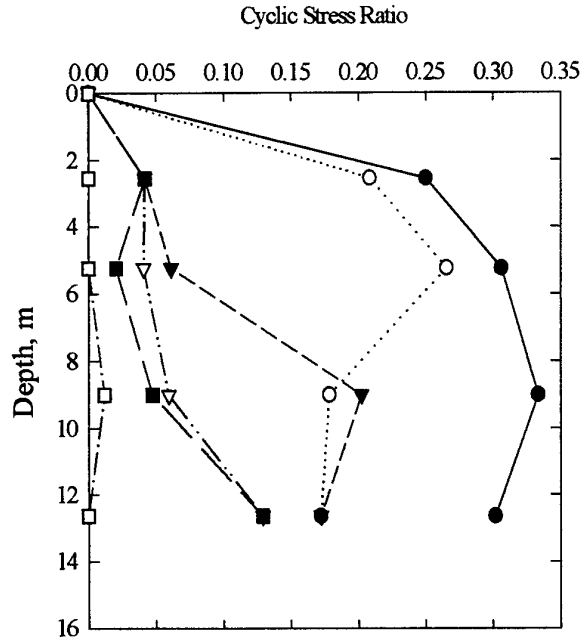
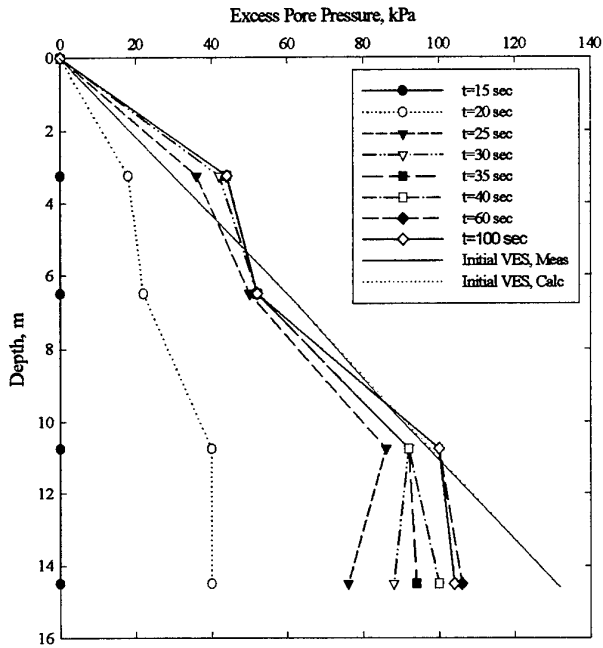
Model 2c-eq1



Model 2c Stress and strain isochrones



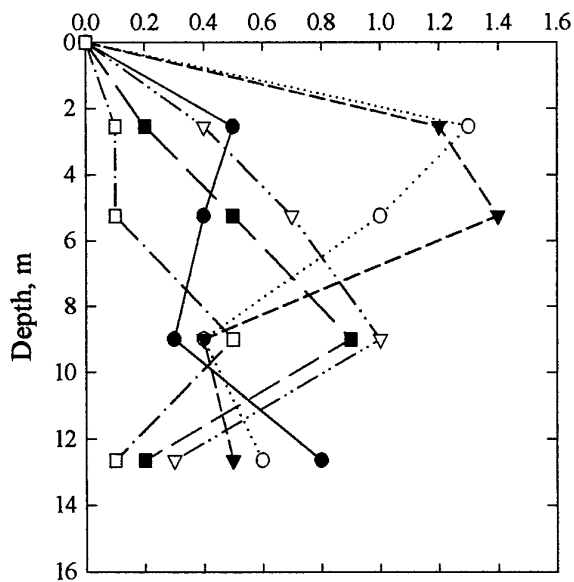
Model 2d



$f = 0.6 \text{ Hz}$
 $a_{\text{max}} = 0.13 \text{ g}$

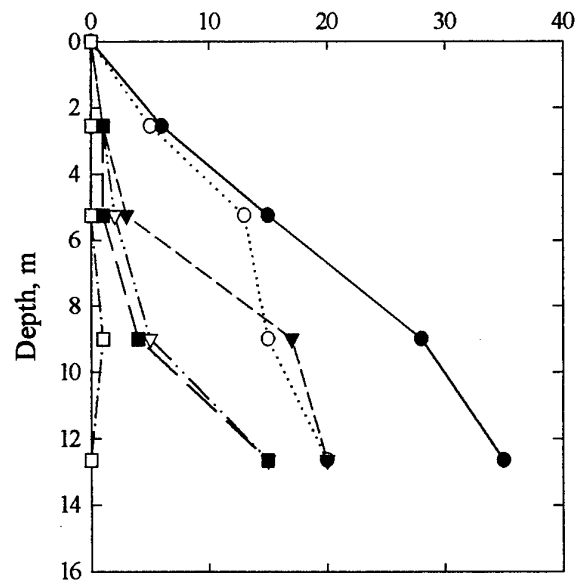
Model 2d-eq1

Cyclic Shear Strain, %

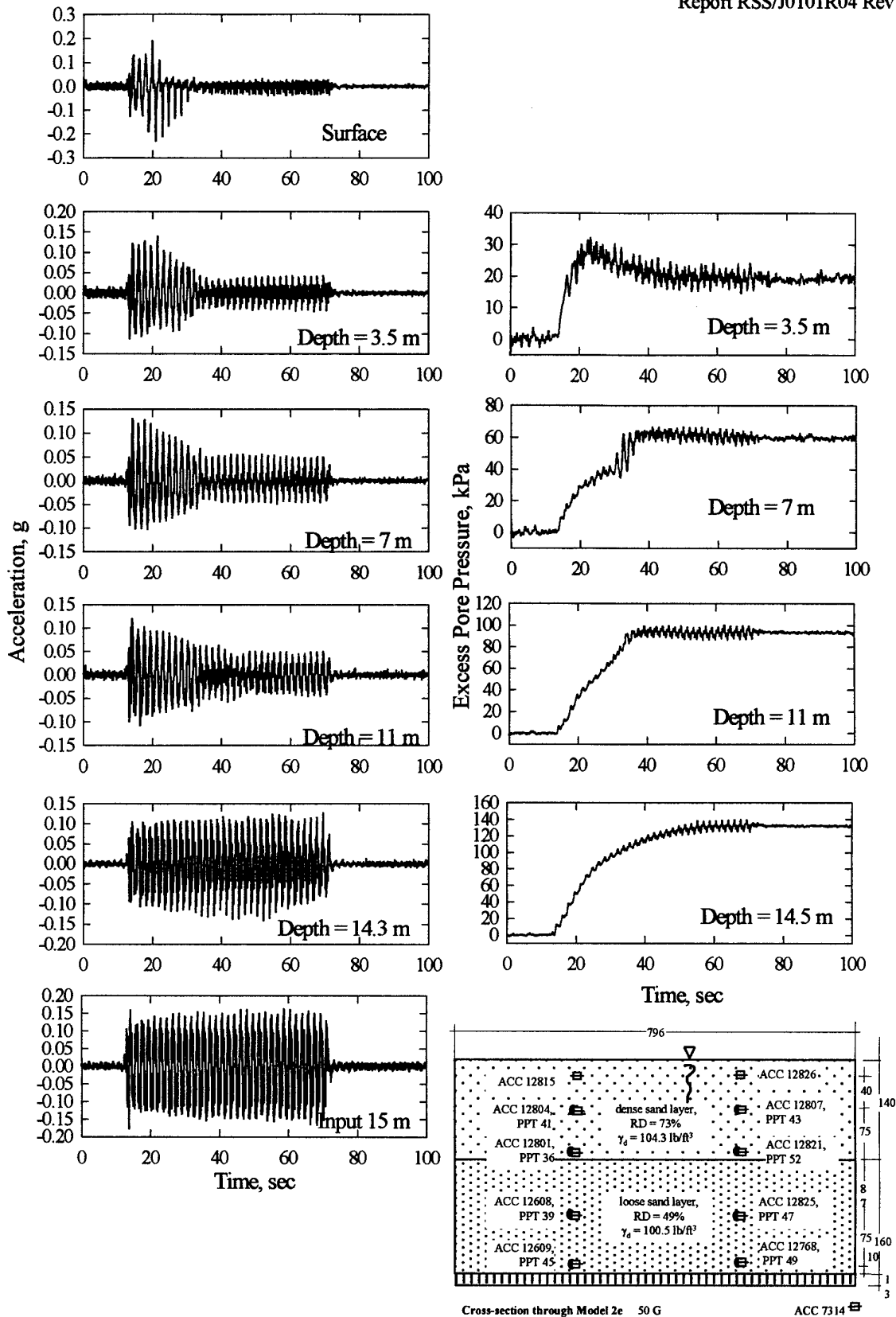


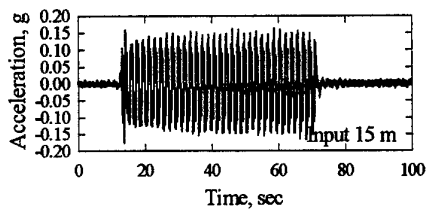
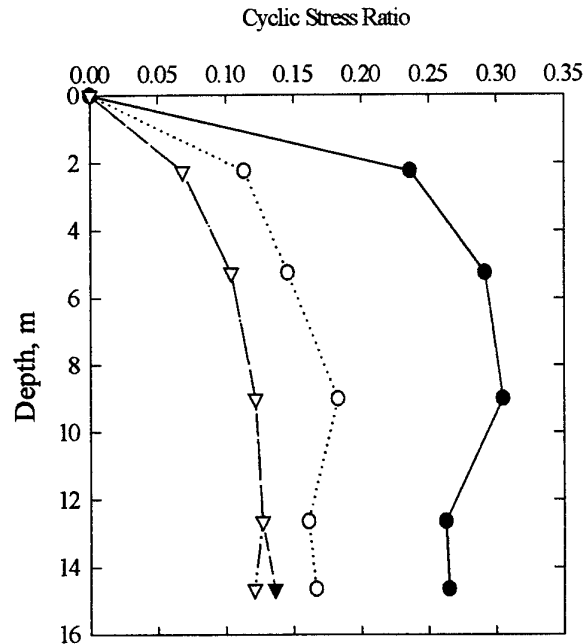
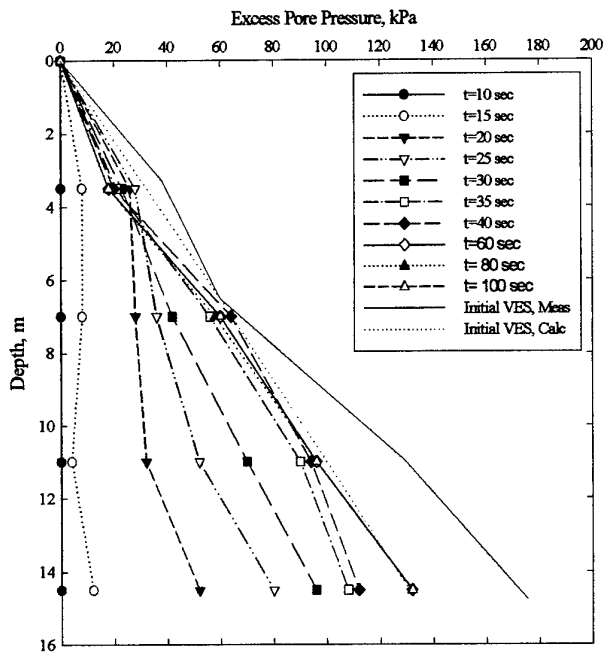
Model 2d-eq1

Cyclic Shear Stress, kPa



Model 2d Stress and strain isochrones

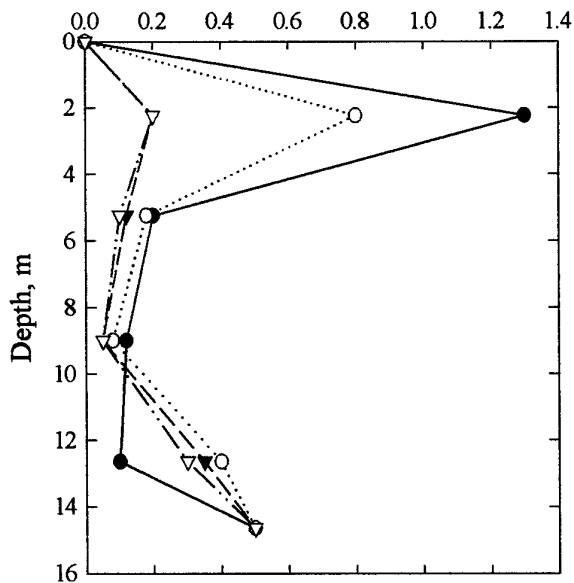




$f = 0.6 \text{ Hz}$
 $a_{\text{max}} = 0.15 \text{ g}$

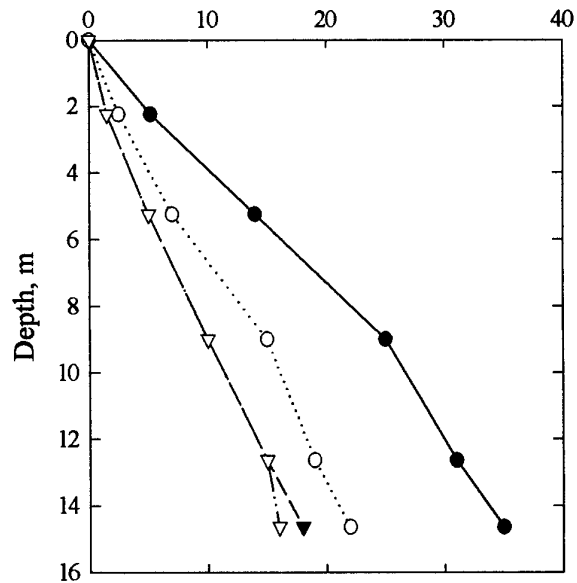
Model 2e-eq1

Cyclic Shear Strain, %

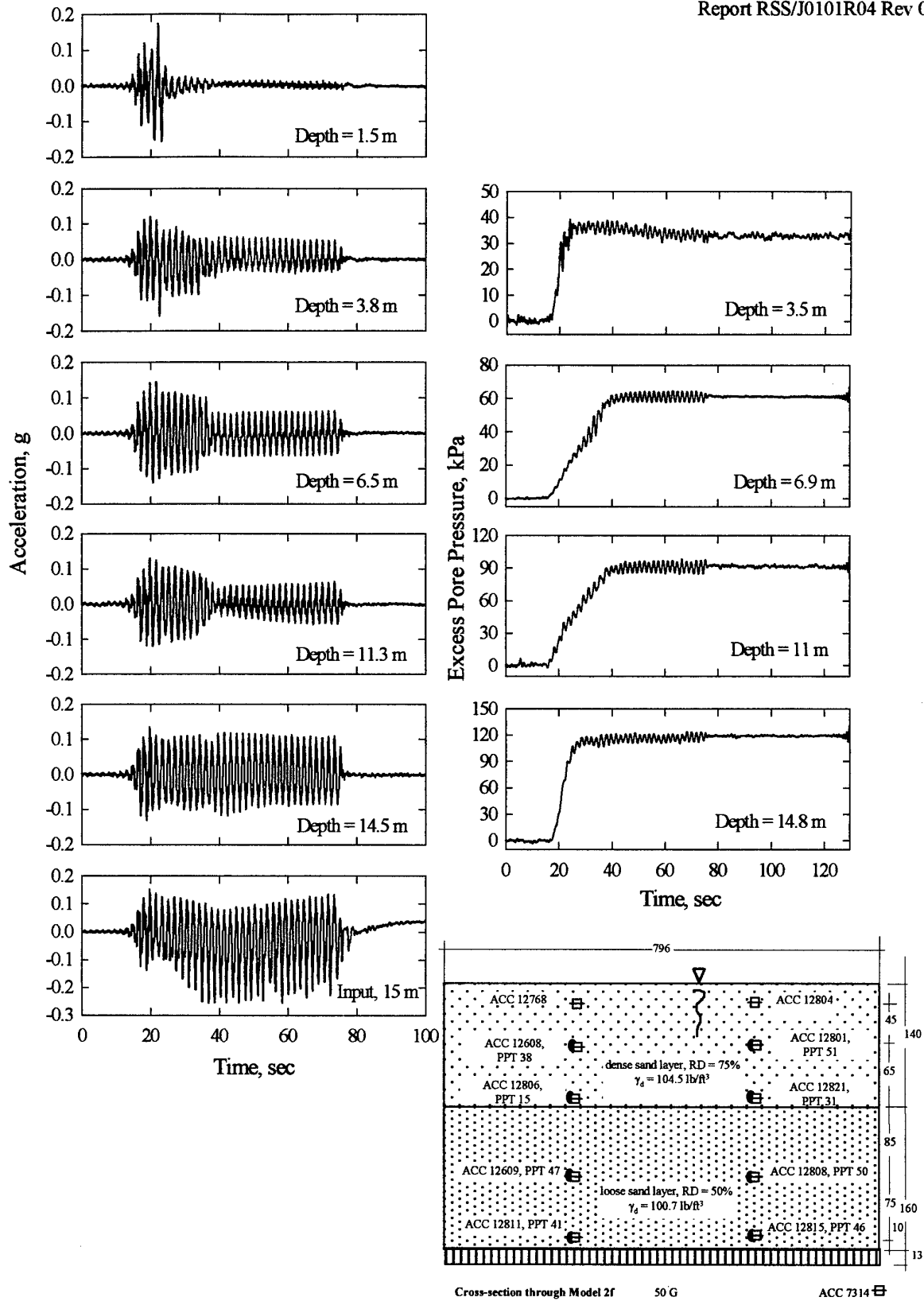


Model 2e-eq1

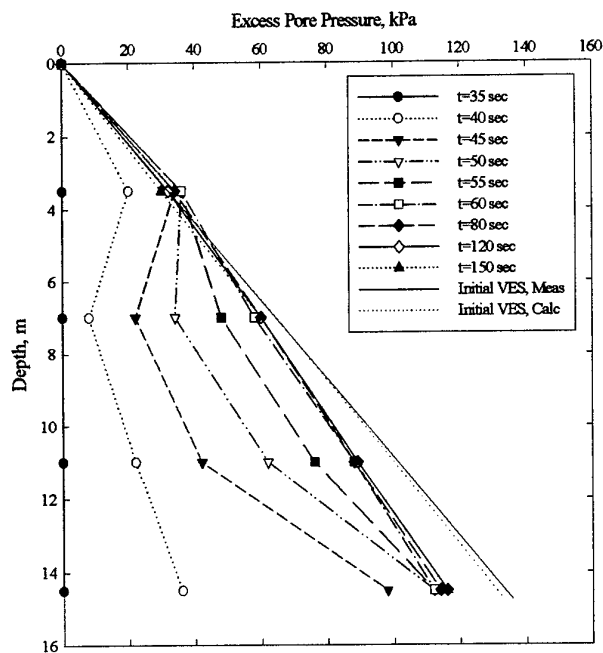
Cyclic Shear Stress, kPa



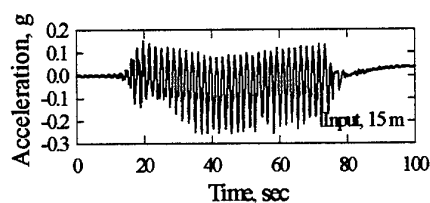
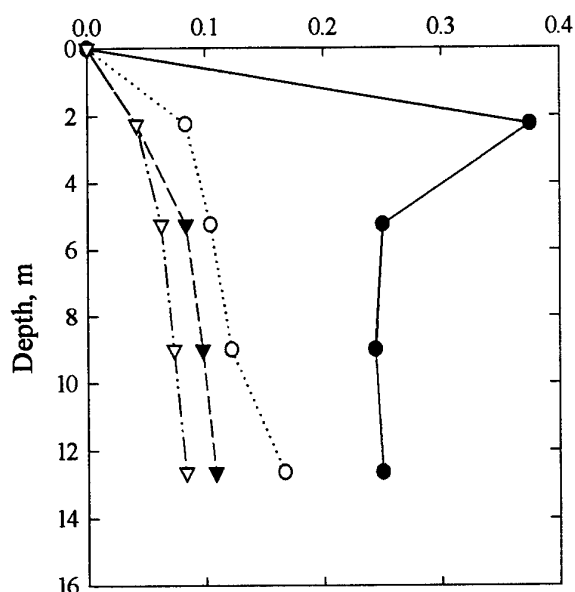
Model 2e Stress and strain isochrones



Model 2f



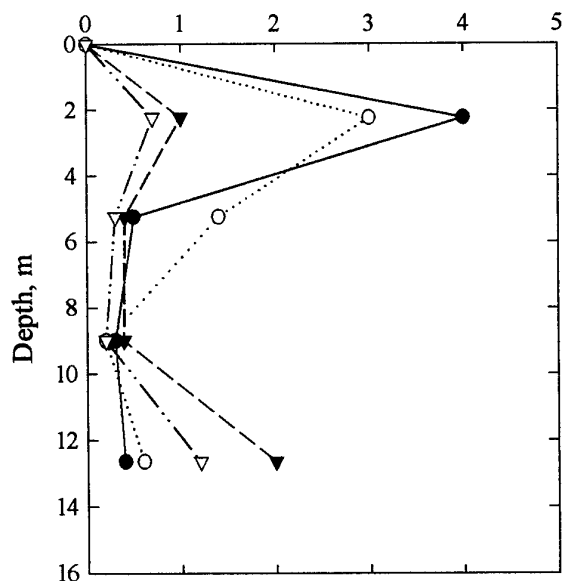
Cyclic Stress Ratio



$f = 0.6 \text{ Hz}$
 $a_{\text{max}} = 0.2 \text{ g}$

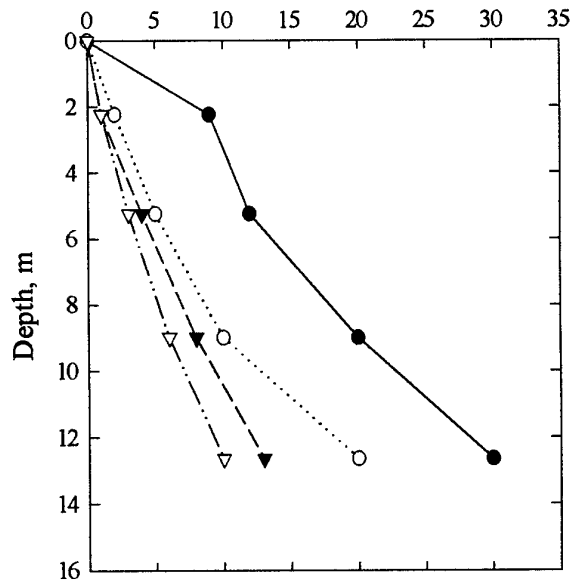
Model 2f-eq1

Cyclic Shear Strain, %

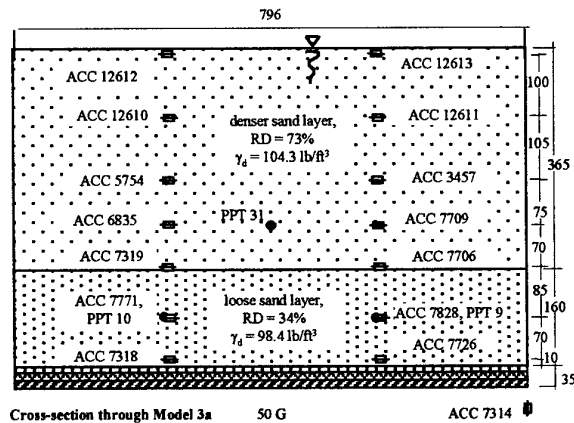
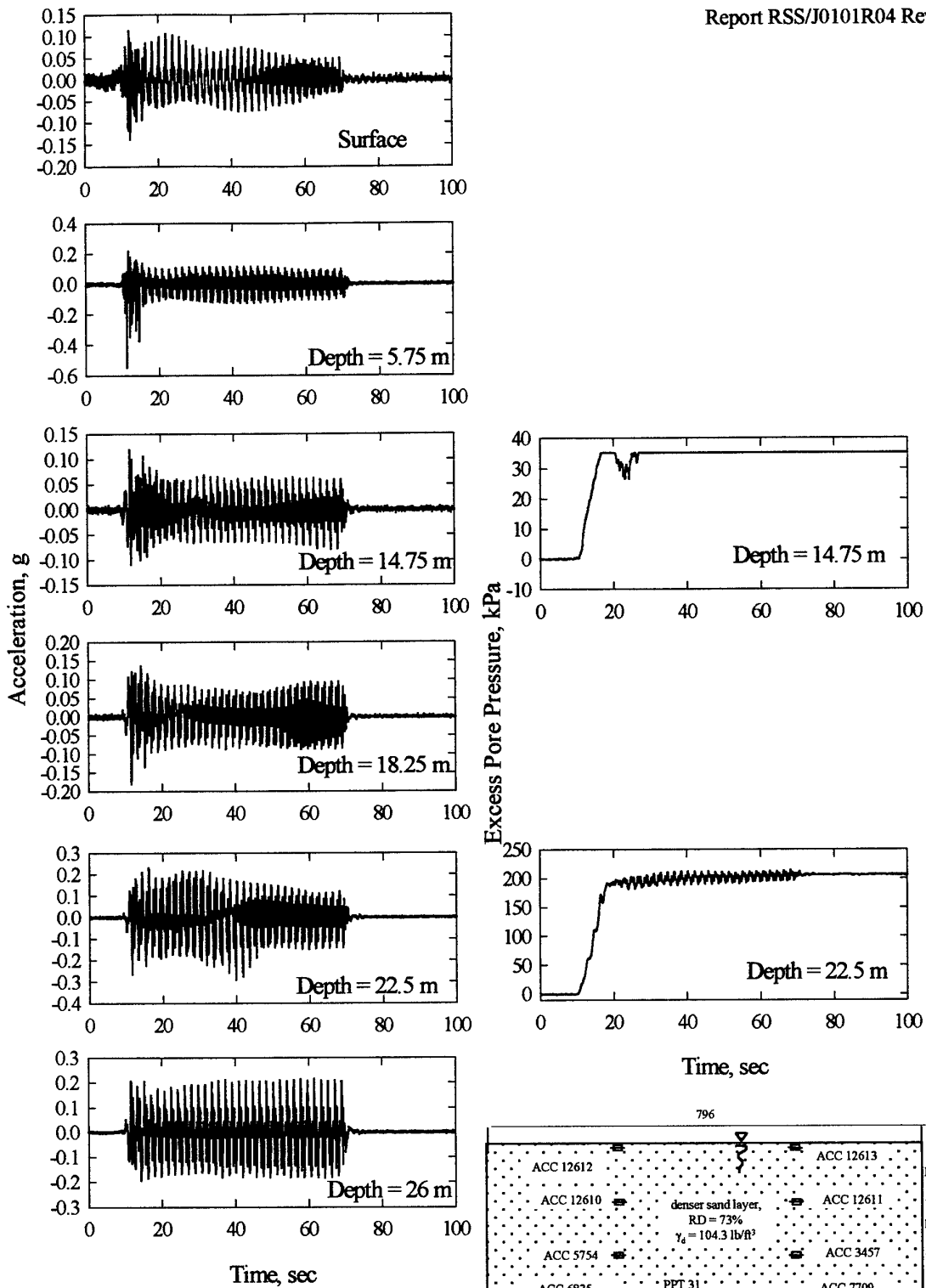


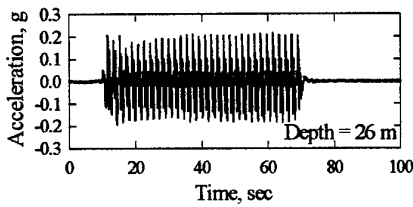
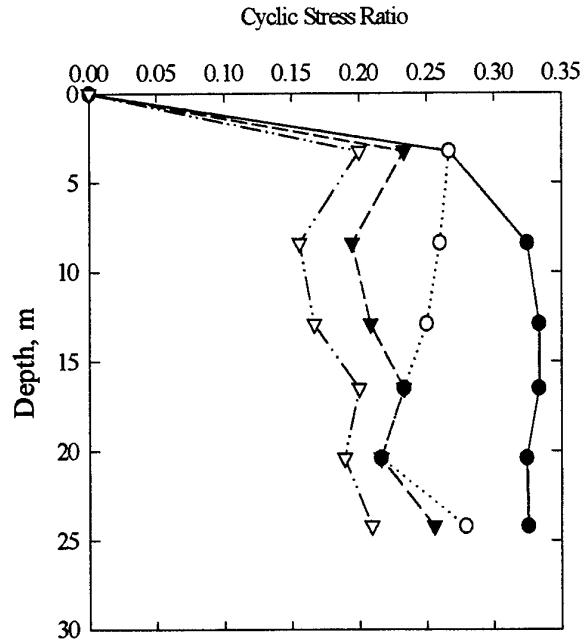
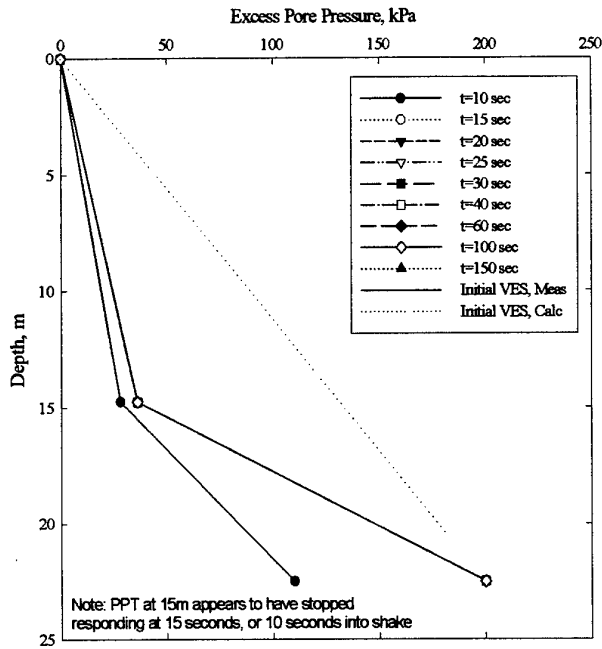
Model 2f-eq1

Cyclic Shear Stress, kPa



Model 2f Stress and strain isochrones

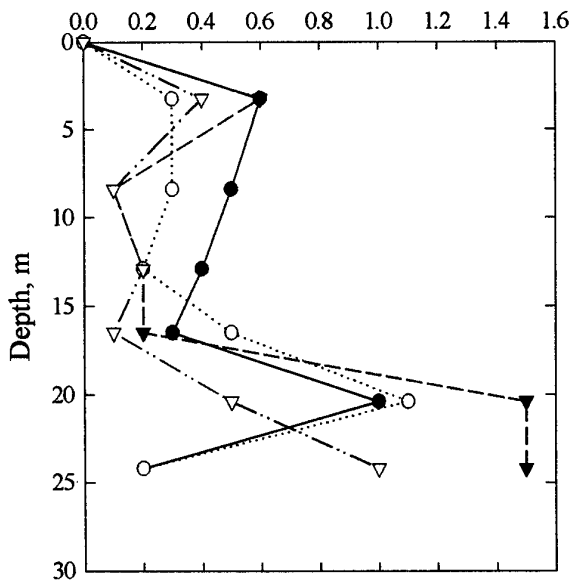




$f = 0.6 \text{ Hz}$
 $a_{\text{max}} = 0.2 \text{ g}$

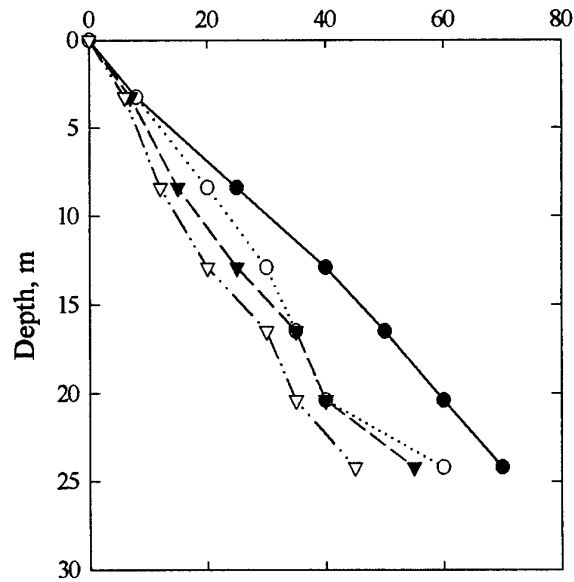
Model 3a-eq1

Cyclic Shear Strain, %

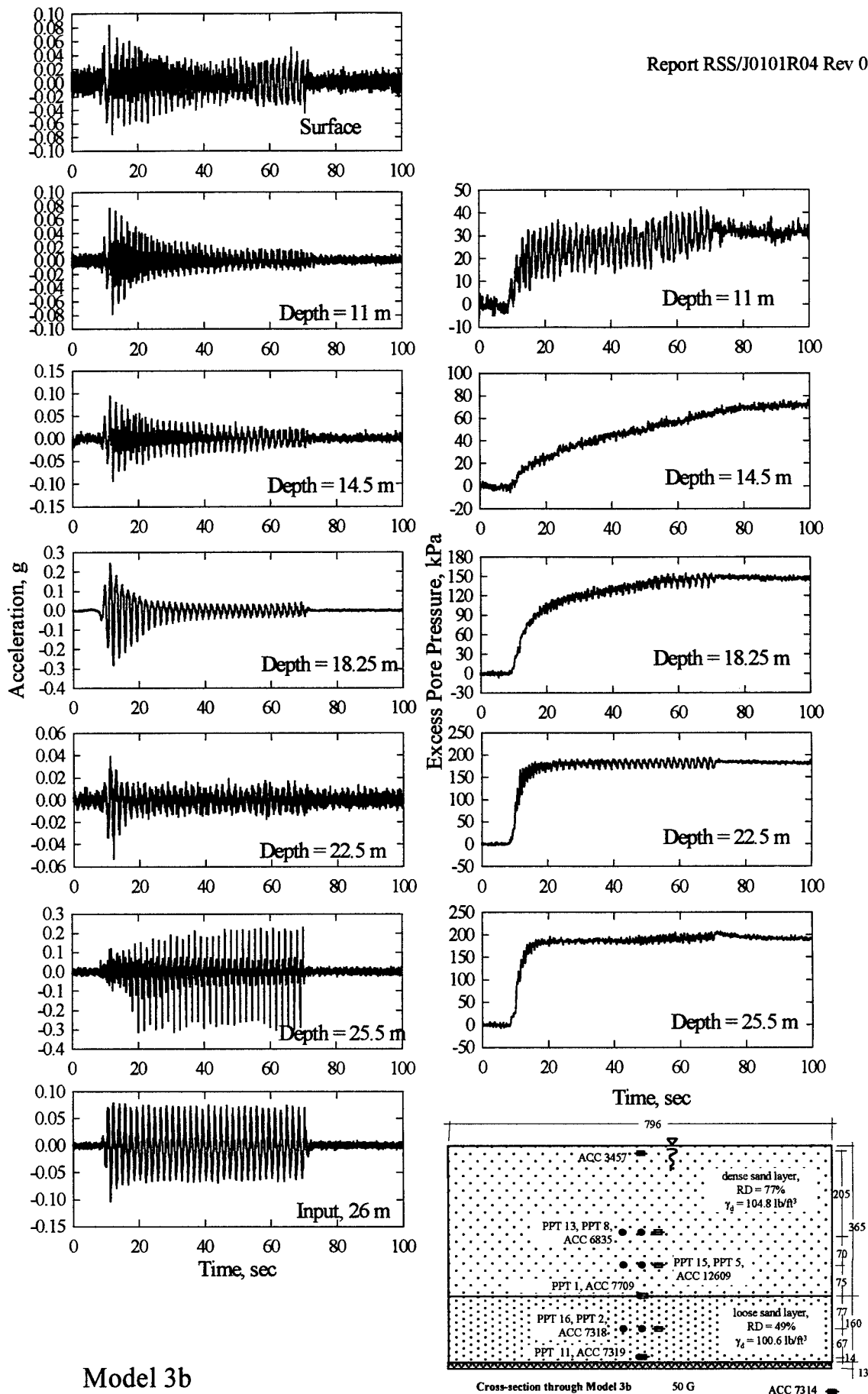


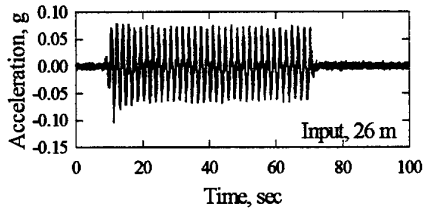
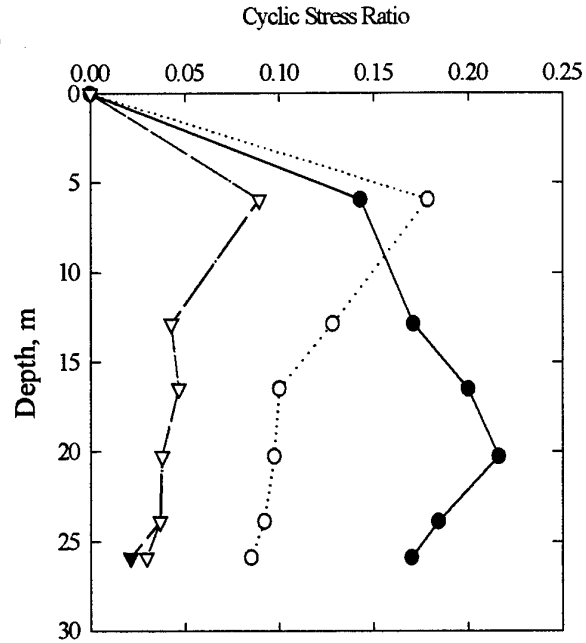
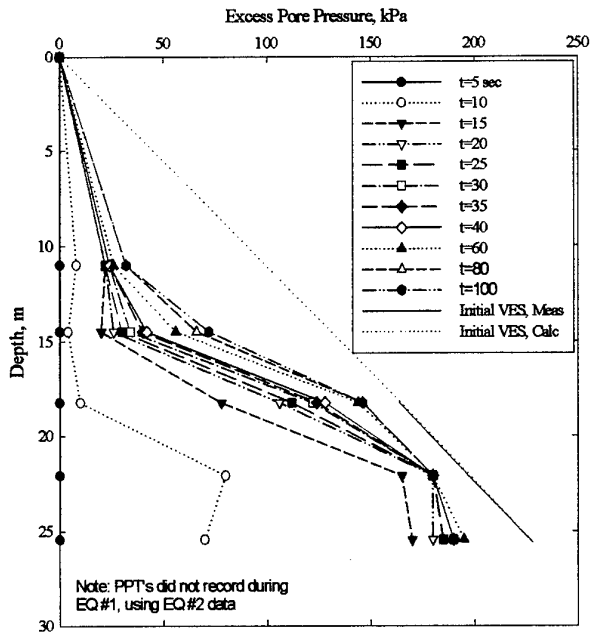
Model 3a-eq1

Cyclic Shear Stress, kPa



Model 3a Stress and strain isochrones

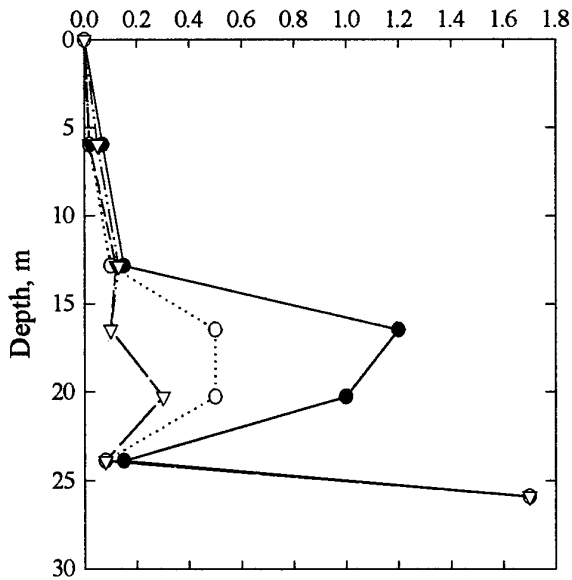




$f = 0.6 \text{ Hz}$
 $a_{\text{max}} = 0.07 \text{ g}$

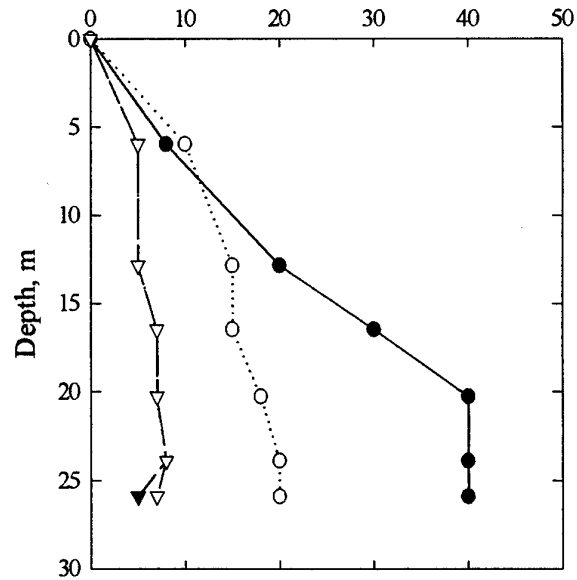
Model 3b-eq1

Cyclic Shear Strain, %

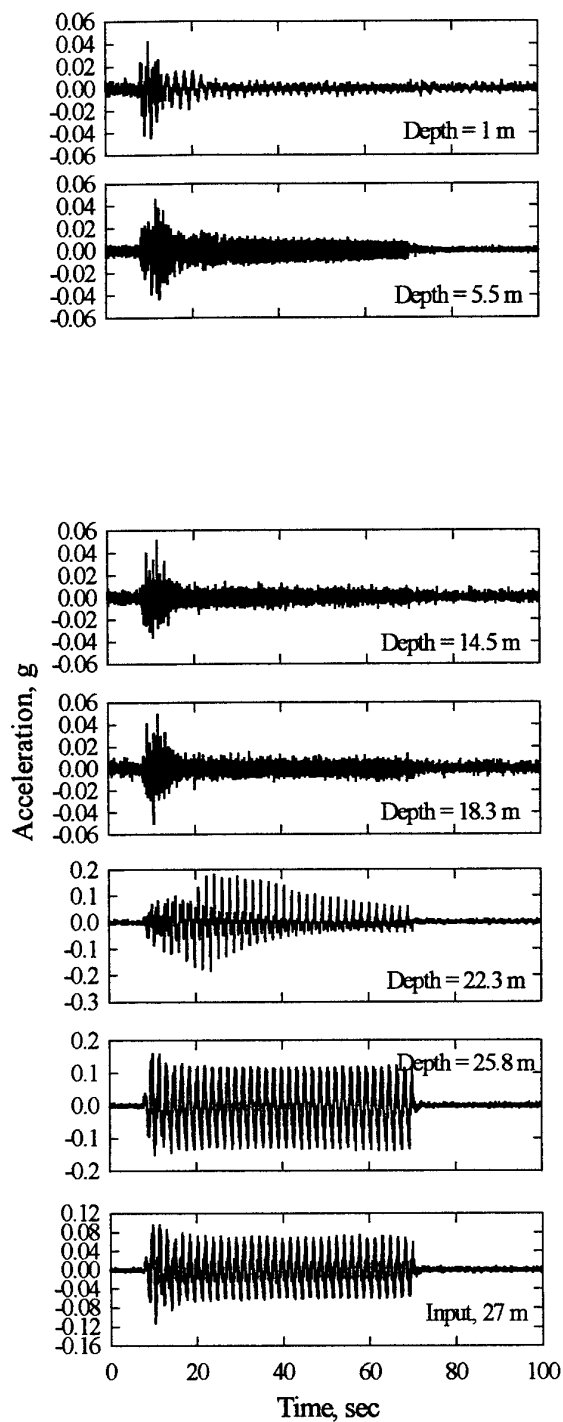


Model 3b-eq1

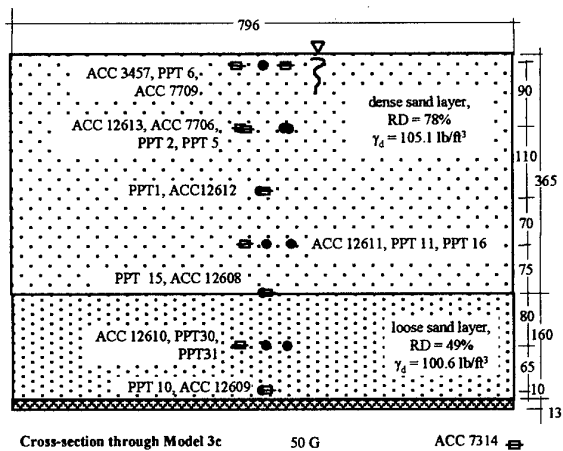
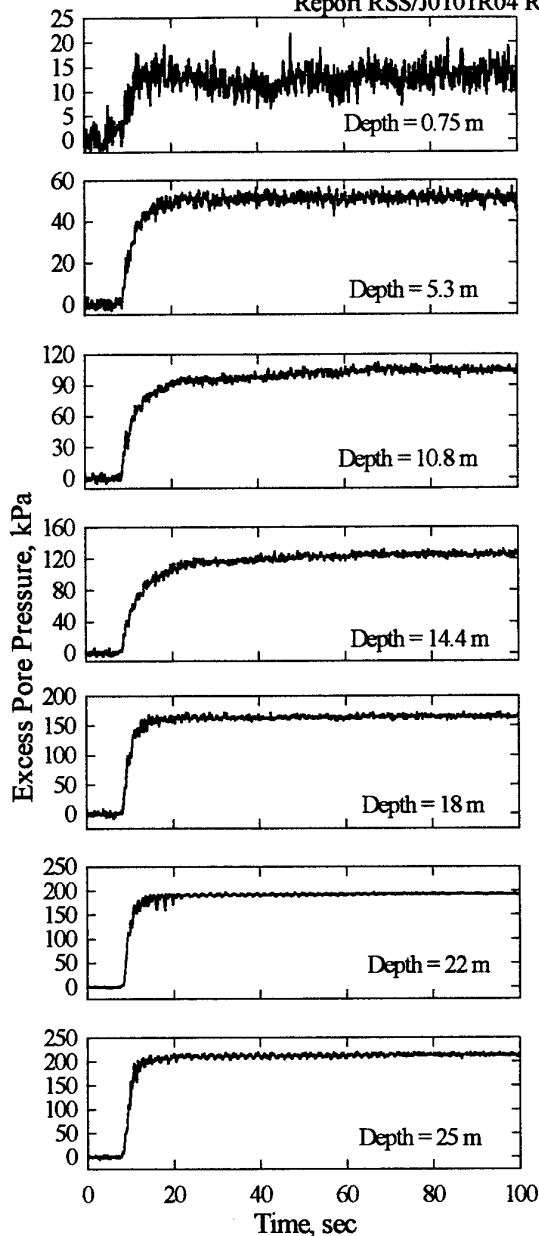
Cyclic Shear Stress, kPa

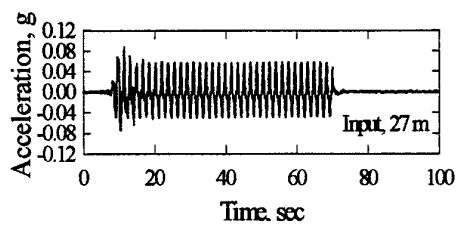
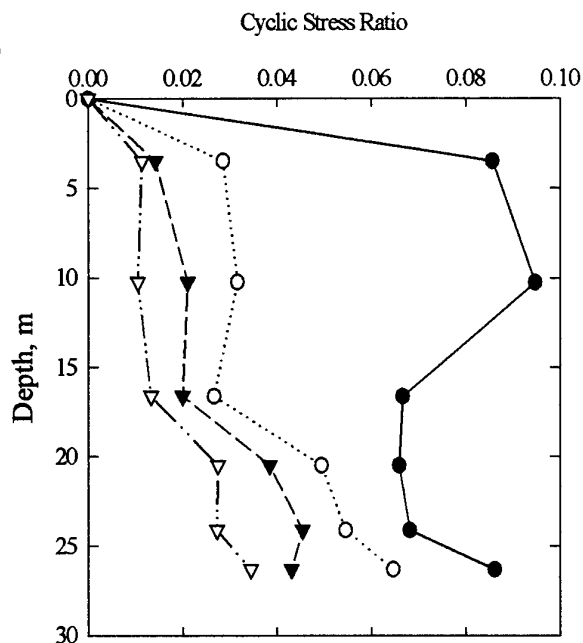
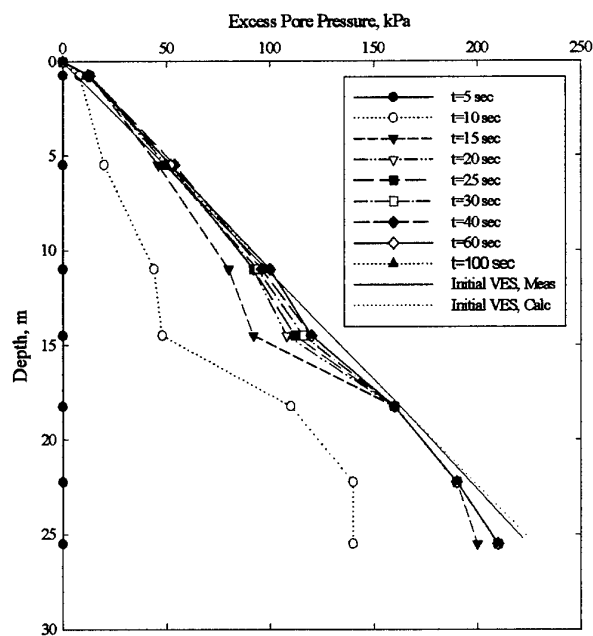


Model 3b Stress and strain isochrones



Model 3c

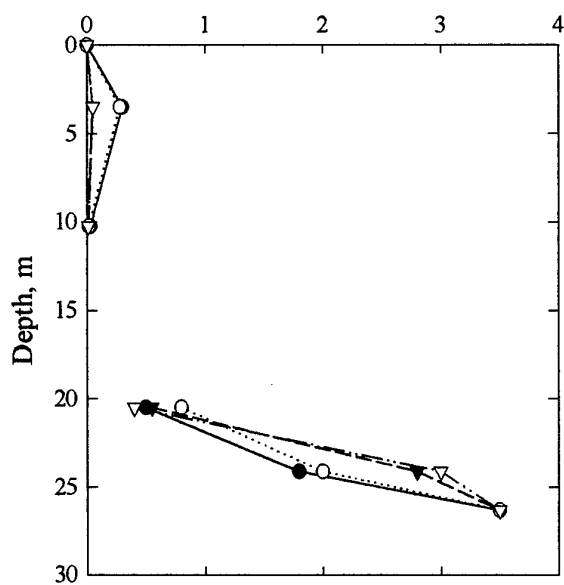




$f = 0.6 \text{ Hz}$
 $a_{\max} = 0.07 \text{ g}$

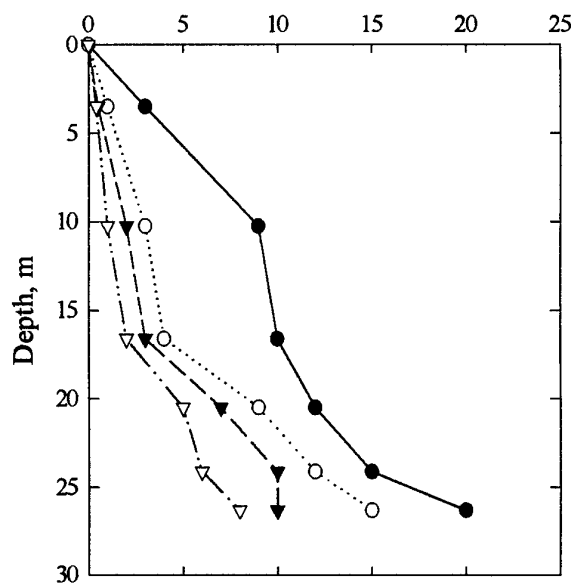
Model 3c-eq1

Cyclic Shear Strain, %

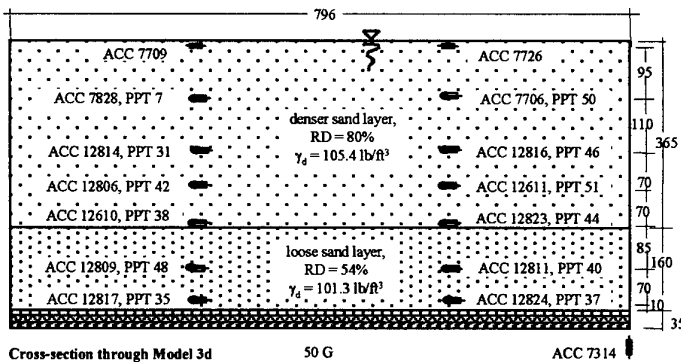
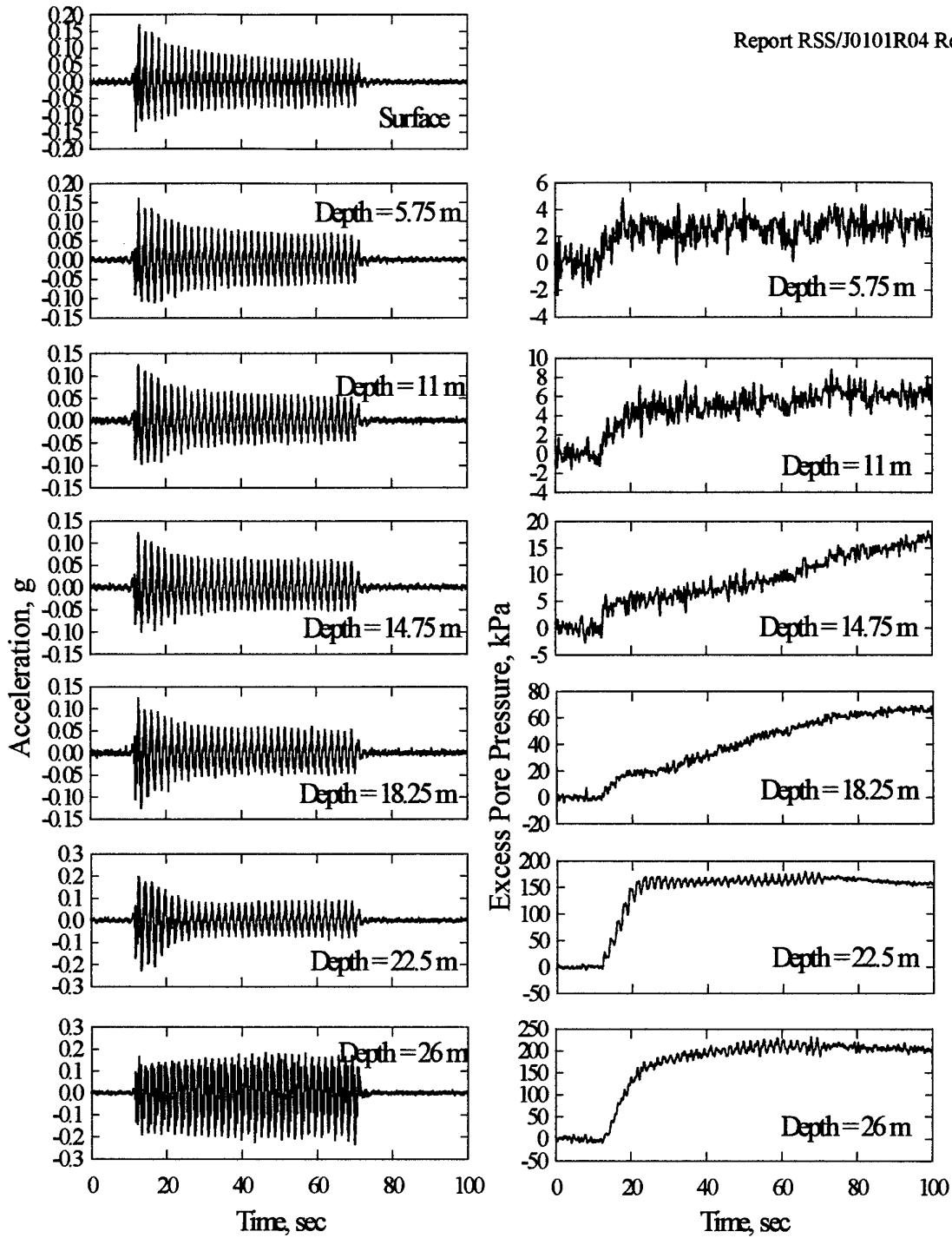


Model 3c-eq1

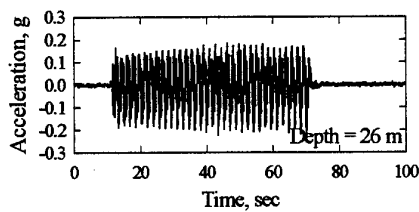
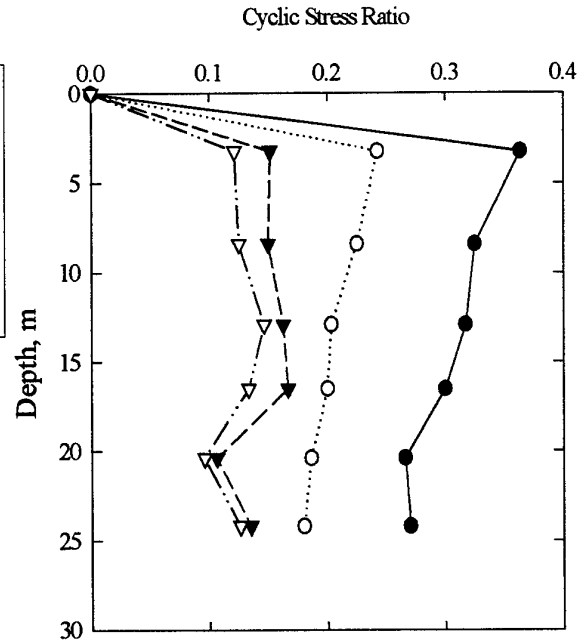
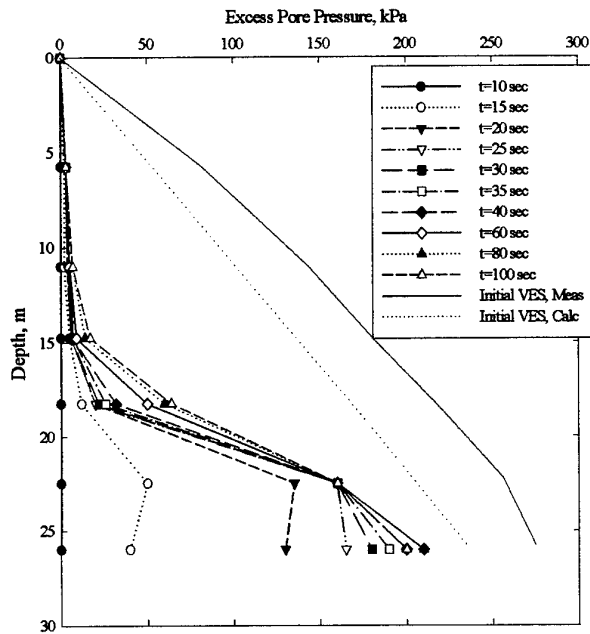
Cyclic Shear Stress, kPa



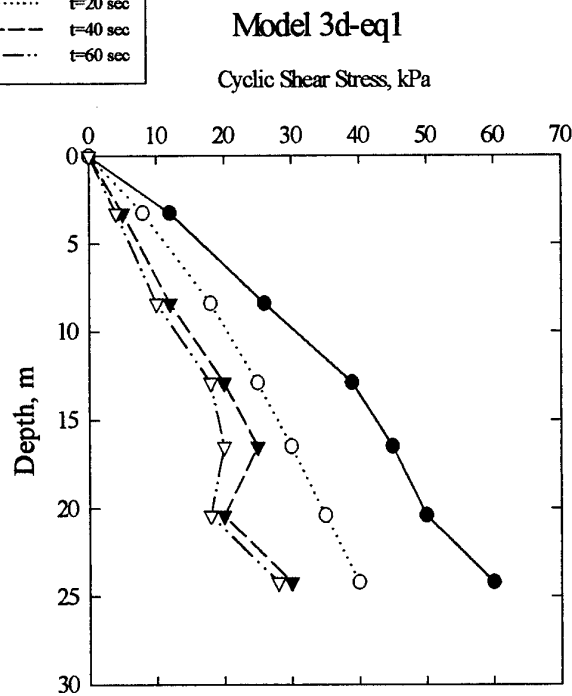
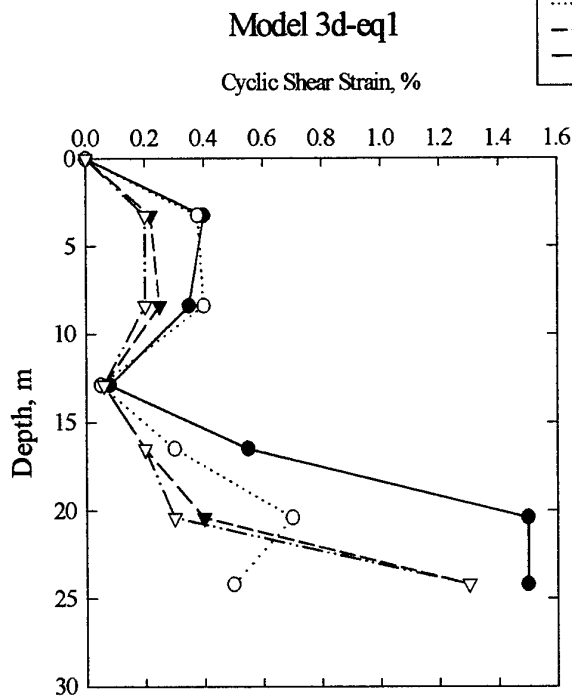
Model 3c Stress and strain isochrones

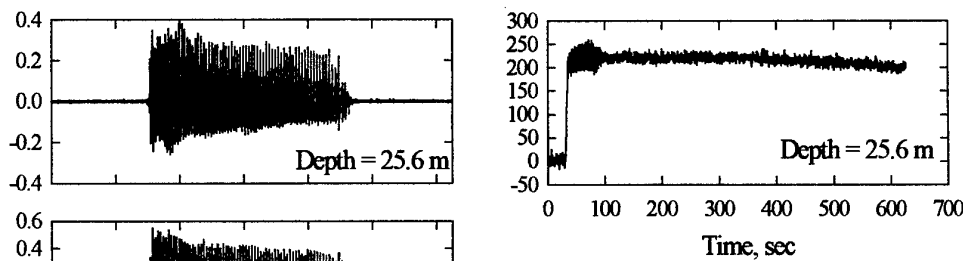
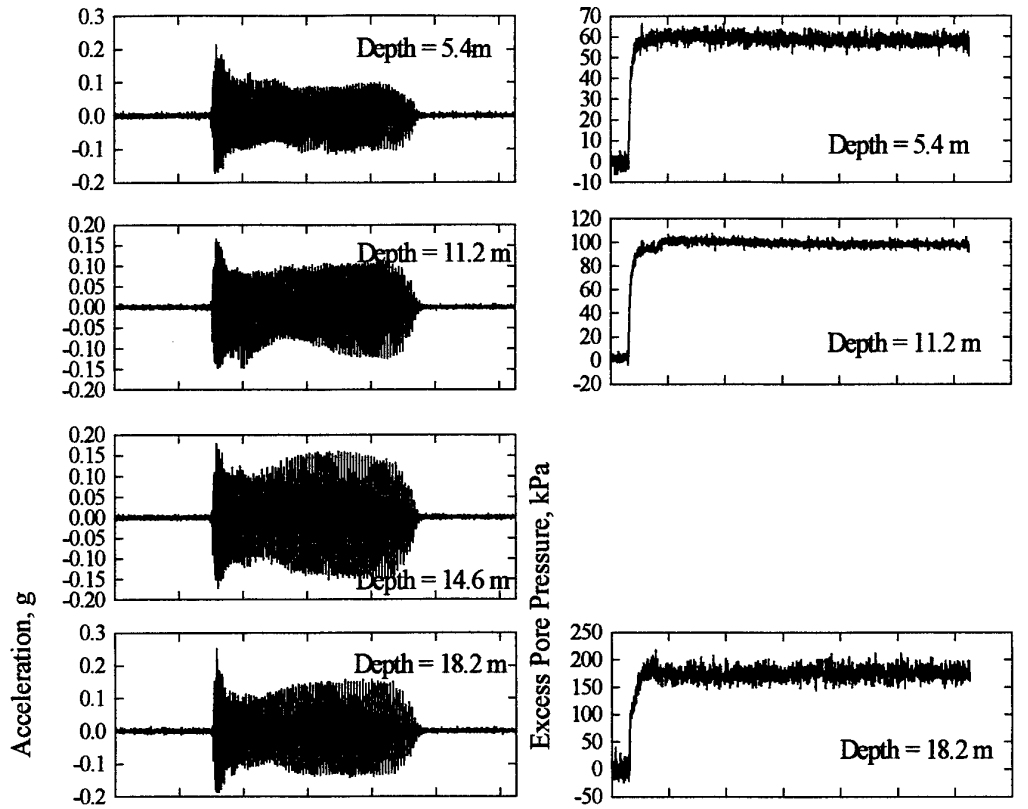


Model 3d

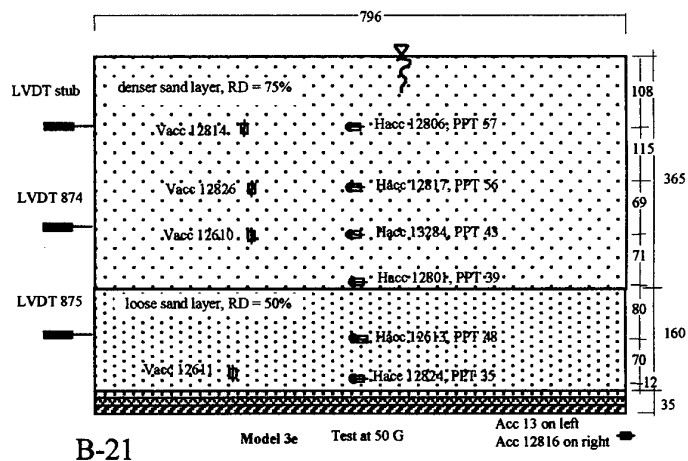


$f = 0.6 \text{ Hz}$
 $a_{\text{max}} = 0.19 \text{ g}$

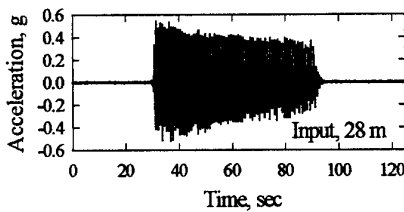
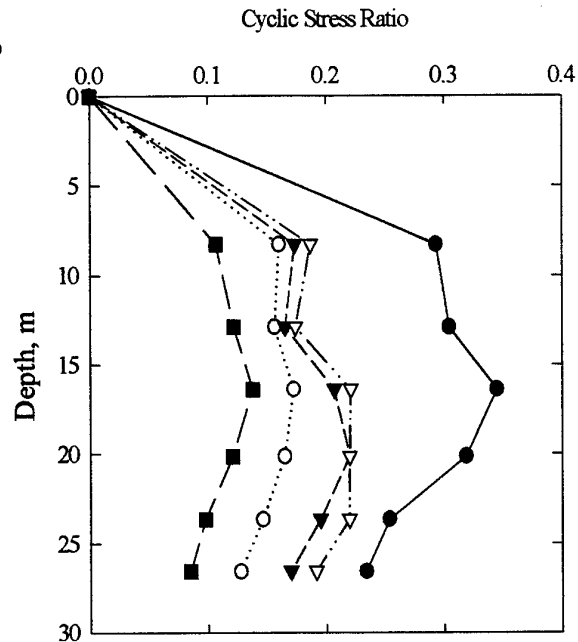
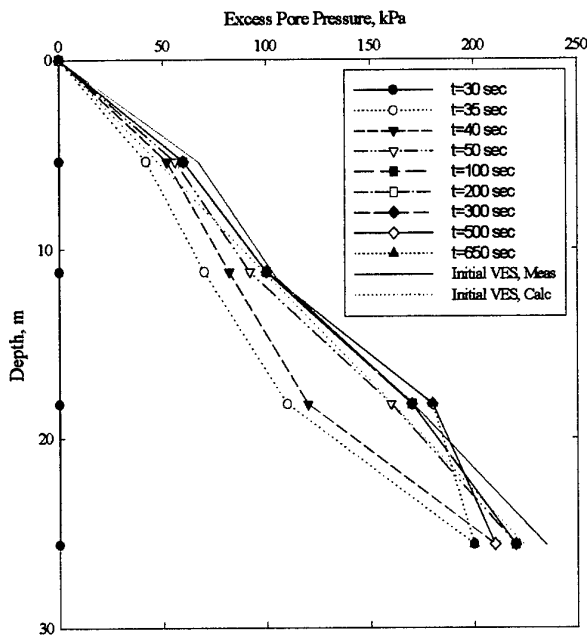




Model 3e



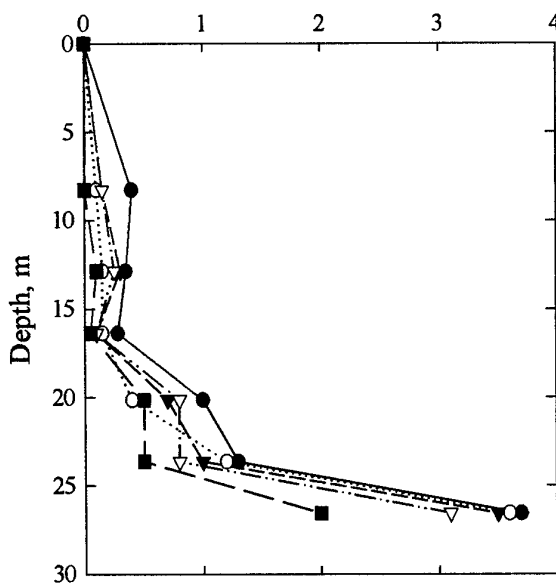
Model 3e (Archtest 2a, no weight)



$f = 1.2 \text{ Hz}$
 $a_{\text{max}} = 0.4 \text{ g}$

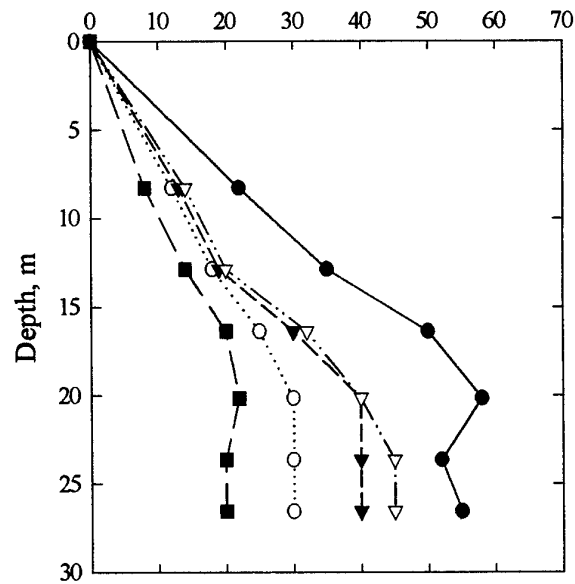
Model 3e-eq1

Cyclic Shear Strain, %

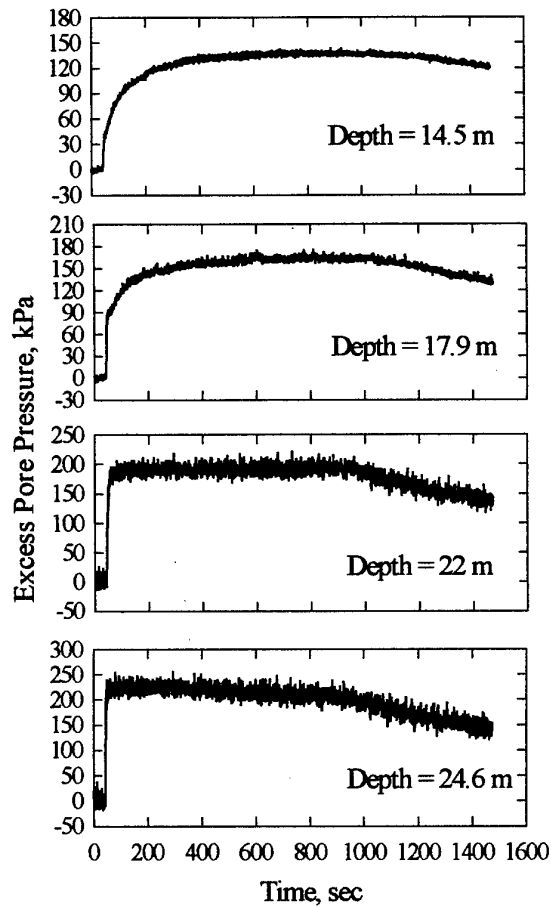
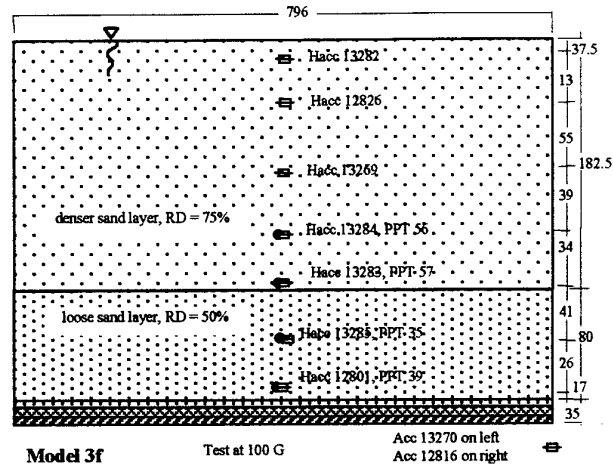
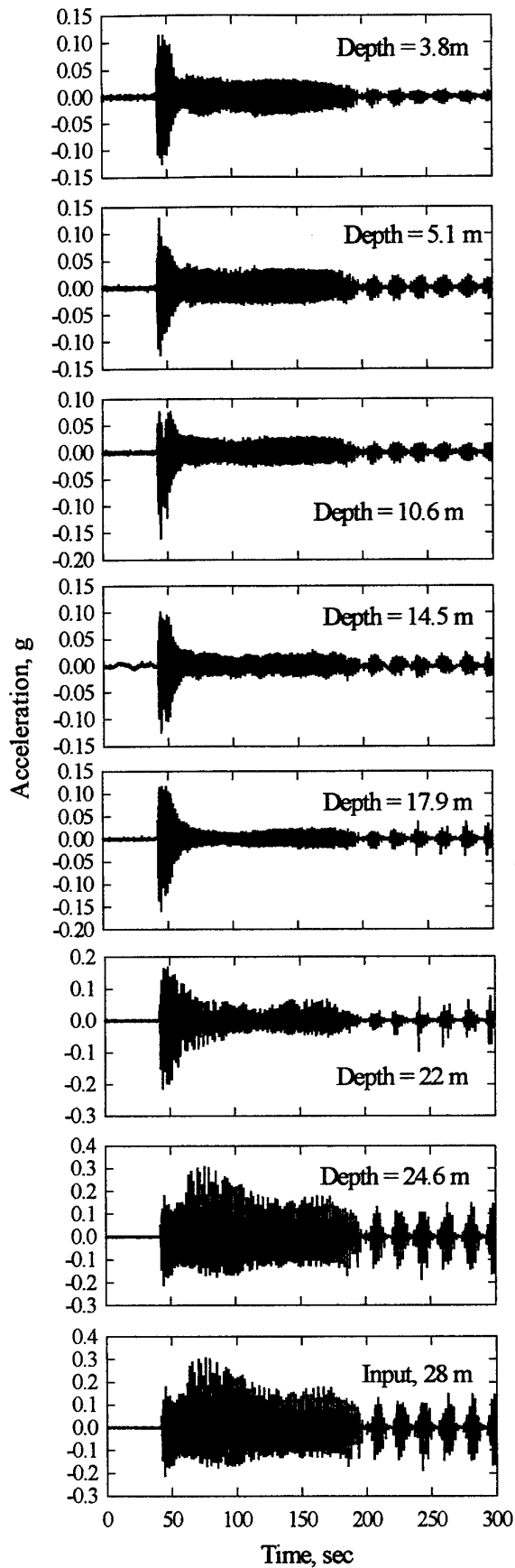


Model 3e-eq1

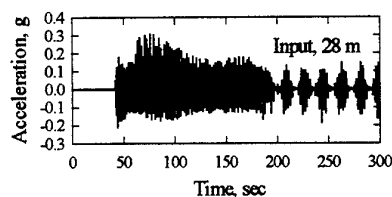
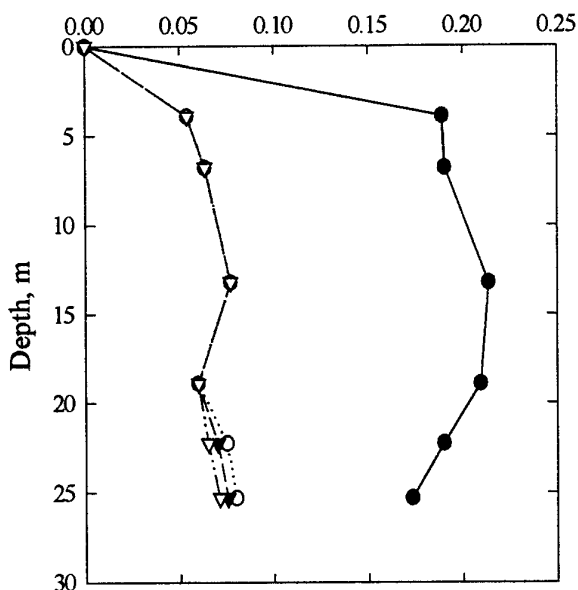
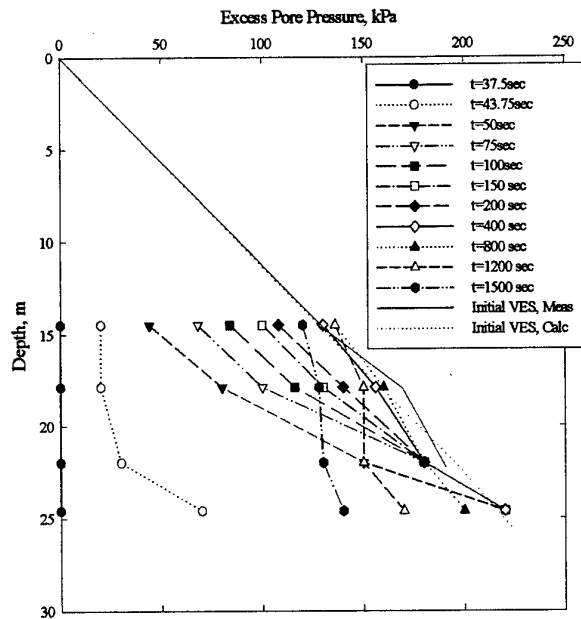
Cyclic Shear Stress, kPa



Model 3e Stress and strain isochrones



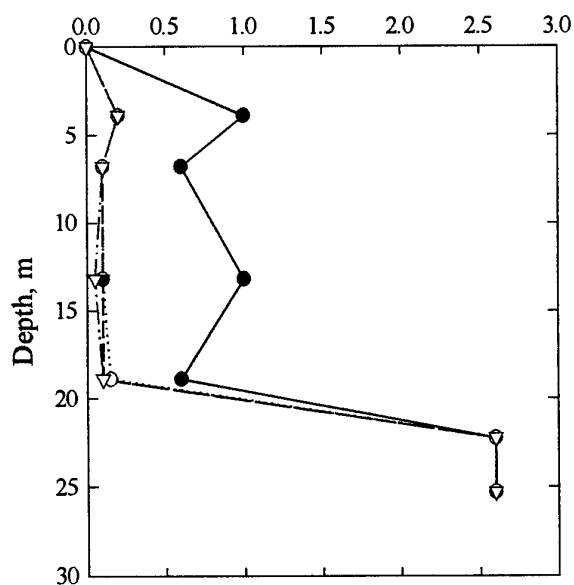
Model 3f



$f = 0.6 \text{ Hz}$
 $a_{\text{max}} = 0.2 \text{ g}$

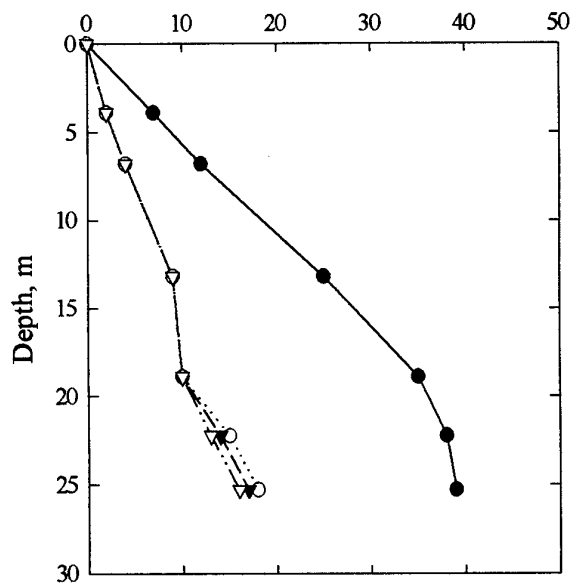
Model 3f-eq1

Cyclic Shear Strain, %

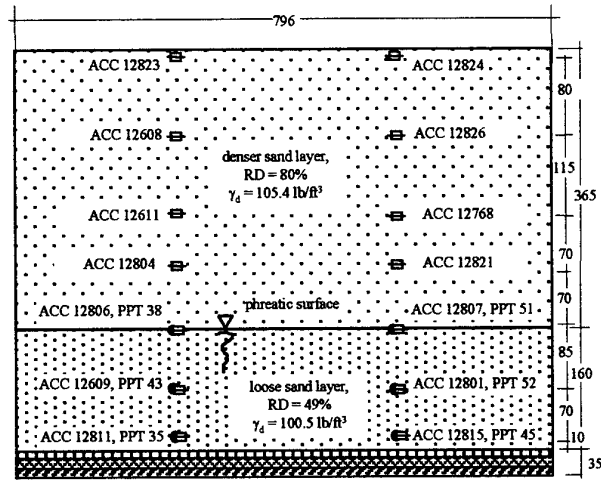
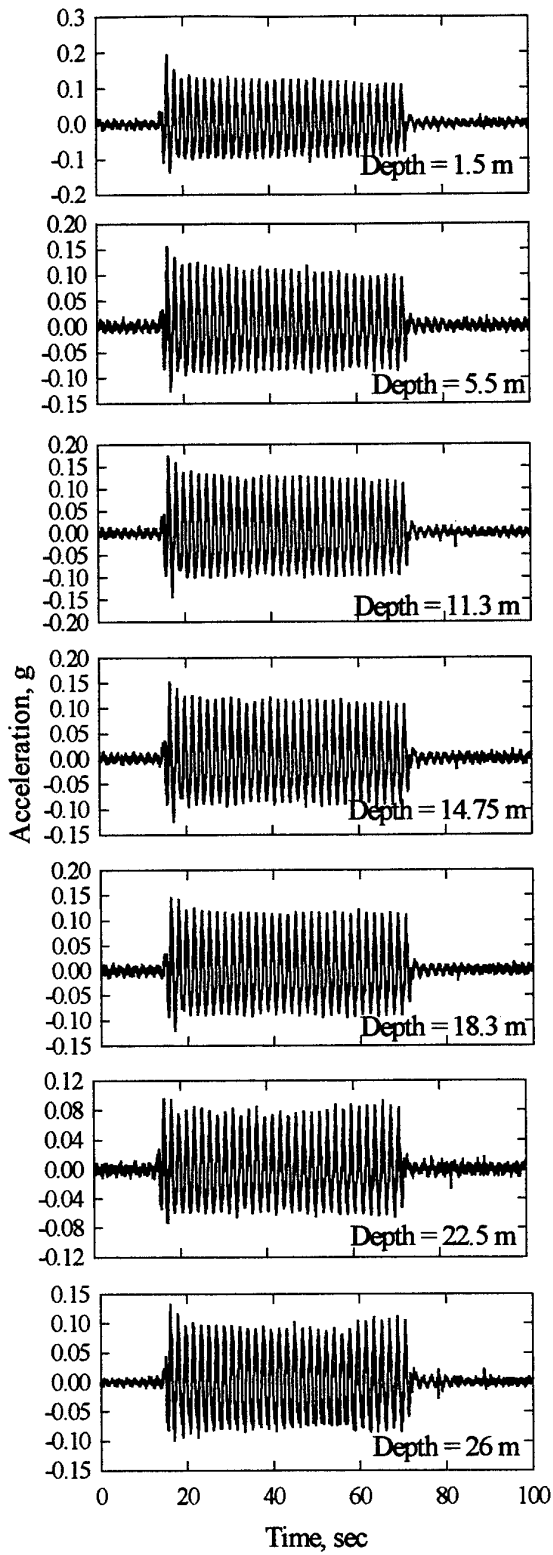


Model 3f-eq1

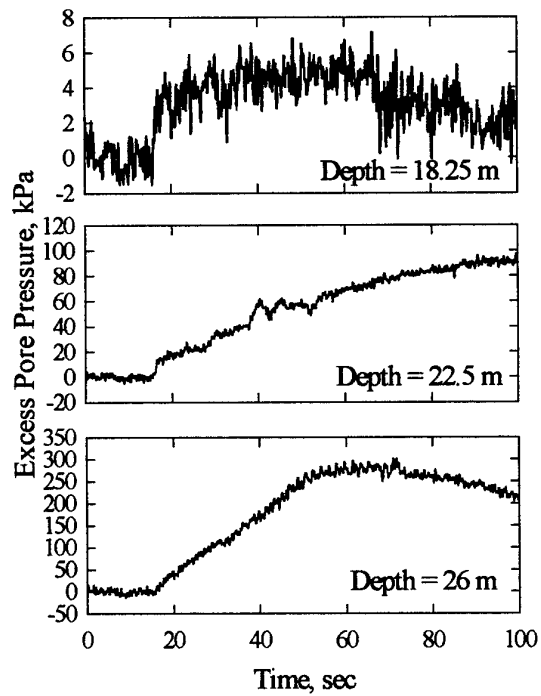
Cyclic Shear Stress, kPa



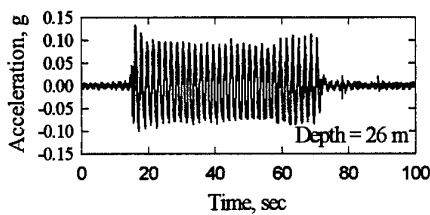
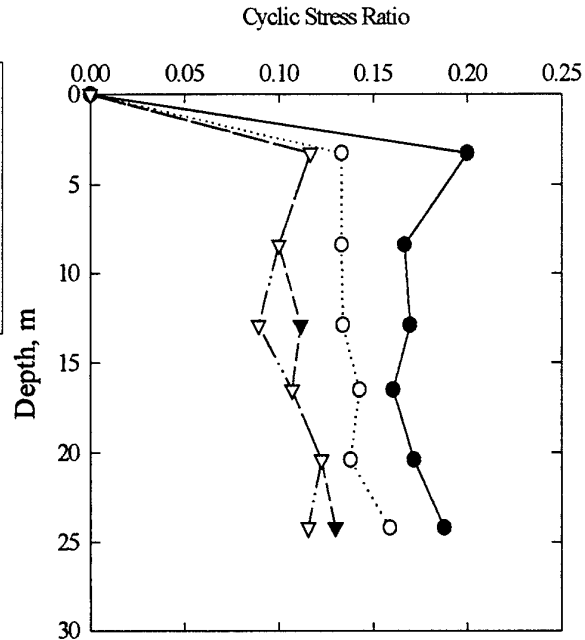
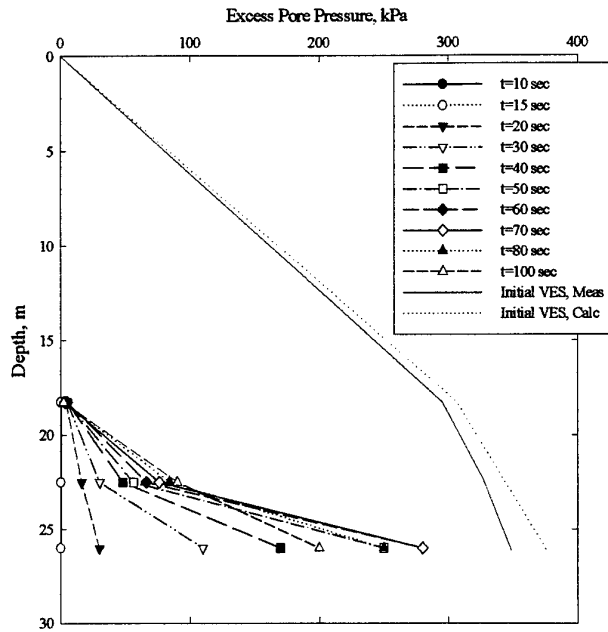
Model 3f Stress and strain isochrones



Cross-section through Model 4a
Saturated loose layer, dense layer not saturated



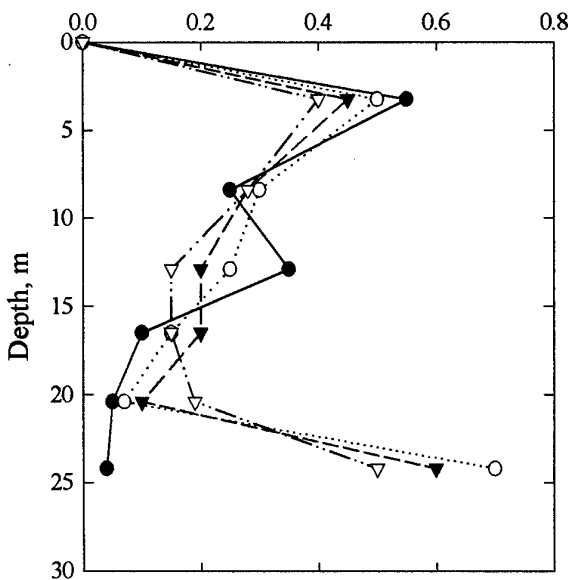
Model 4a



$f = 0.6 \text{ Hz}$
 $a_{\text{max}} = 0.09 \text{ g}$

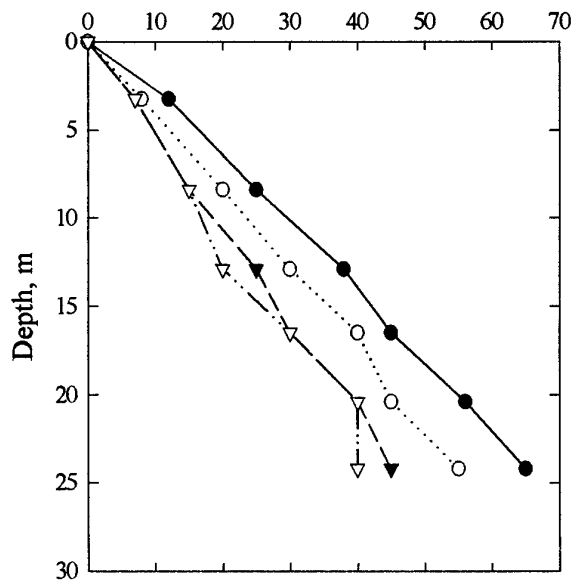
Model 4a-eq1

Cyclic Shear Strain, %

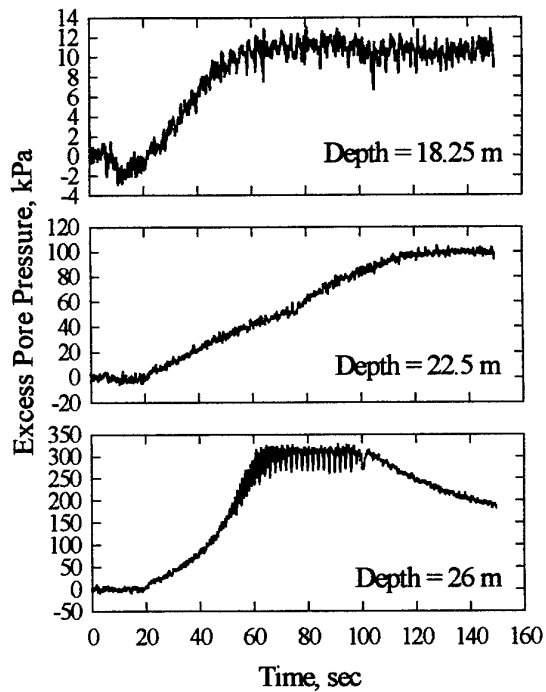
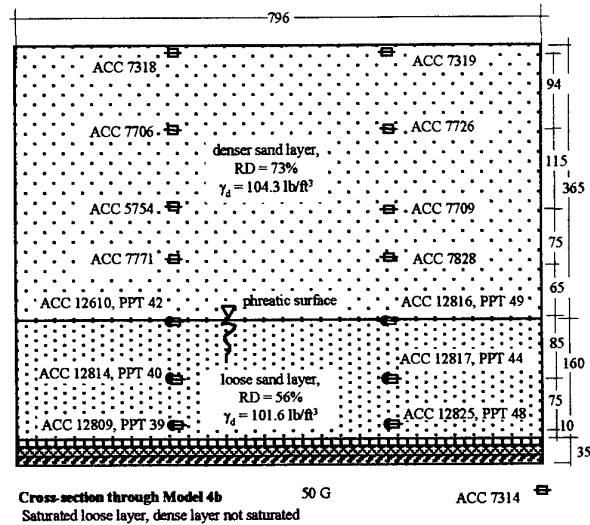
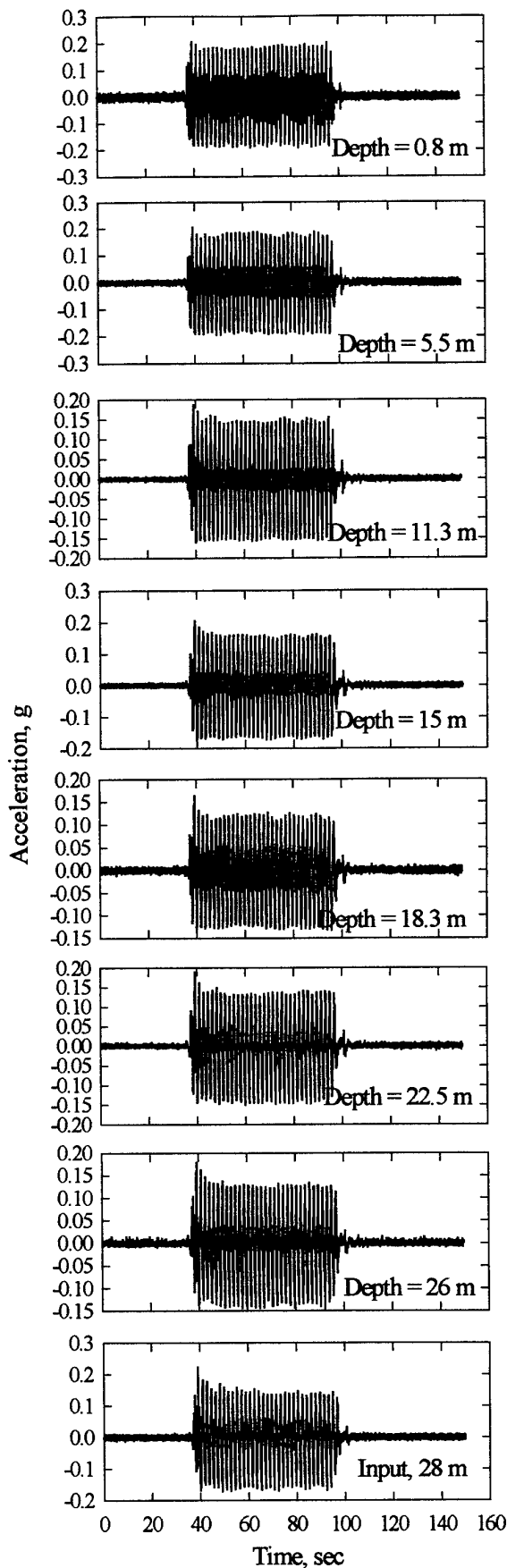


Model 4a-eq1

Cyclic Shear Stress, kPa

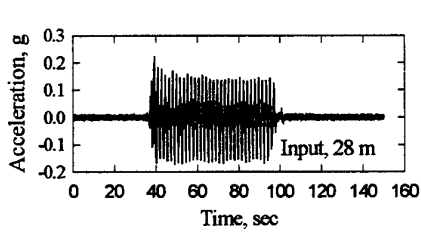
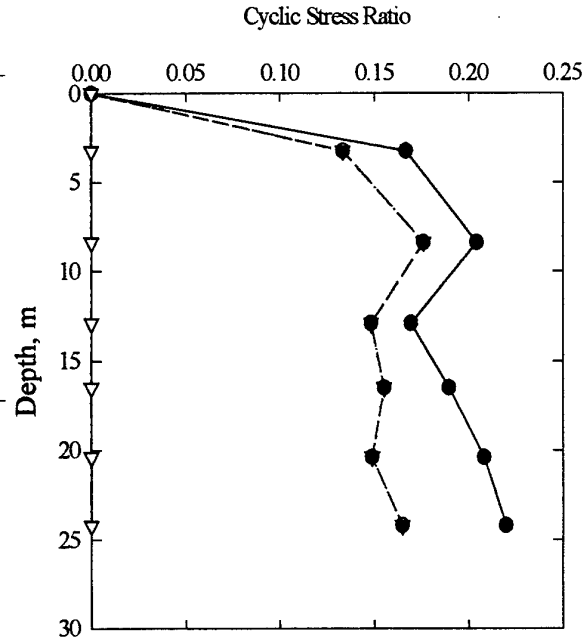
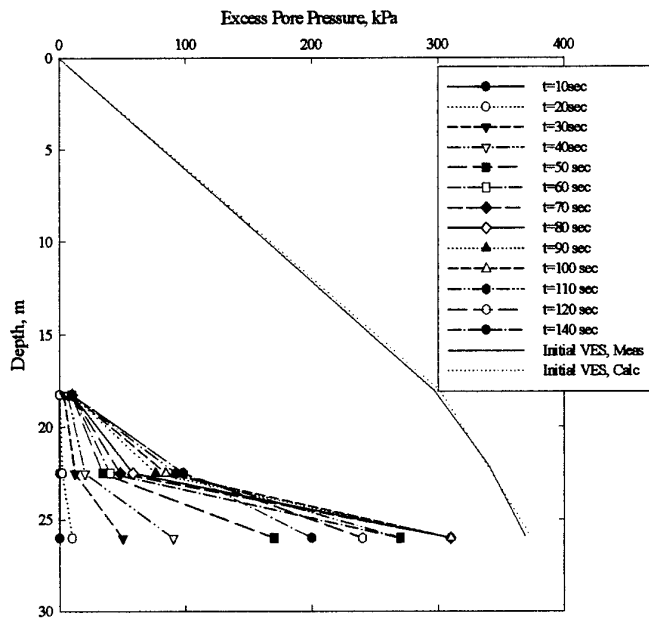


Model 4a Stress and strain isochrones



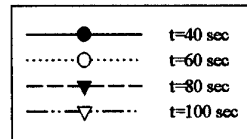
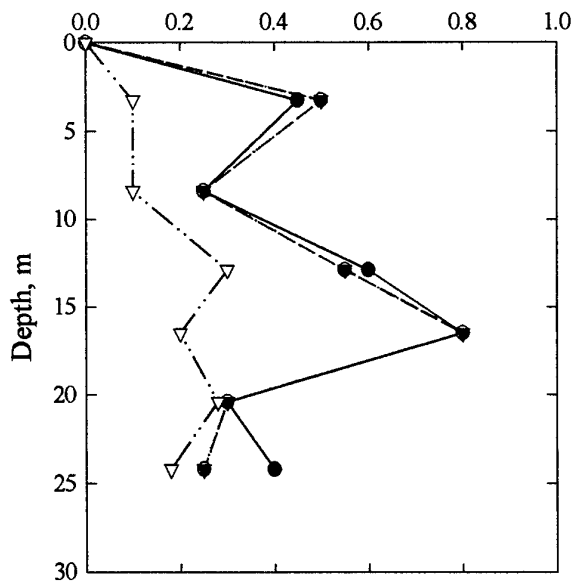
Model 4b

Model 4b-eq1



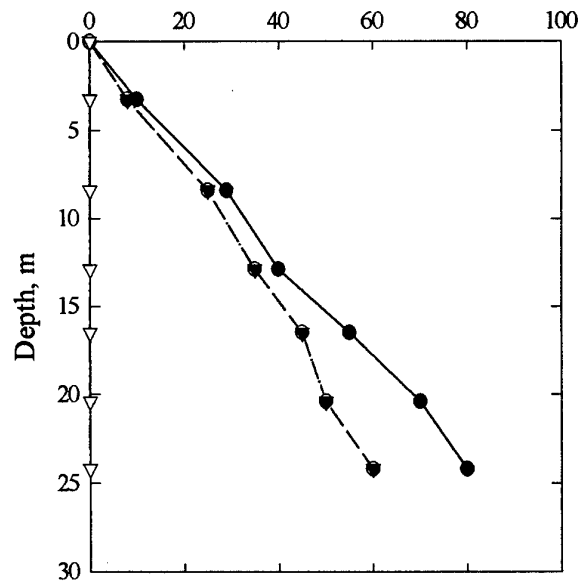
Model 4b-eq1

Cyclic Shear Strain, %

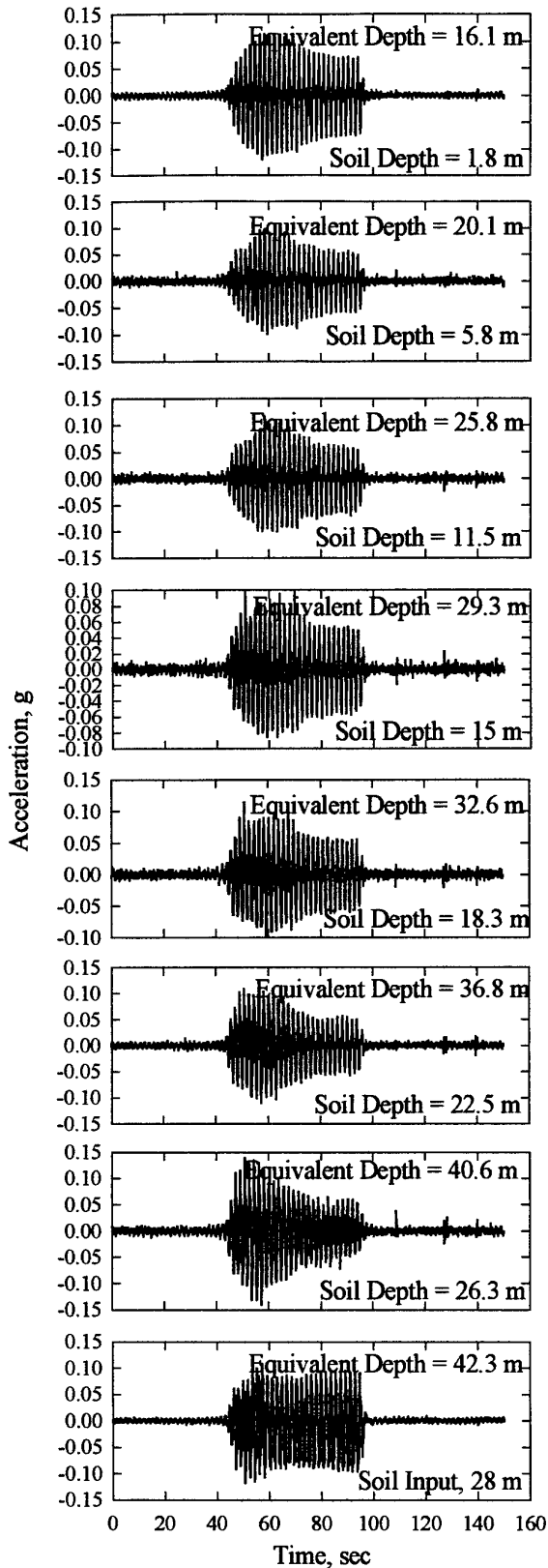


Model 4b-eq1

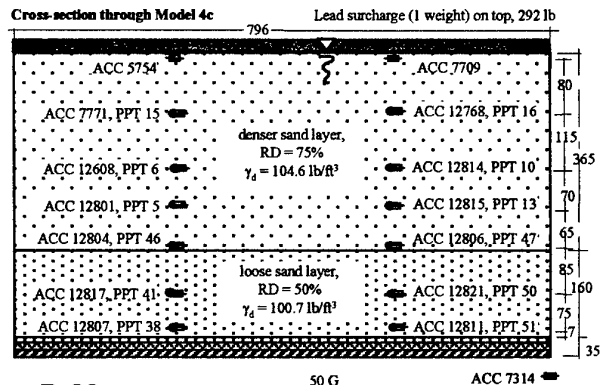
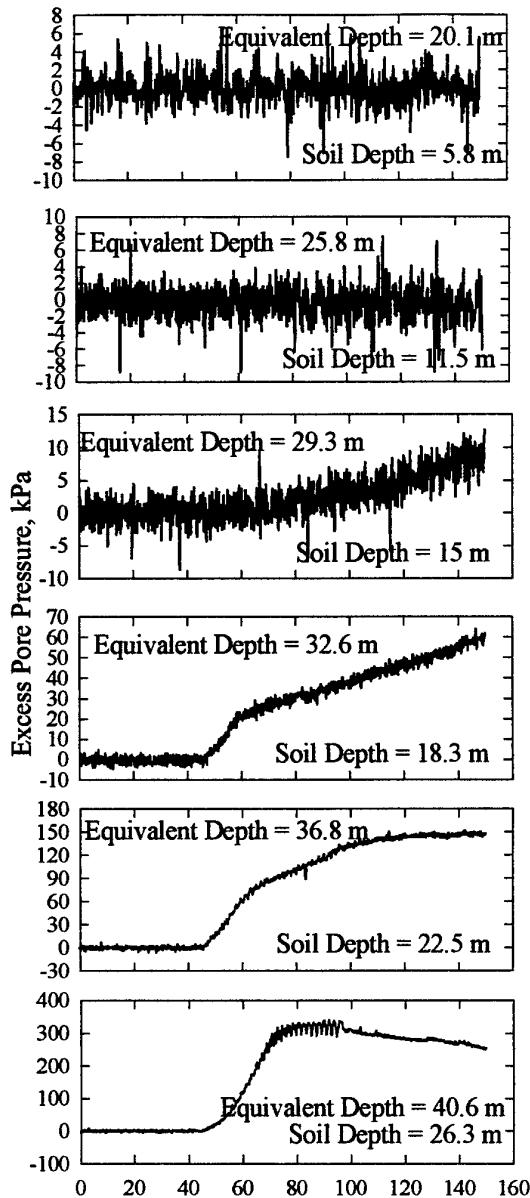
Cyclic Shear Stress, kPa

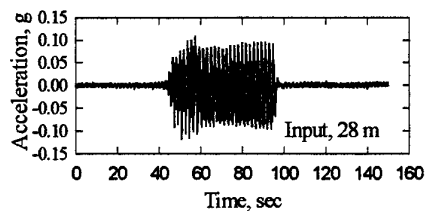
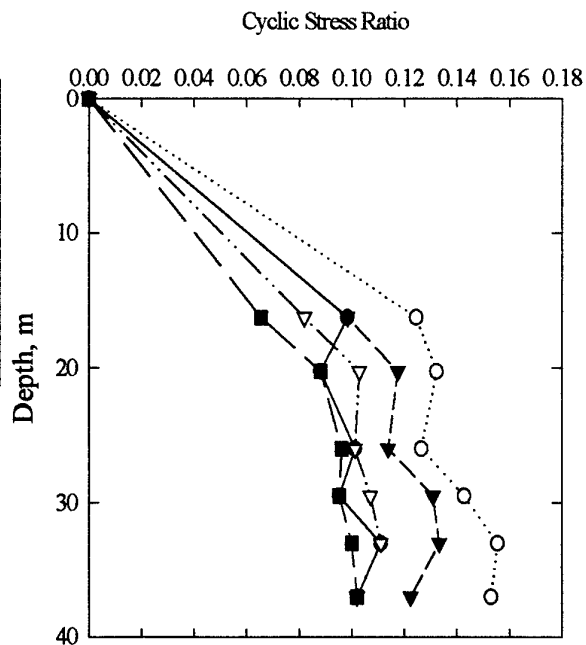
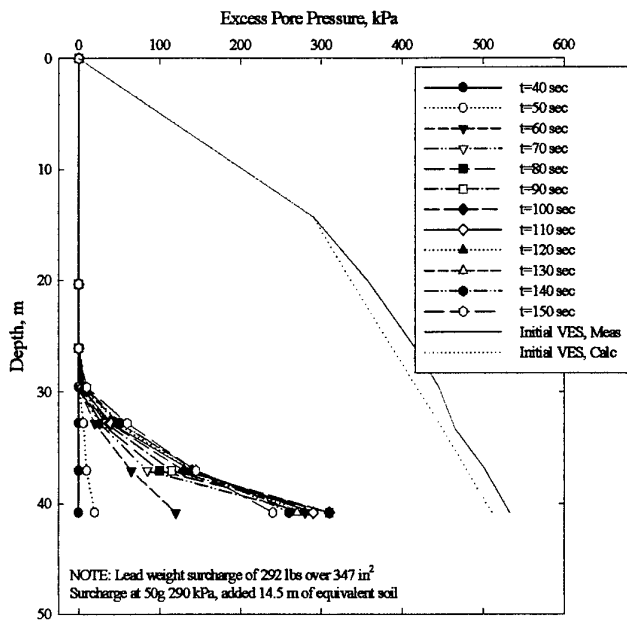


Model 4b Stress and strain isochrones

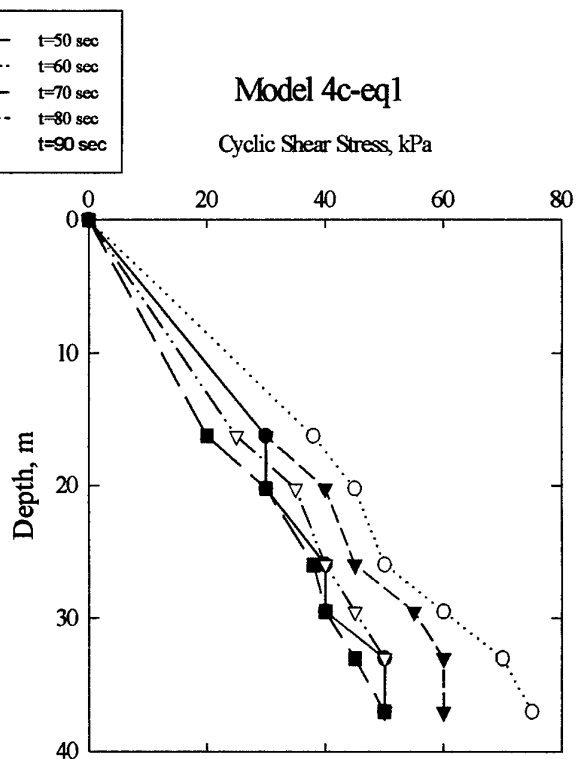
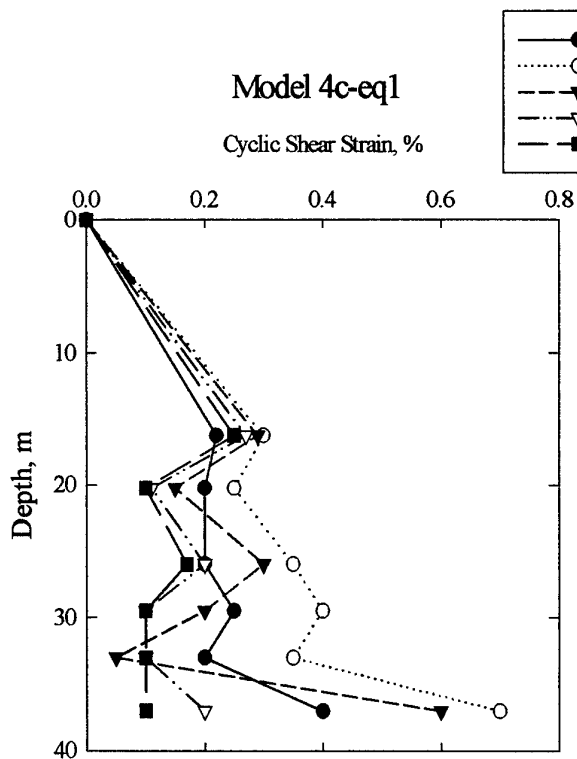


Model 4c

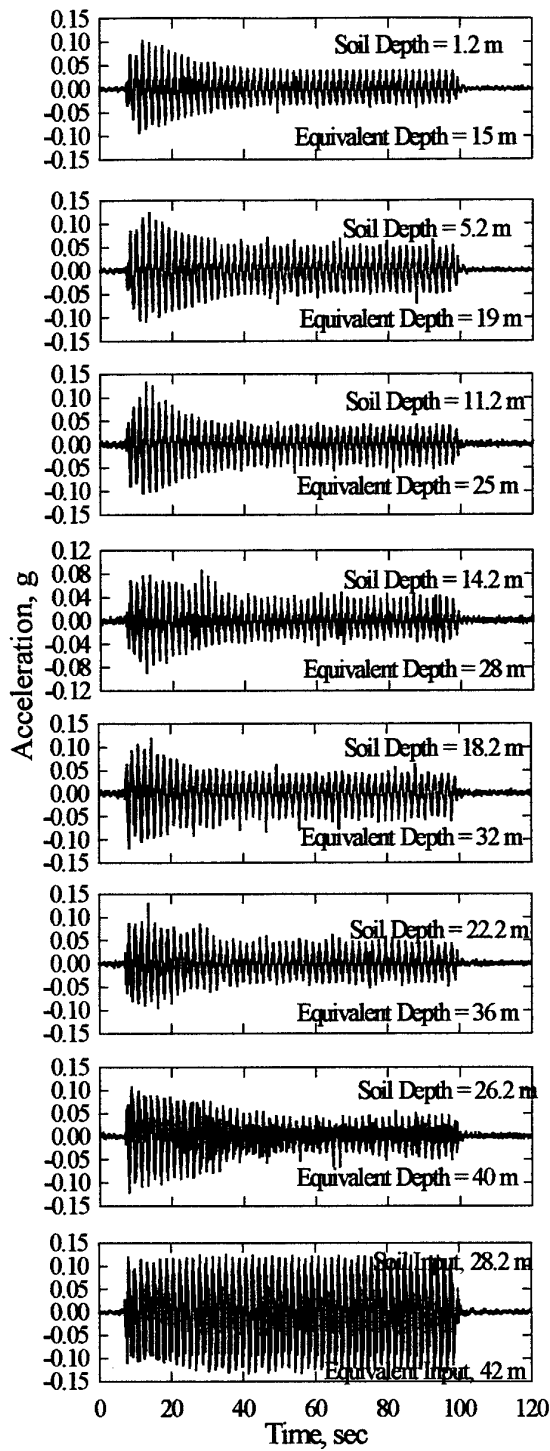




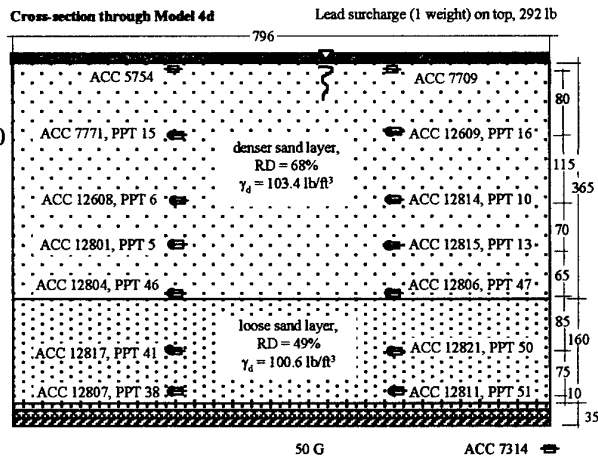
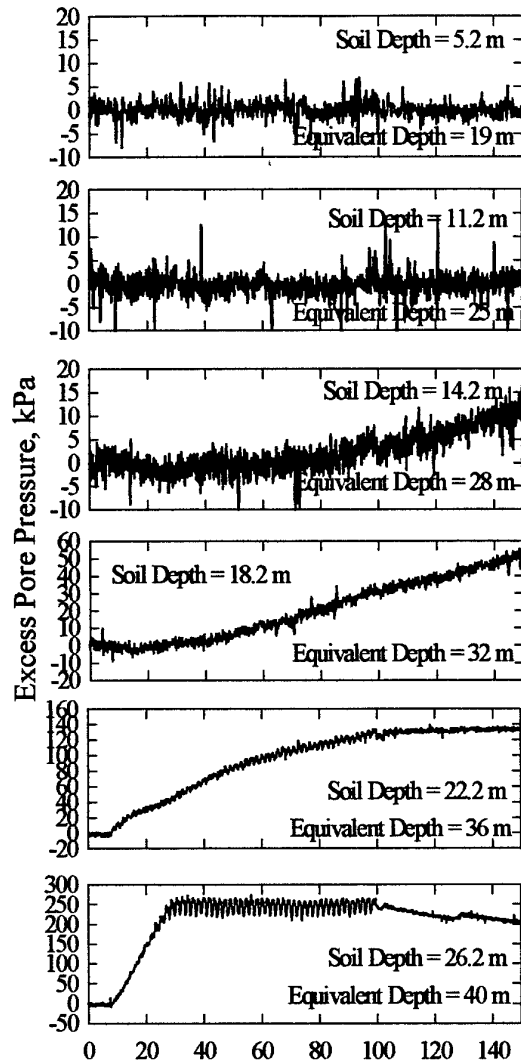
$f = 0.6 \text{ Hz}$
 $a_{\text{max}} = 0.08 \text{ g}$

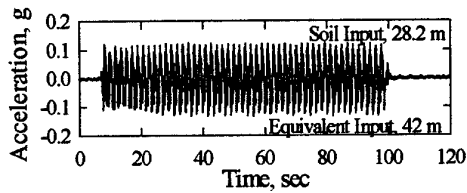
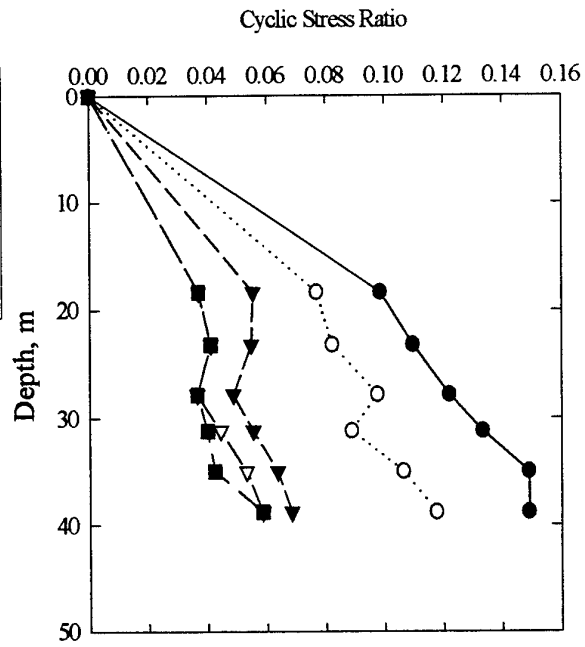
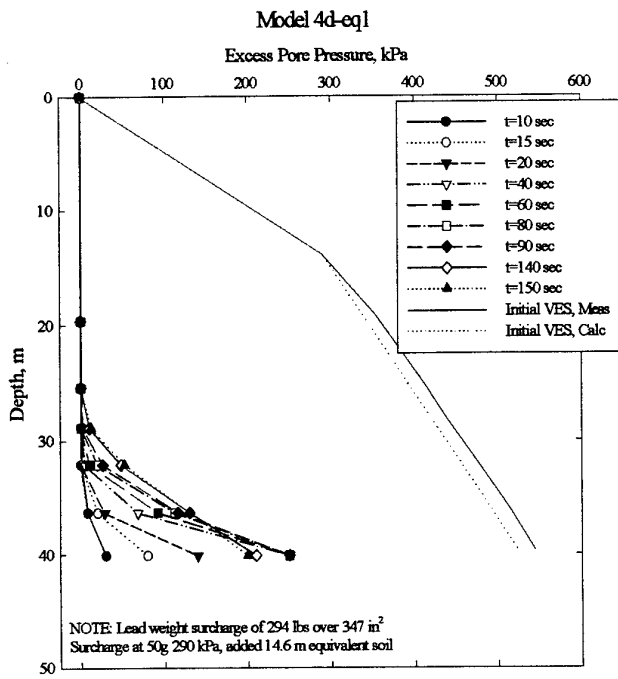


Model 4c Stress and strain isochrones

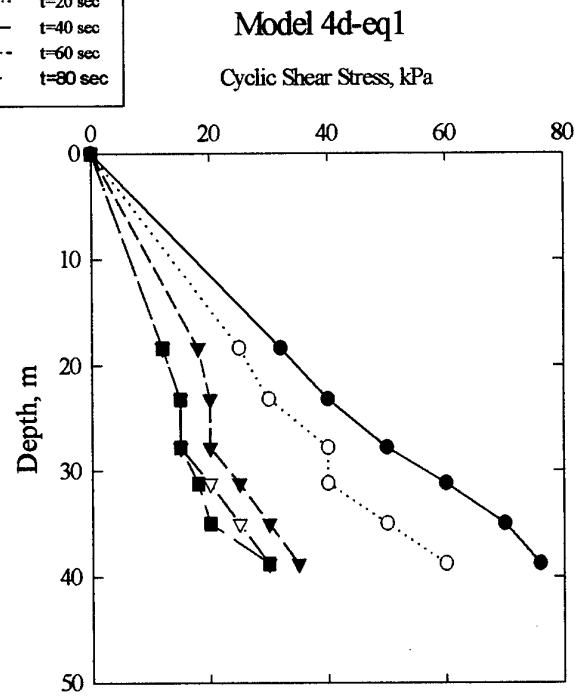
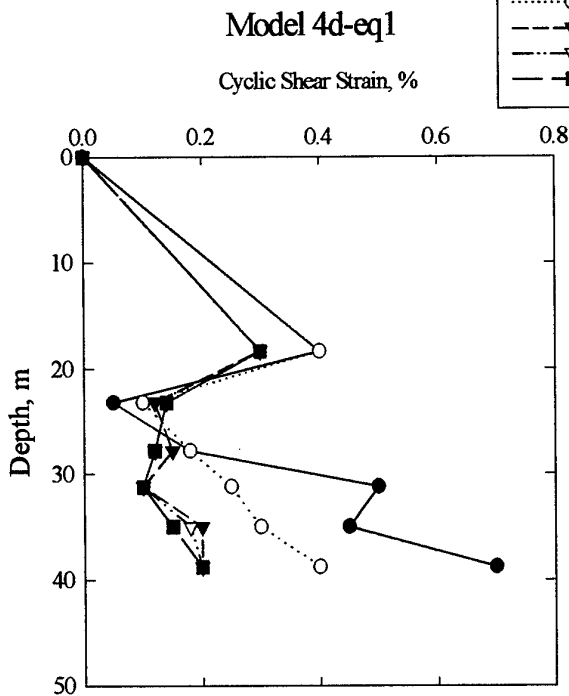


Model 4d

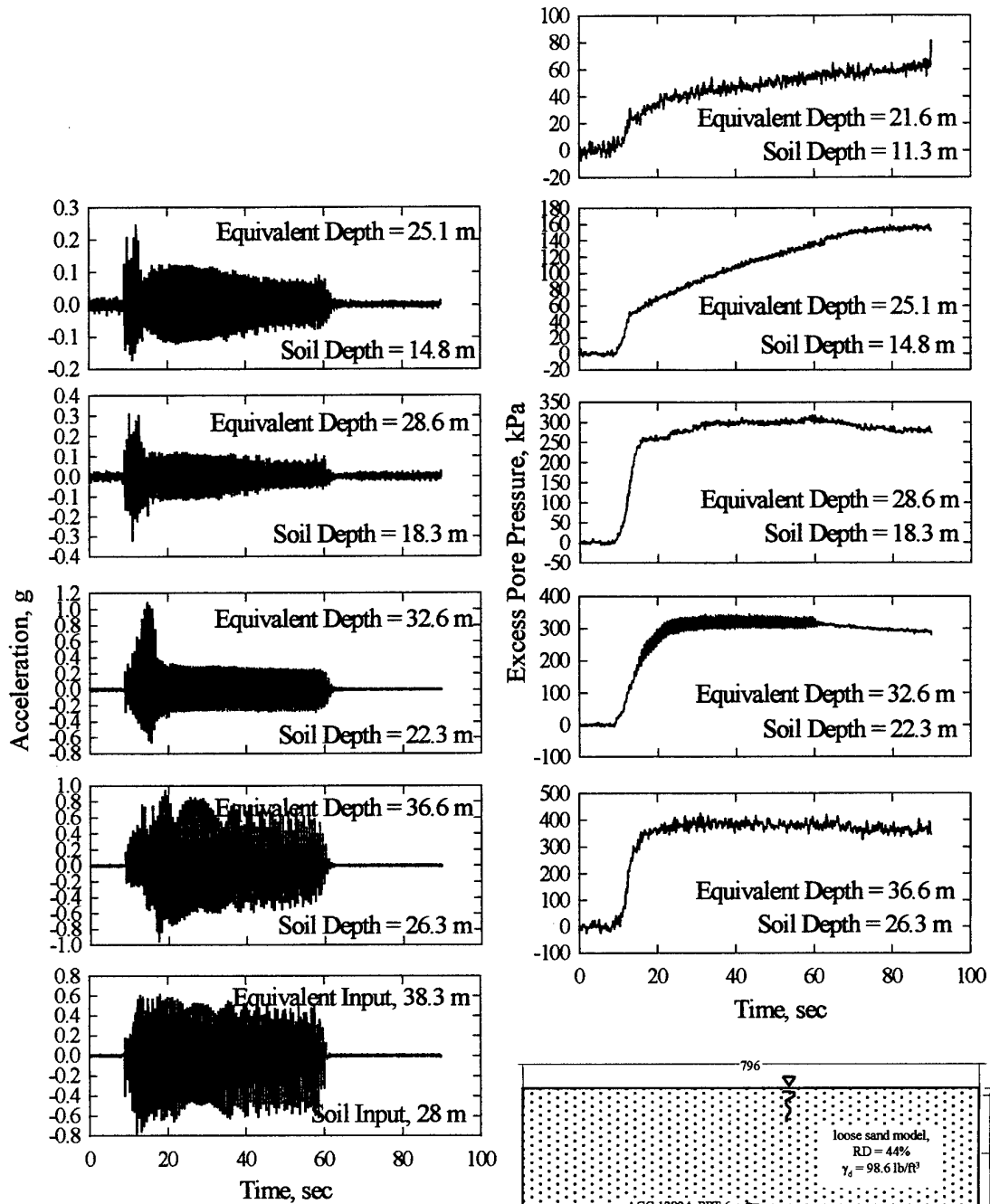




$f = 0.6 \text{ Hz}$
 $a_{\text{max}} = 0.1 \text{ g}$



Model 4d Stress and strain isochrones

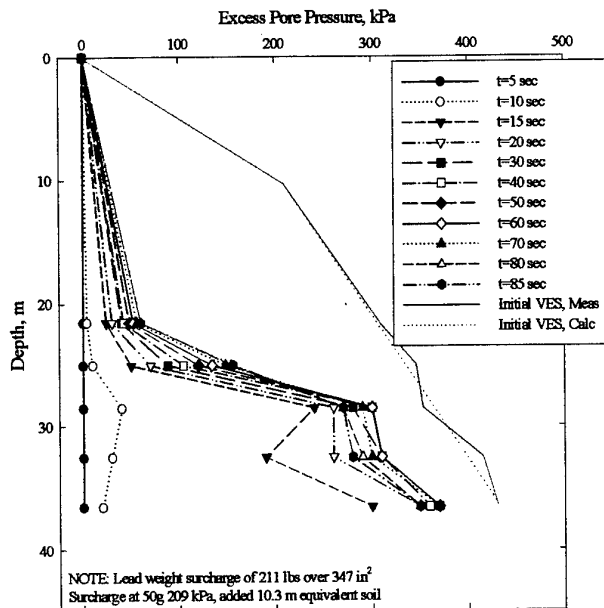


Model 4e

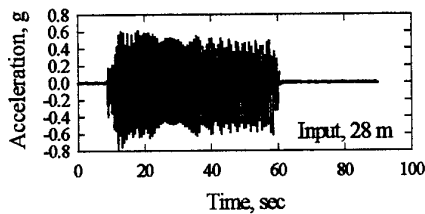
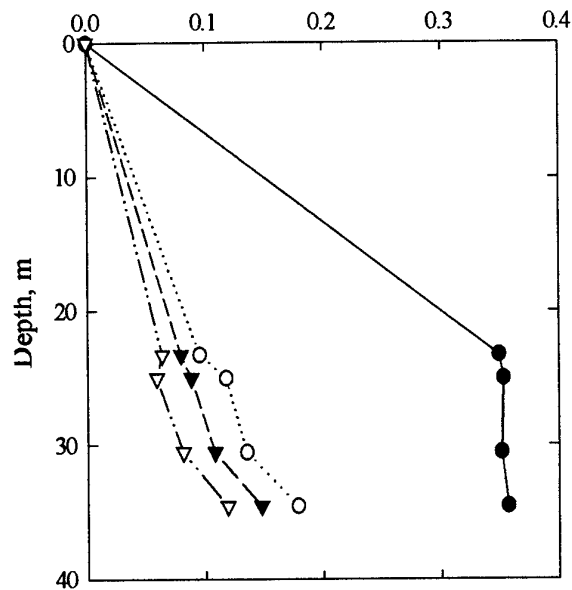
Cross-section through Model 4e 50 G
Lead surcharge (3 strips) on top, 211.00 lb

ACC 12807 left, ACC 12821 right, ACC 12611 on center lead weight

Model 4e-eq1



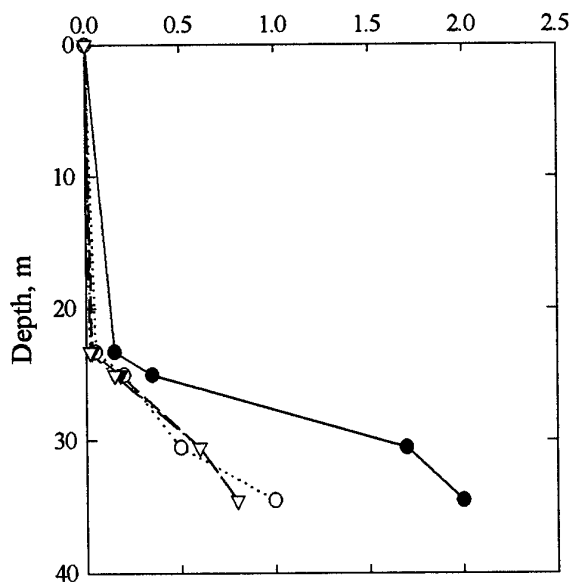
Cyclic Stress Ratio



$f = 1.5 \text{ Hz}$
 $a_{\text{max}} = 0.5 \text{ g}$

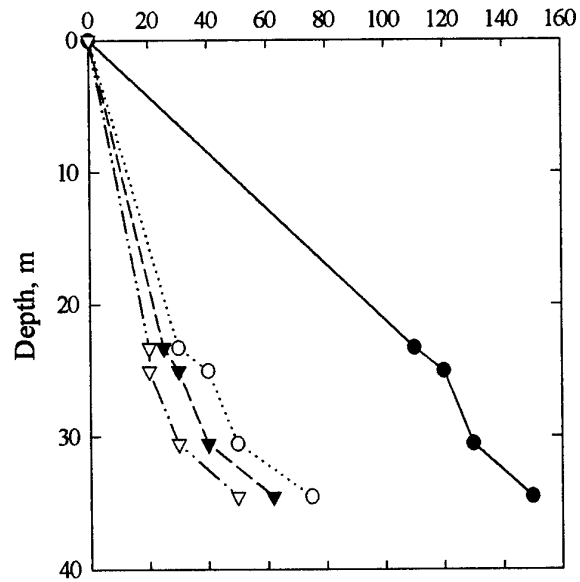
Model 4e-eq1

Cyclic Shear Strain, %

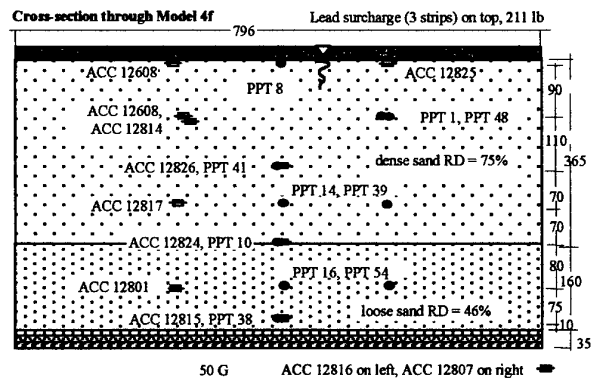
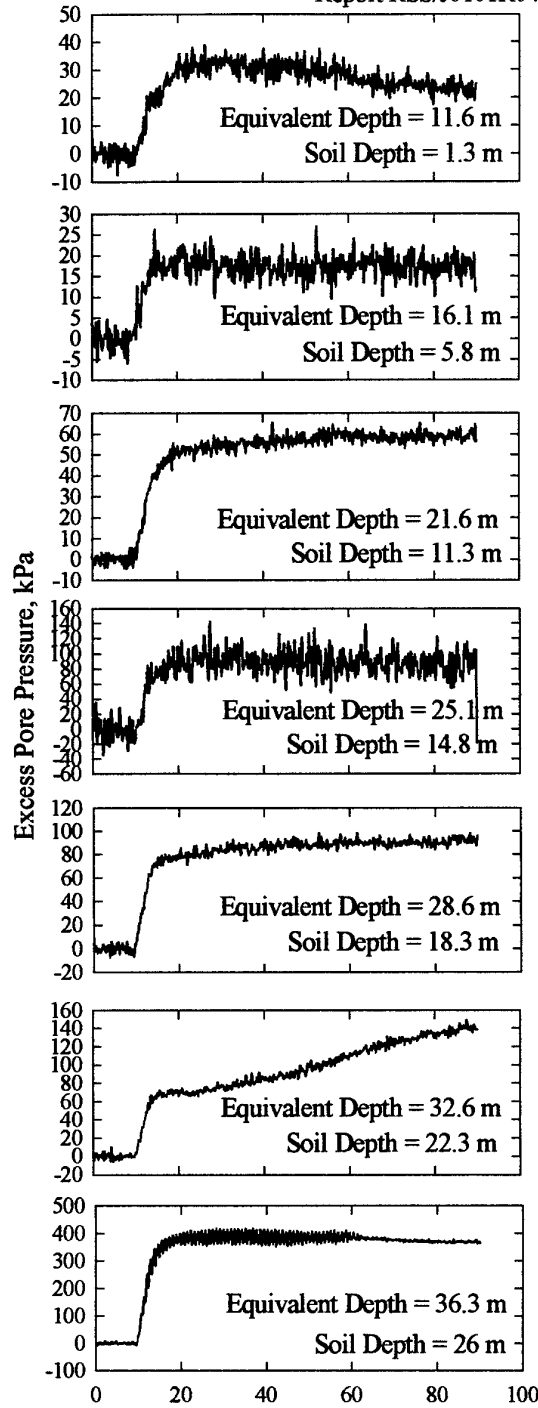
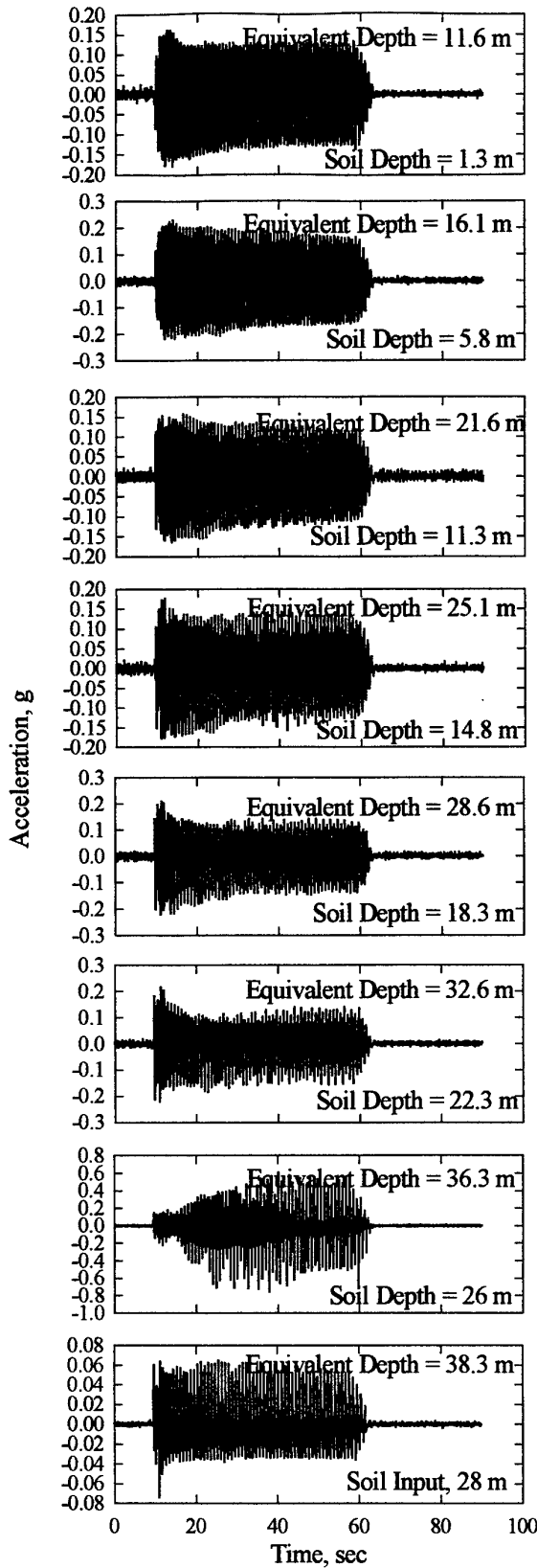


Model 4e-eq1

Cyclic Shear Stress, kPa

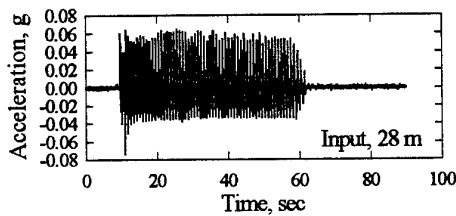
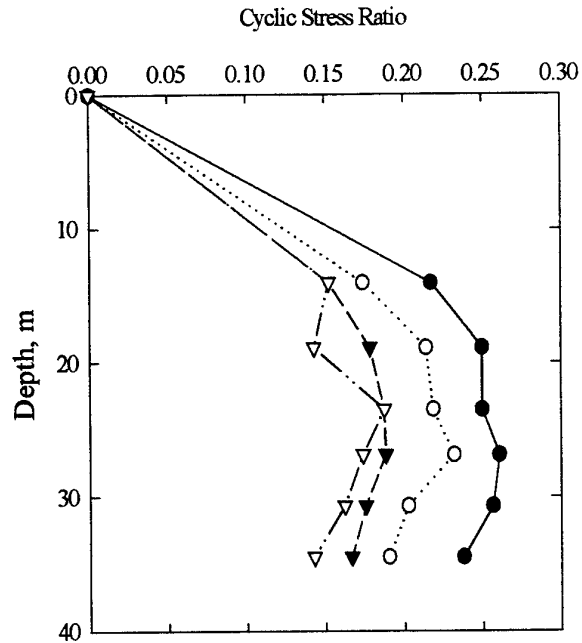
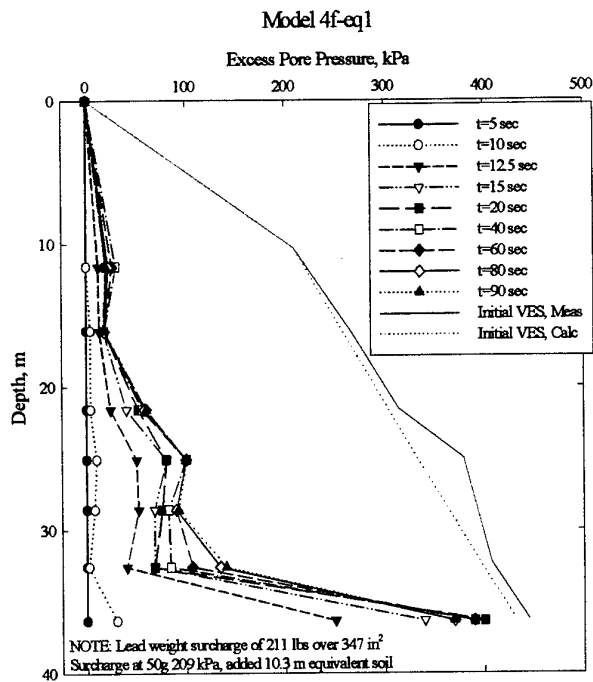


Model 4e Stress and strain isochrones

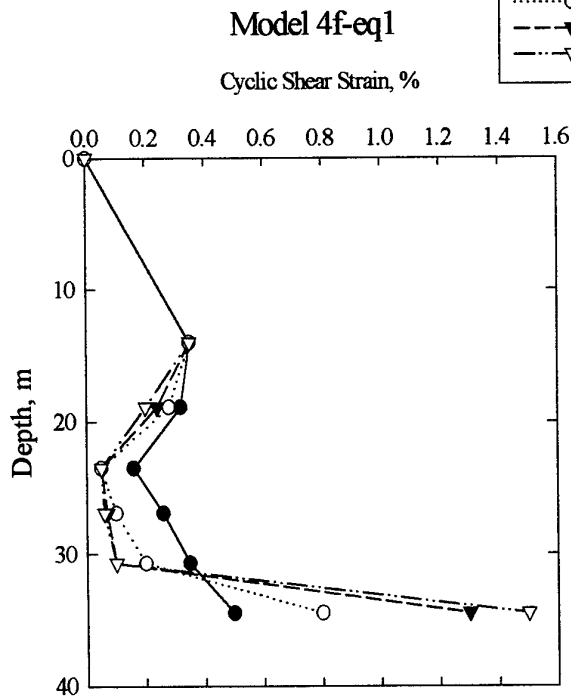


Model 4f

B-35



$f = 1.2 \text{ Hz}$
 $a_{\text{max}} = 0.06 \text{ g}$

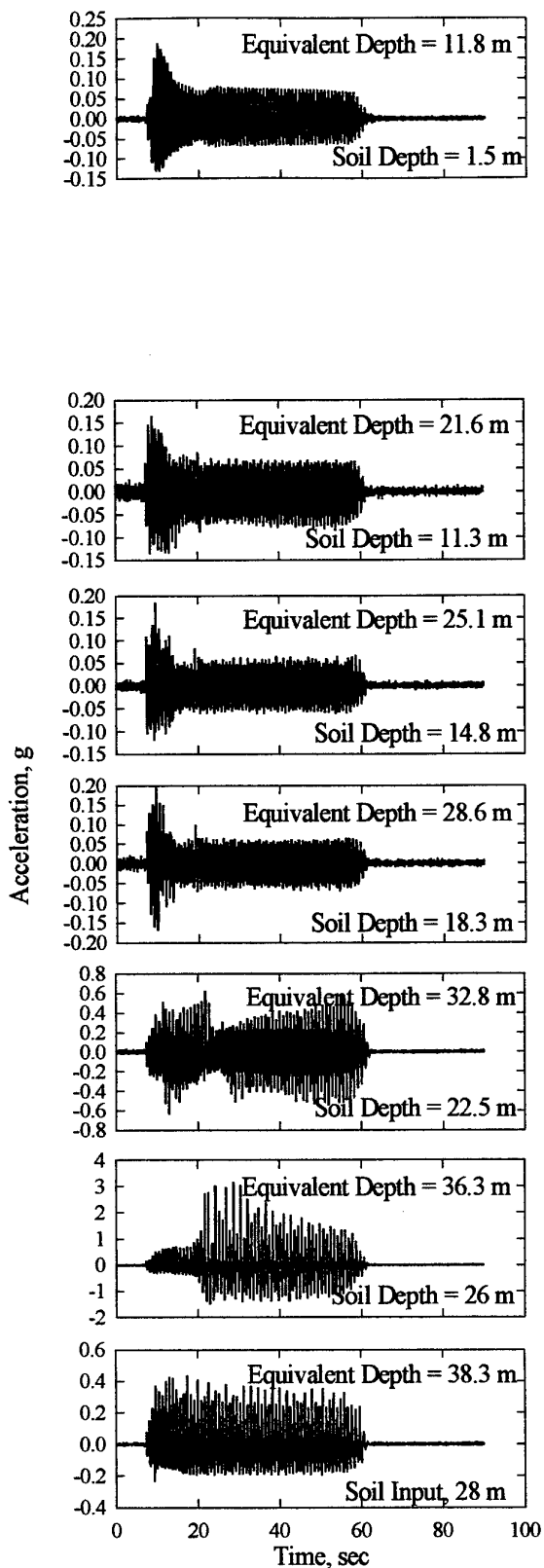


Model 4f-eq1

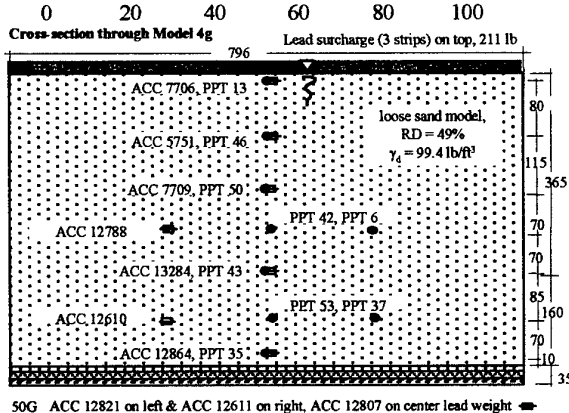
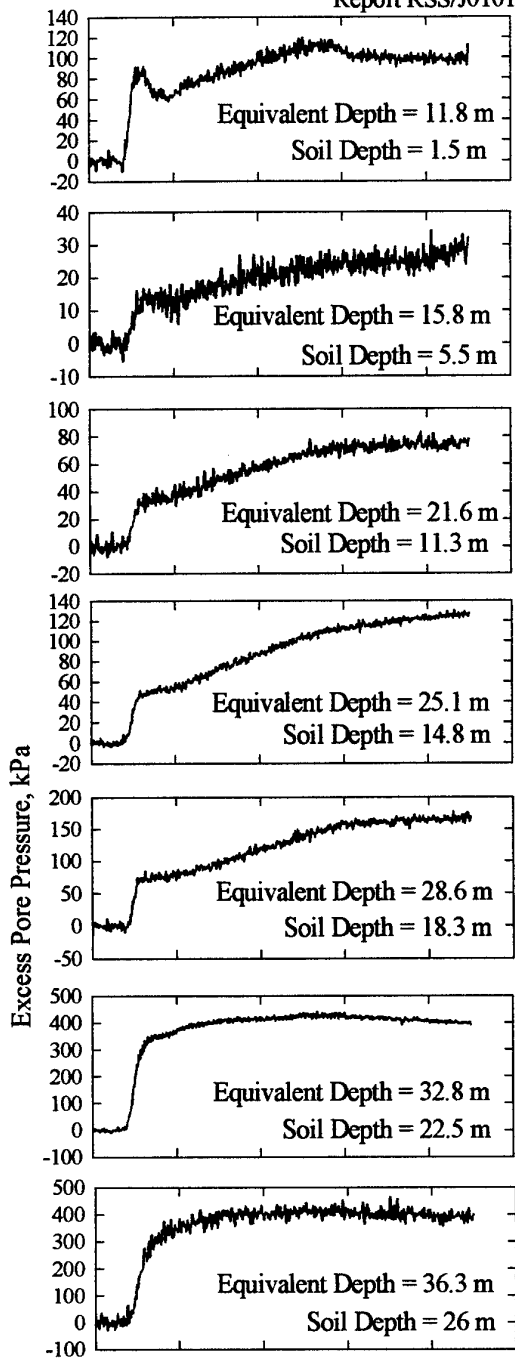
Cyclic Shear Stress, kPa

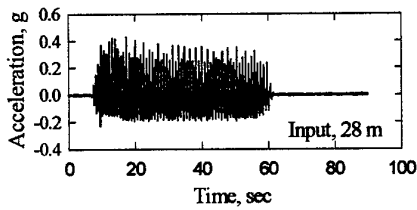
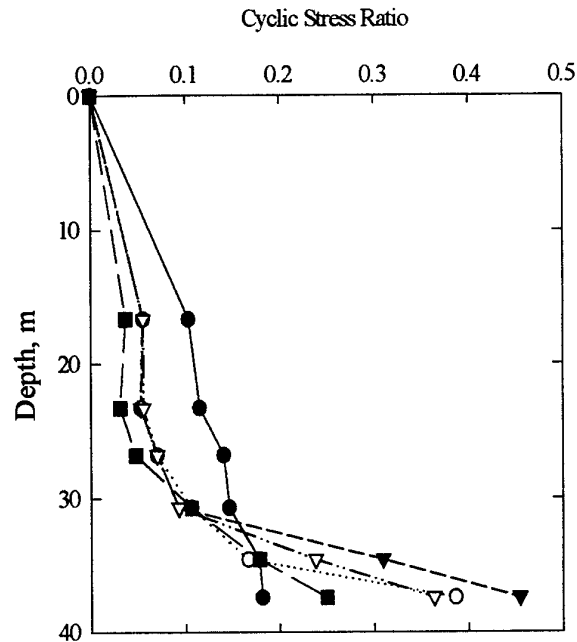
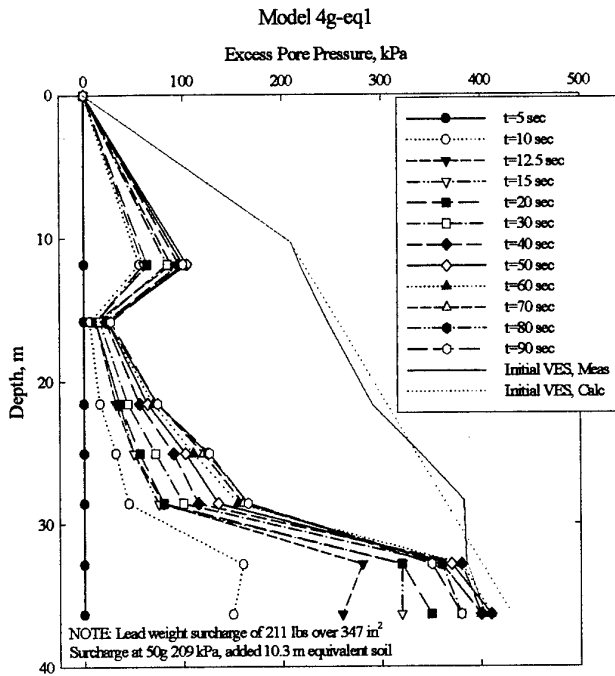
Depth, m

Model 4f Stress and strain isochrones

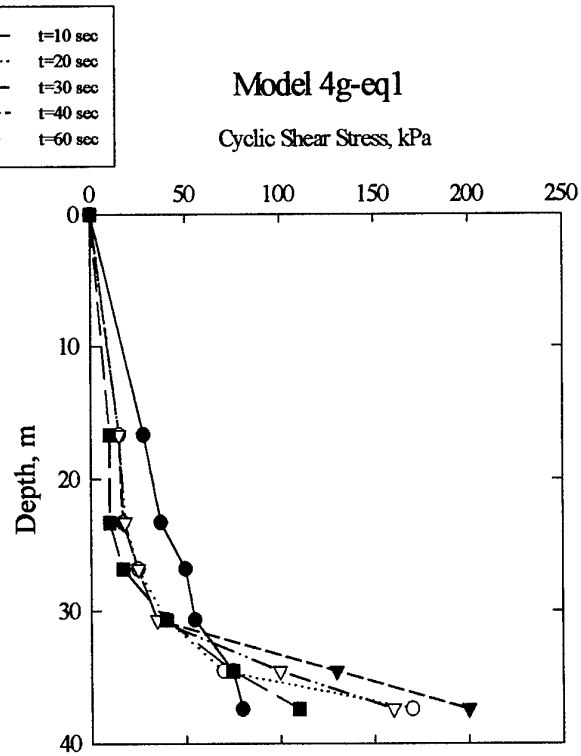
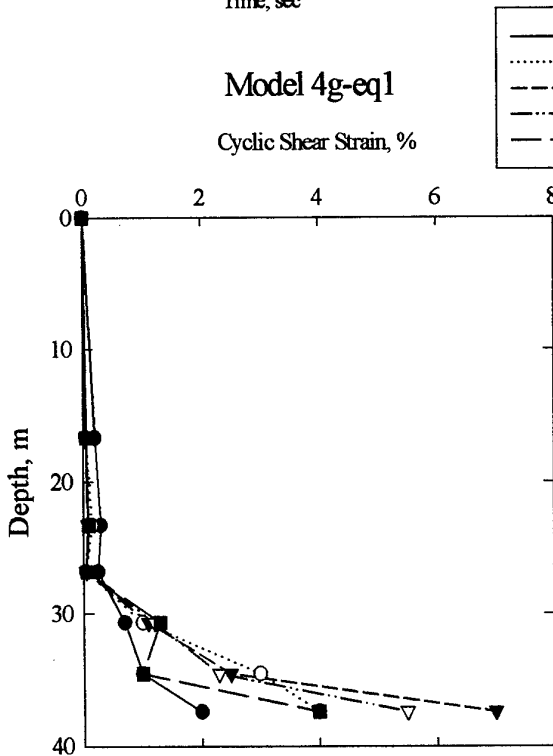


Model 4g

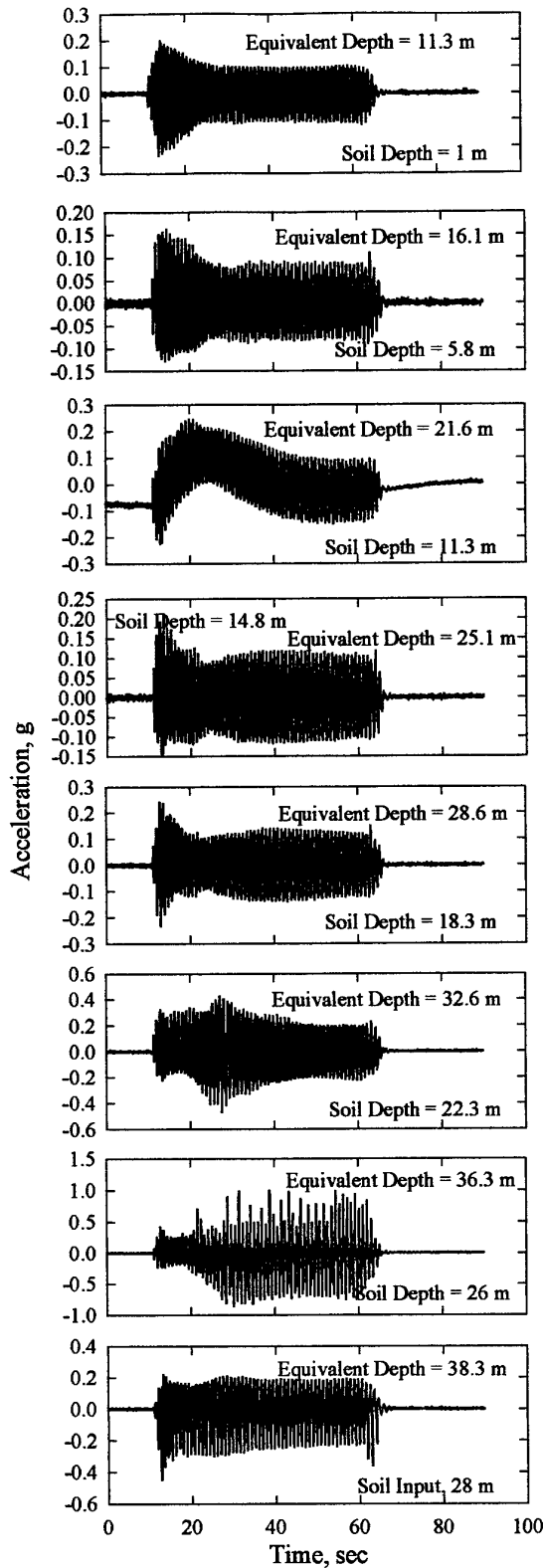




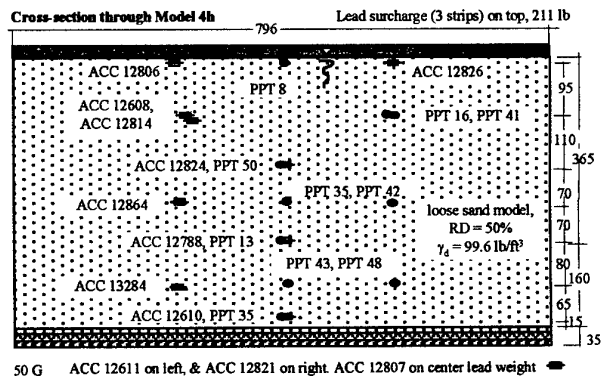
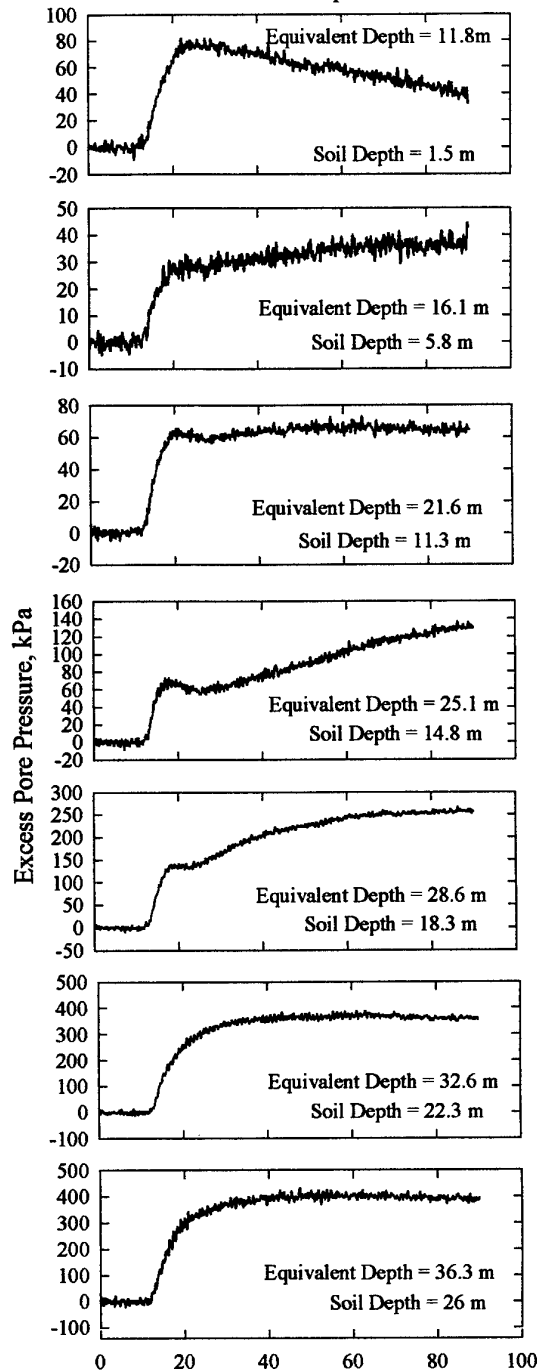
$f = 1.15 \text{ Hz}$
 $a_{\text{max}} = 0.3 \text{ g}$

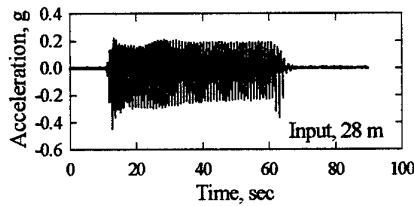
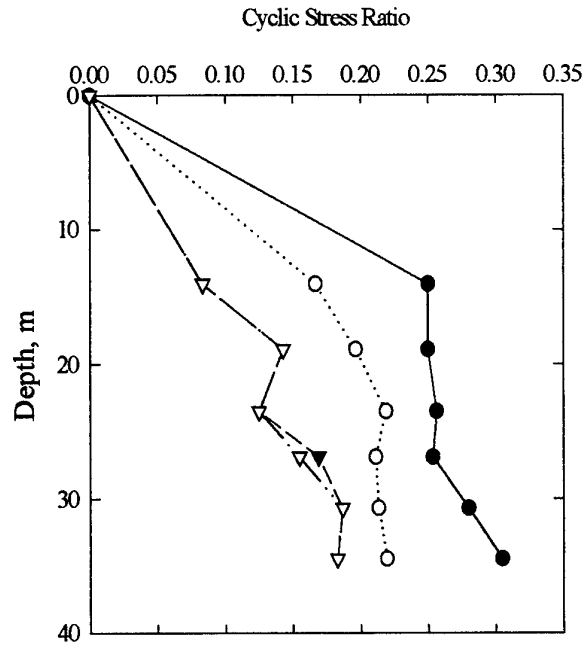
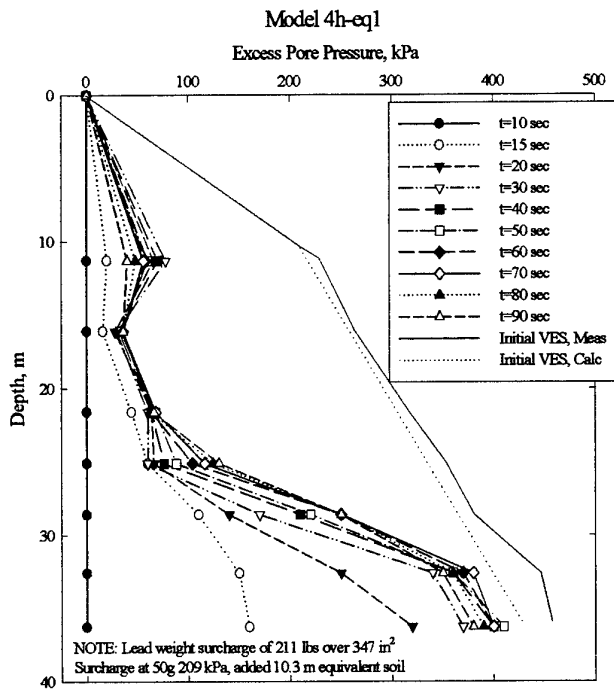


Model 4g Stress and strain isochrones

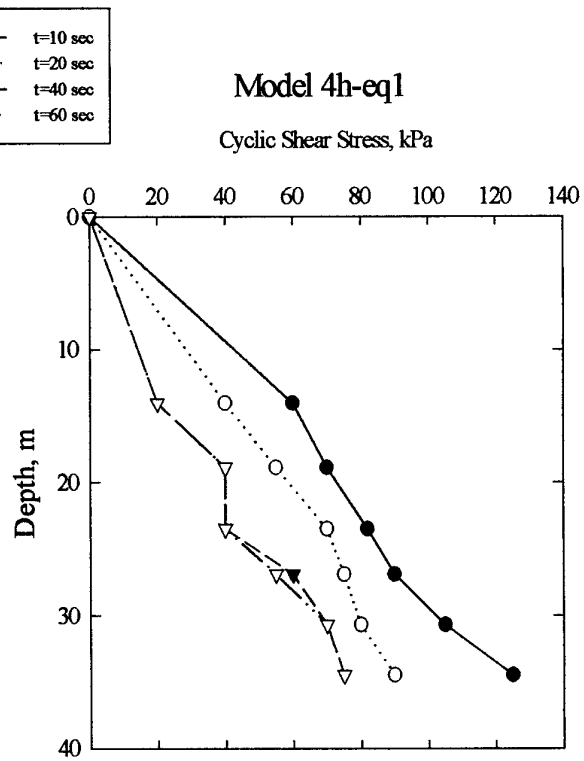
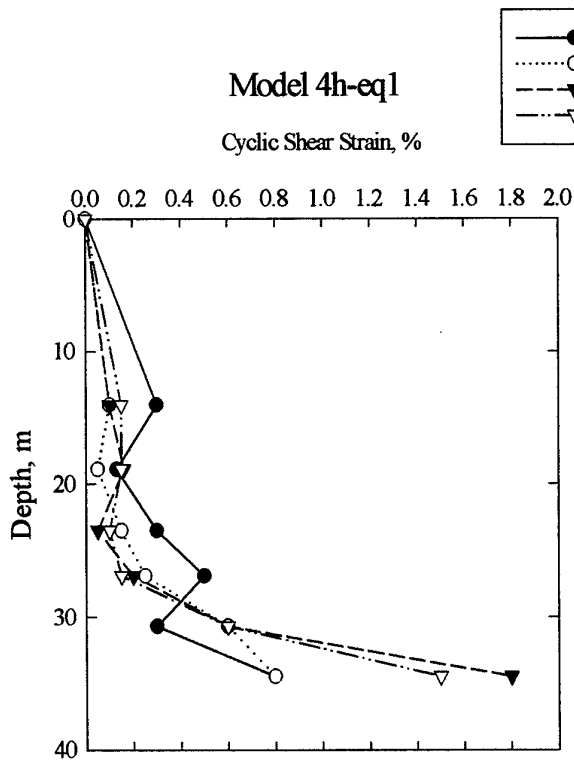


Model 4h

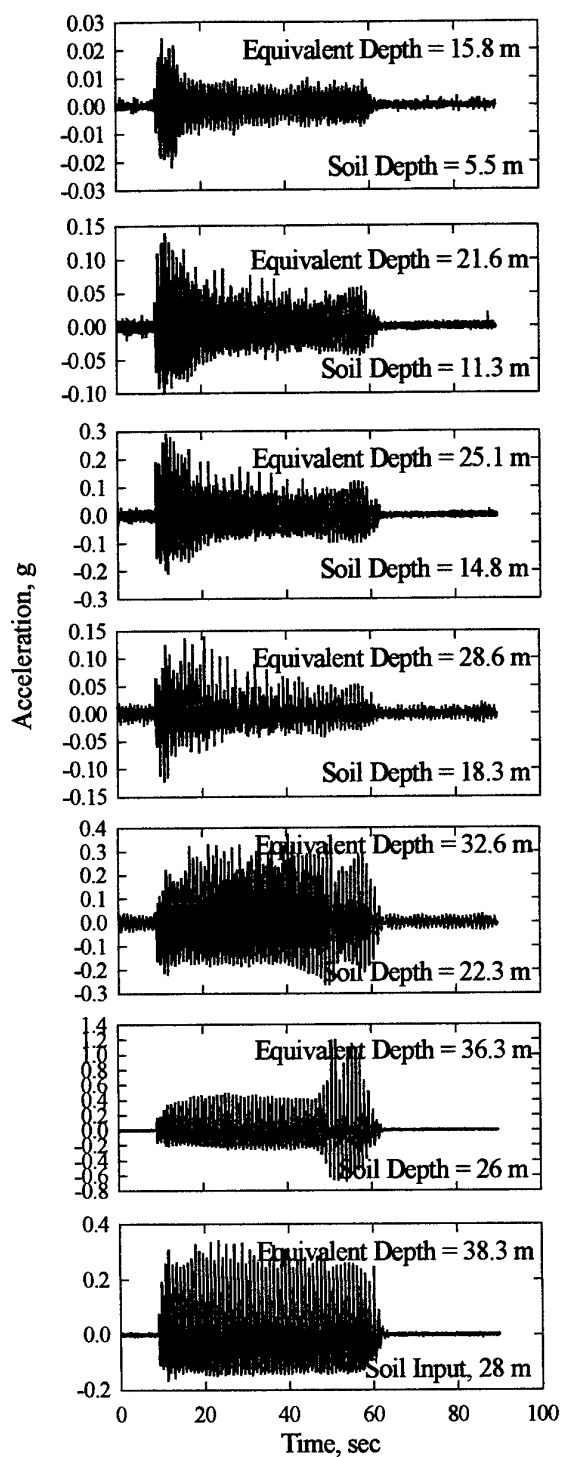




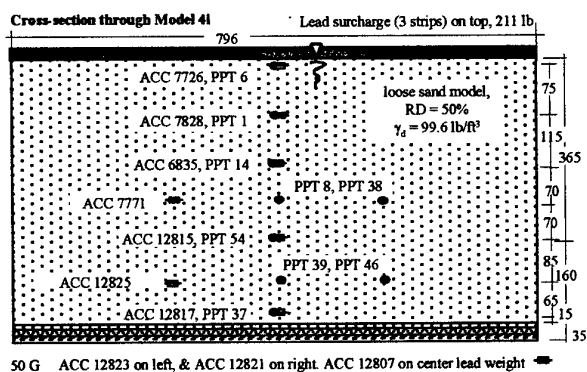
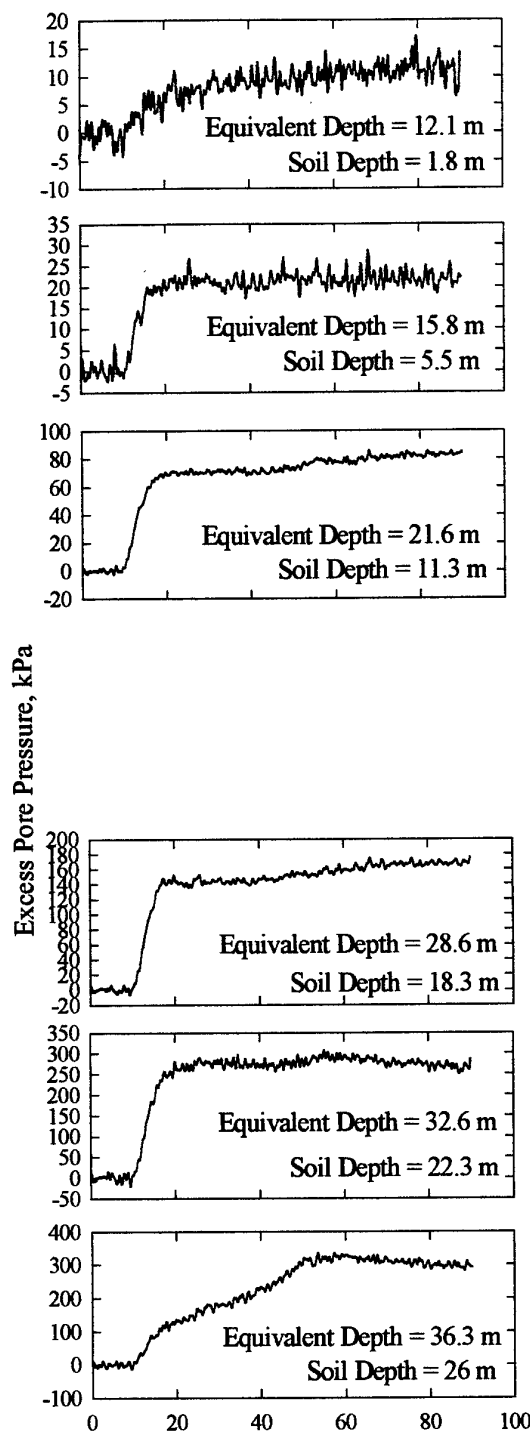
$f = 1.1 \text{ Hz}$
 $a_{\text{max}} = 0.25 \text{ g}$

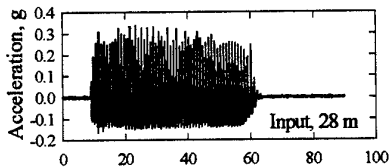
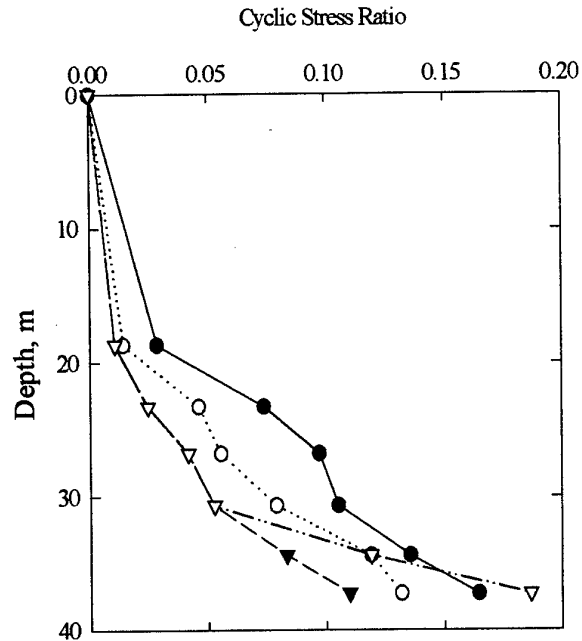
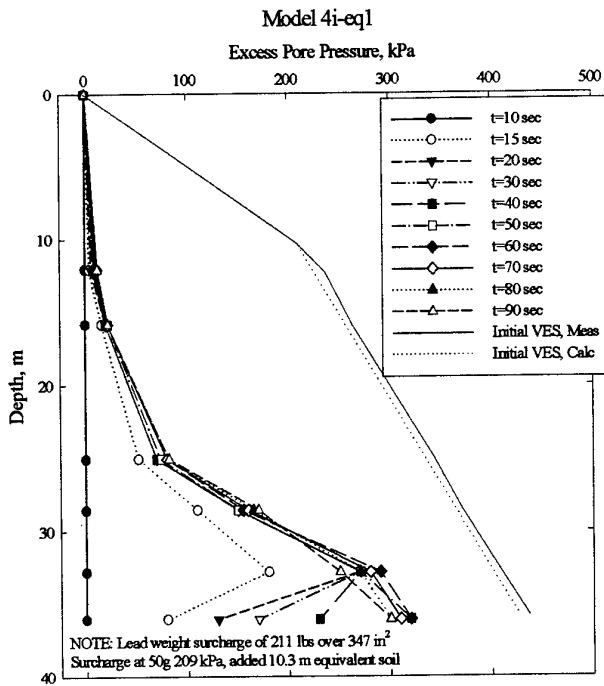


Model 4h Stress and strain isochrones

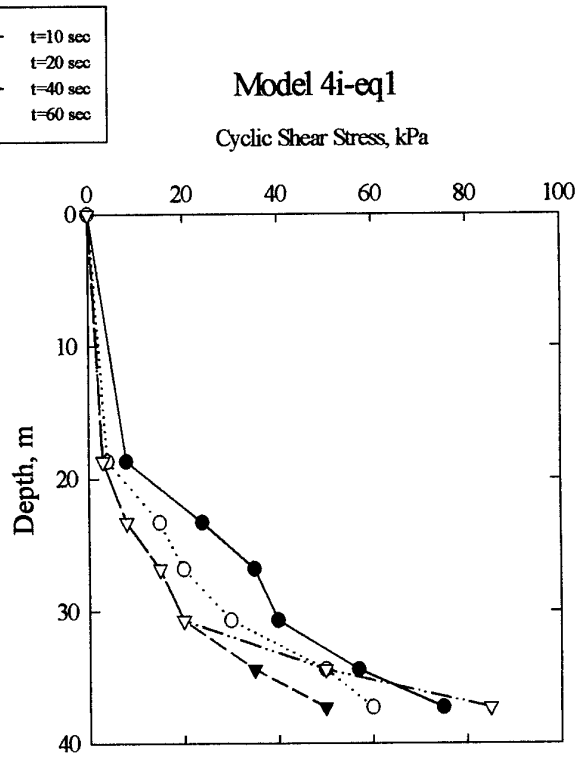
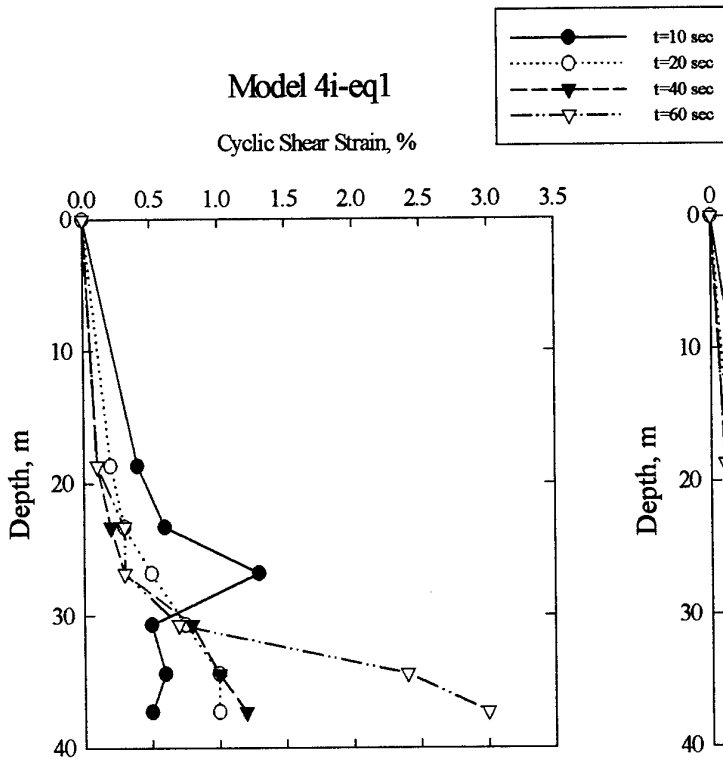


Model 4i

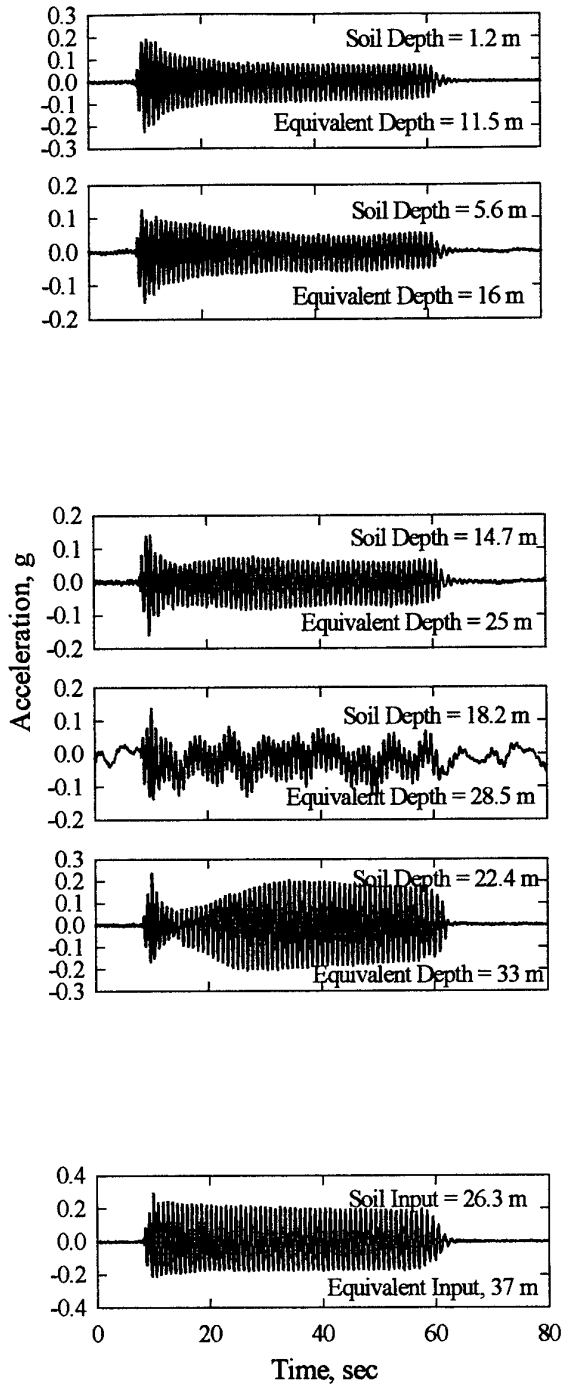




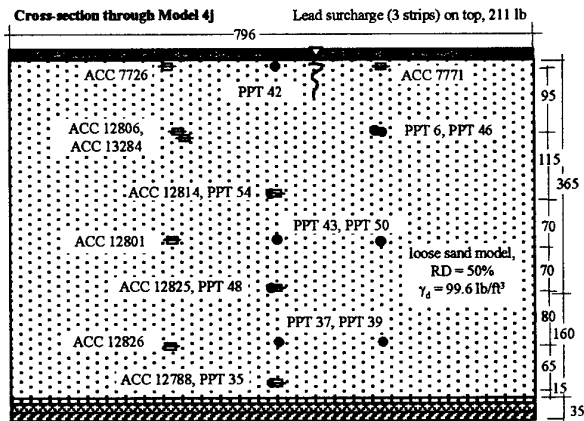
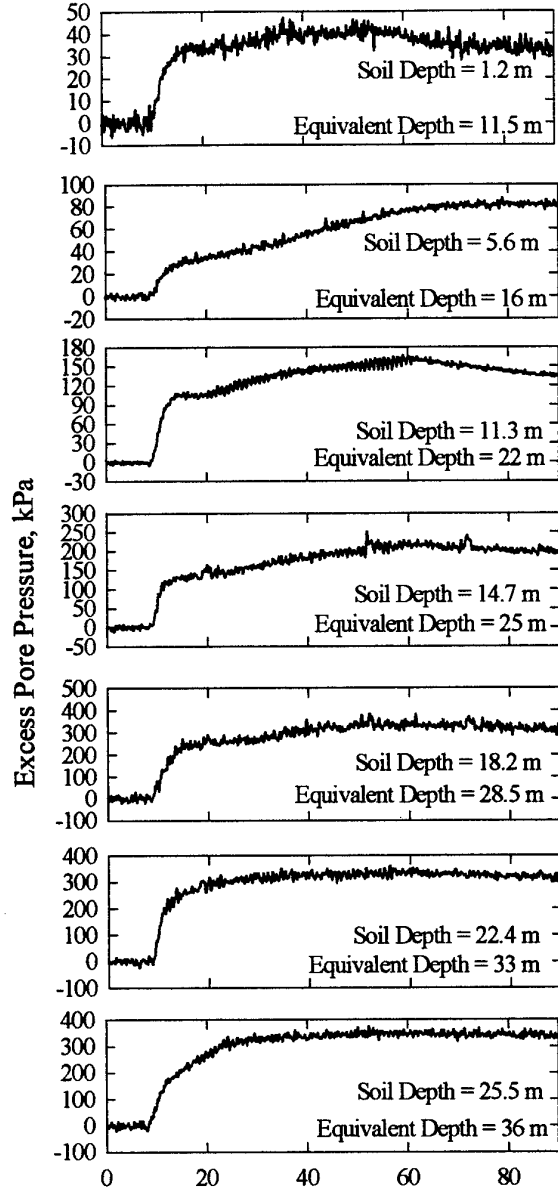
$f = 1.1 \text{ Hz}$
 $a_{\text{max}} = 0.3 \text{ g}$



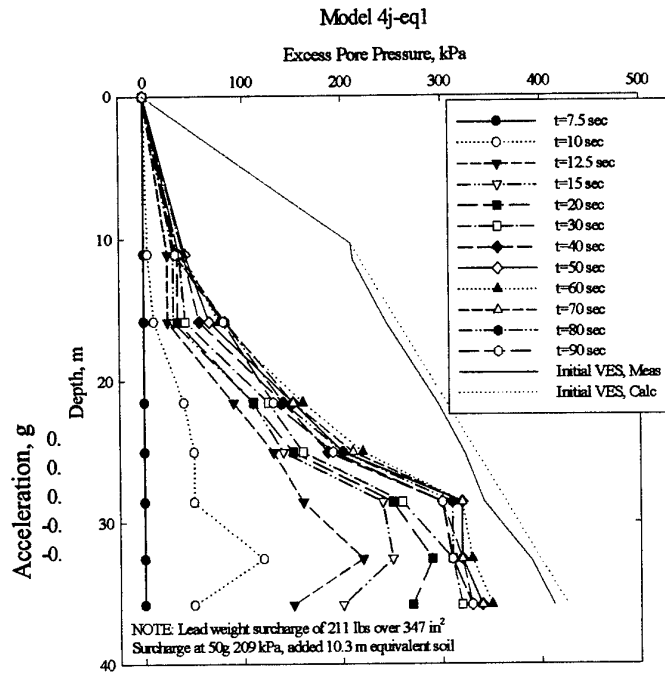
Model 4i Stress and strain isochrones



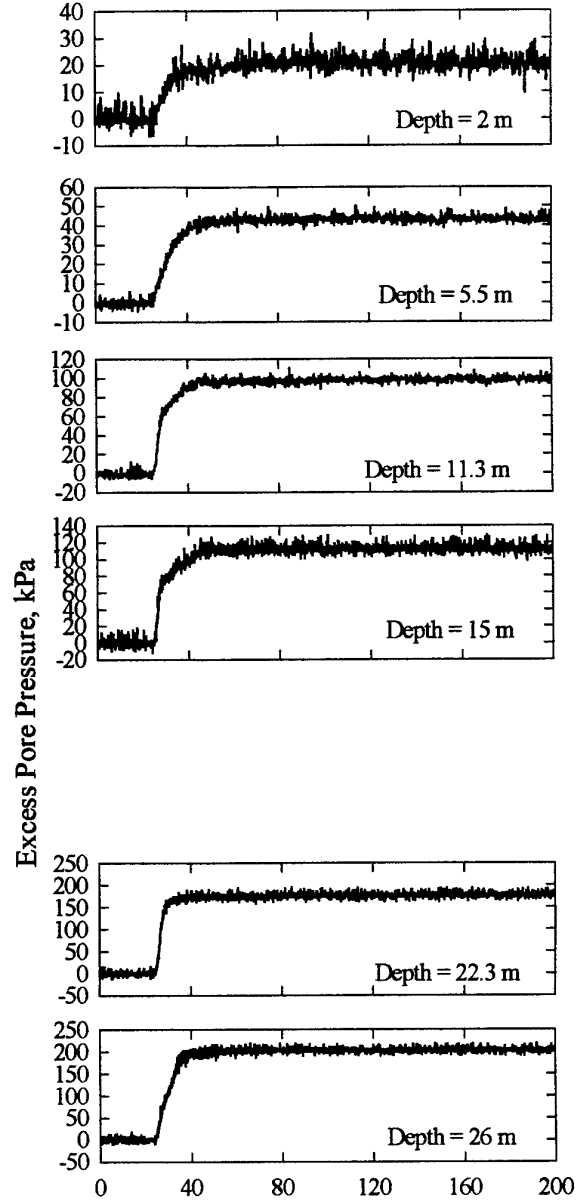
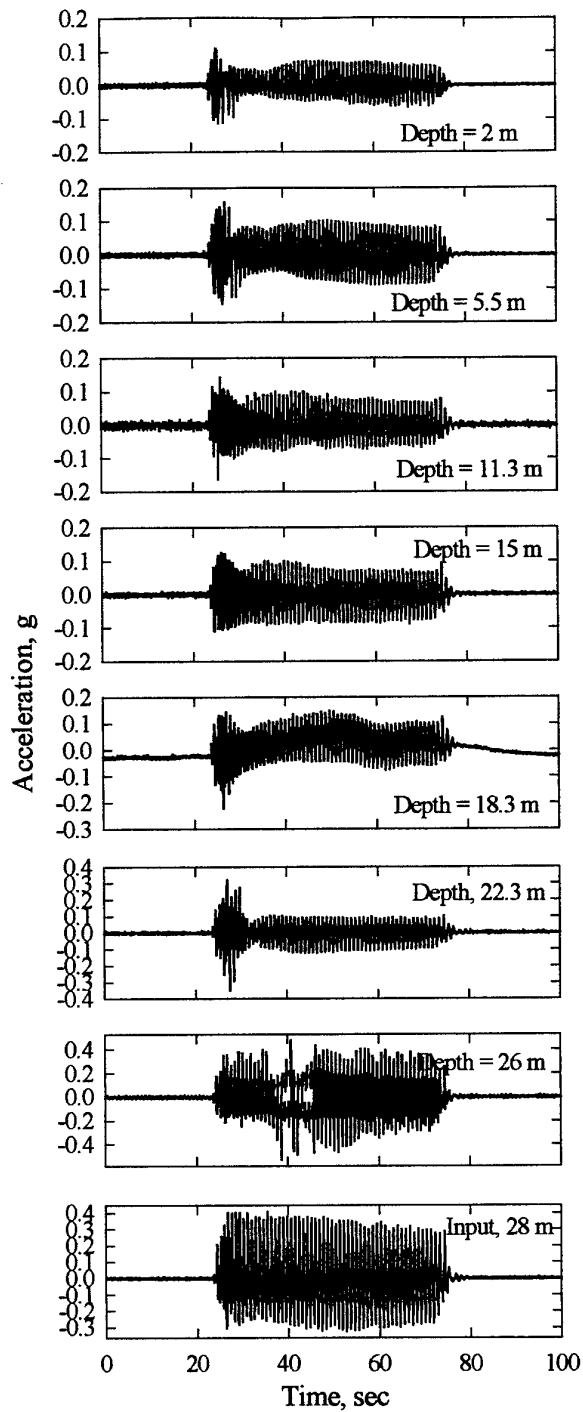
Model 4j



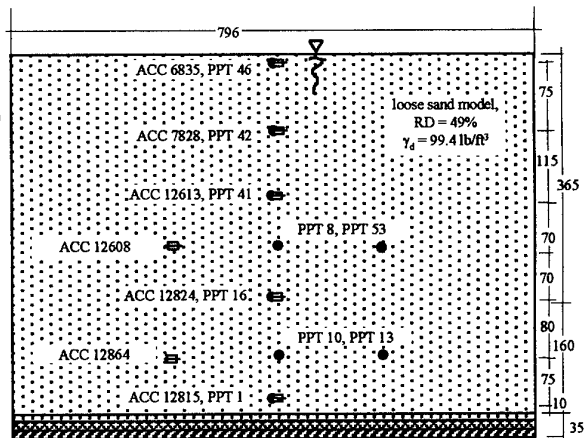
50 G ACC 12823 on left, & ACC 12821 on right. ACC 12807 on center lead weight



Model 4j Stress and strain isochrones



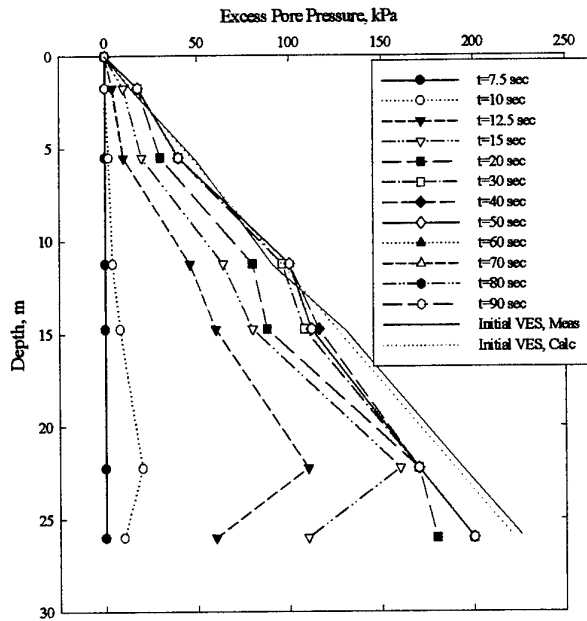
Model 4k



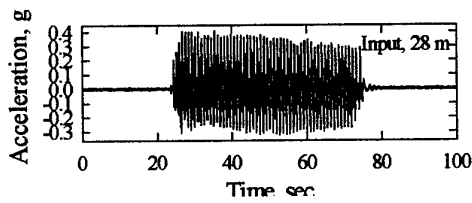
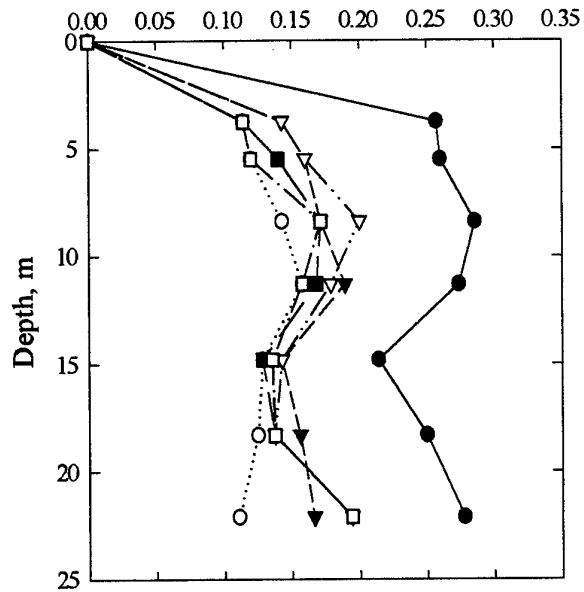
B-45

Cross-section through Model 4k 50 G ACC 12823 on left, & ACC 12821 on right

Model 4k-eq1



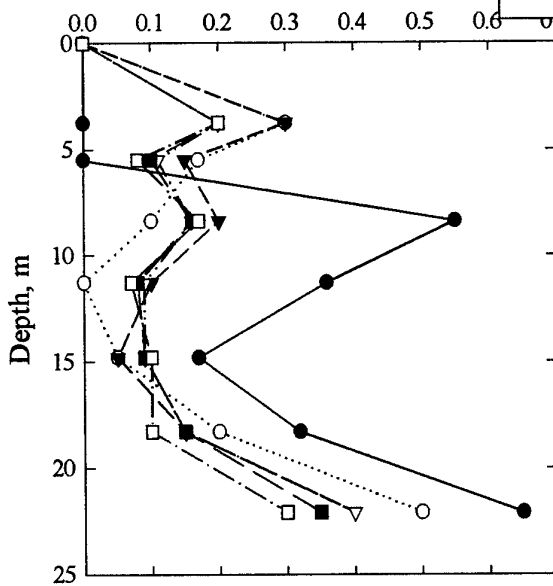
Cyclic Stress Ratio



$f = 1.1 \text{ Hz}$
 $a_{\max} = 0.3 \text{ g}$

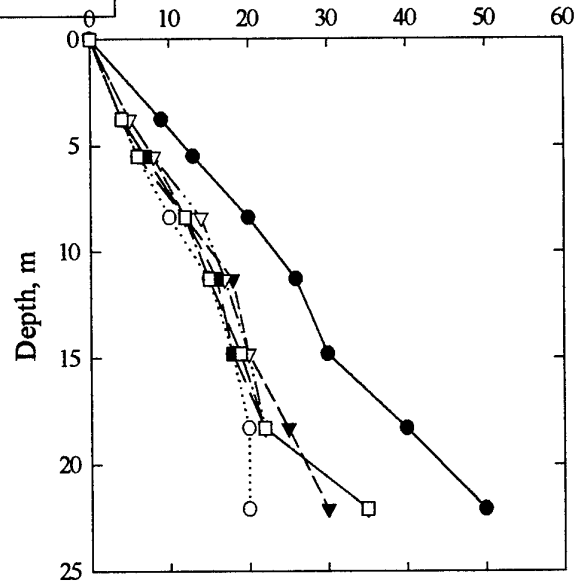
Model 4k-eq1

Cyclic Shear Strain, %

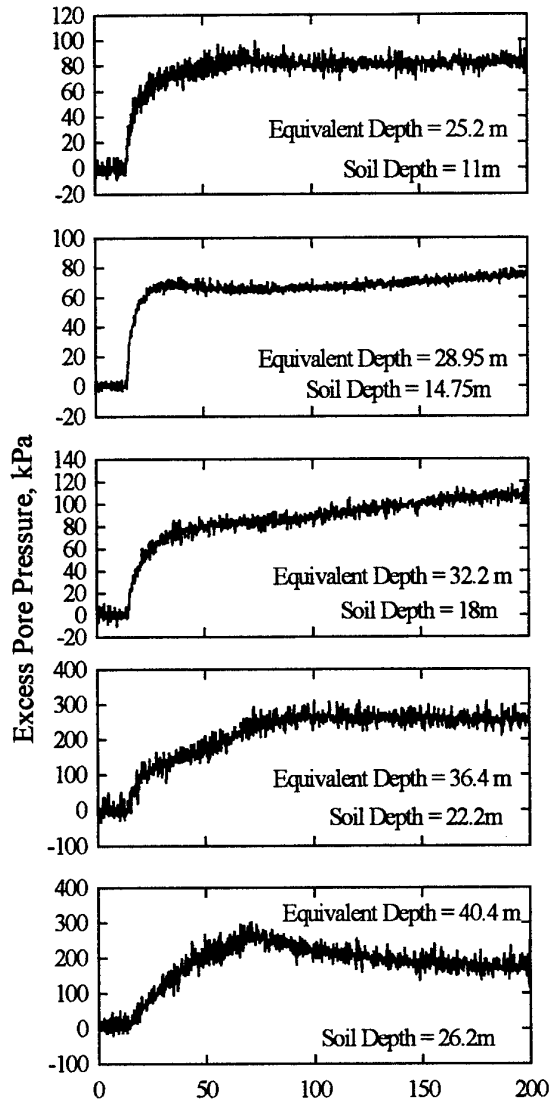
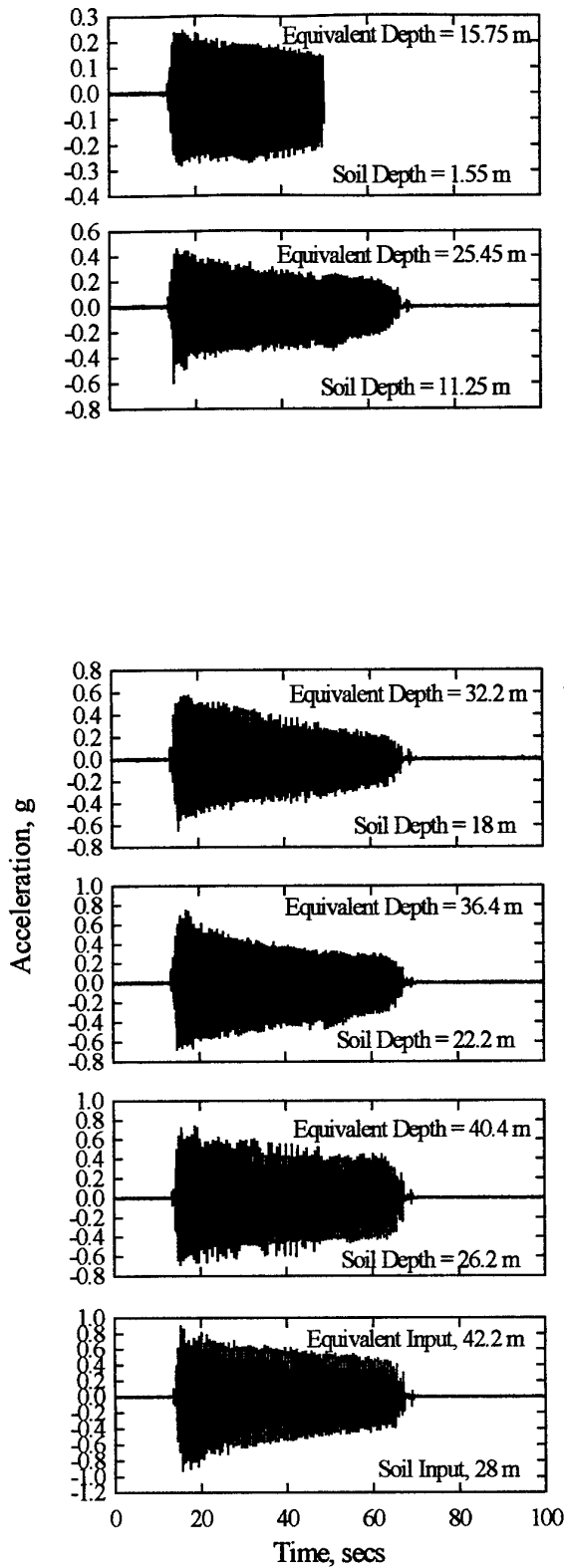


Model 4k-eq1

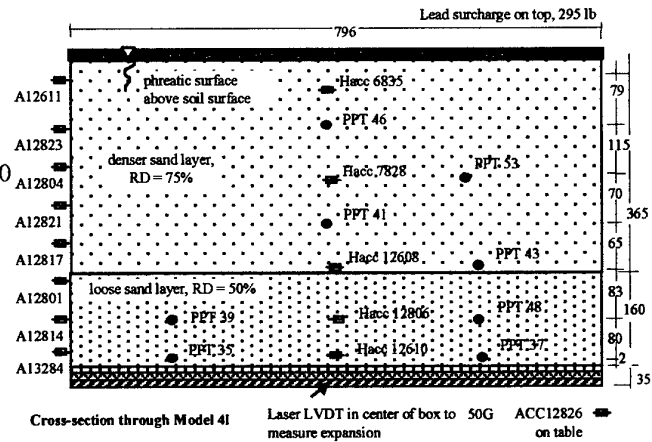
Cyclic Shear Stress, kPa



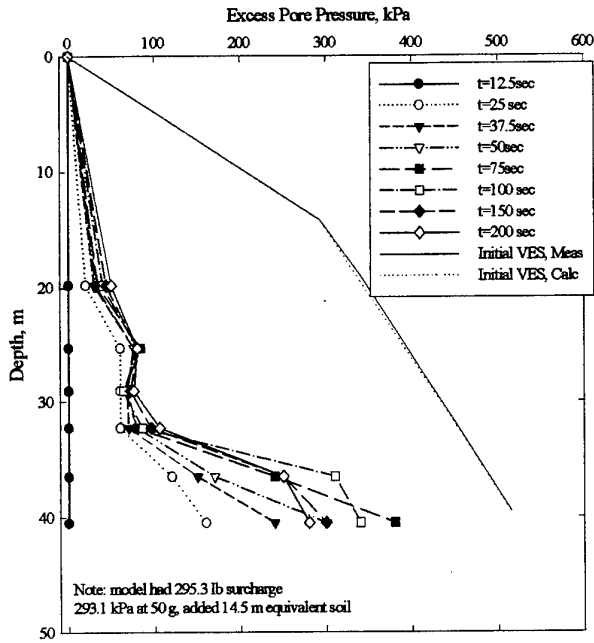
Model 4k Stress and strain isochrones



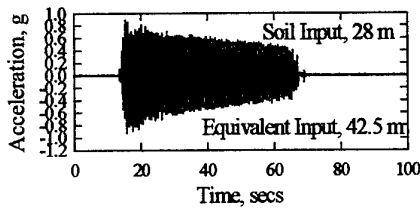
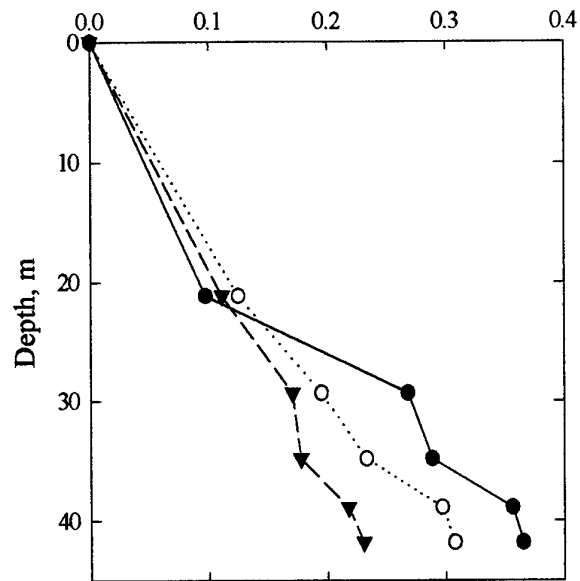
Model 41



Model 4l (Box Sticking)



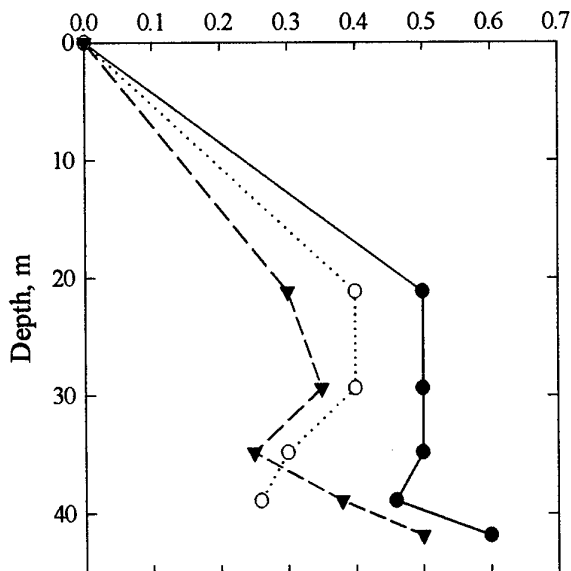
Cyclic Stress Ratio



$f = 1.5 \text{ Hz}$
 $a_{\text{max}} = 0.6 \text{ g}$

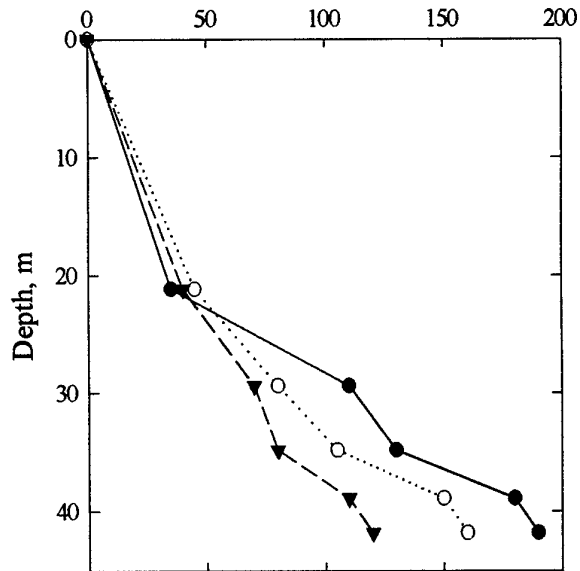
Model 4l-eq1

Cyclic Shear Strain, %

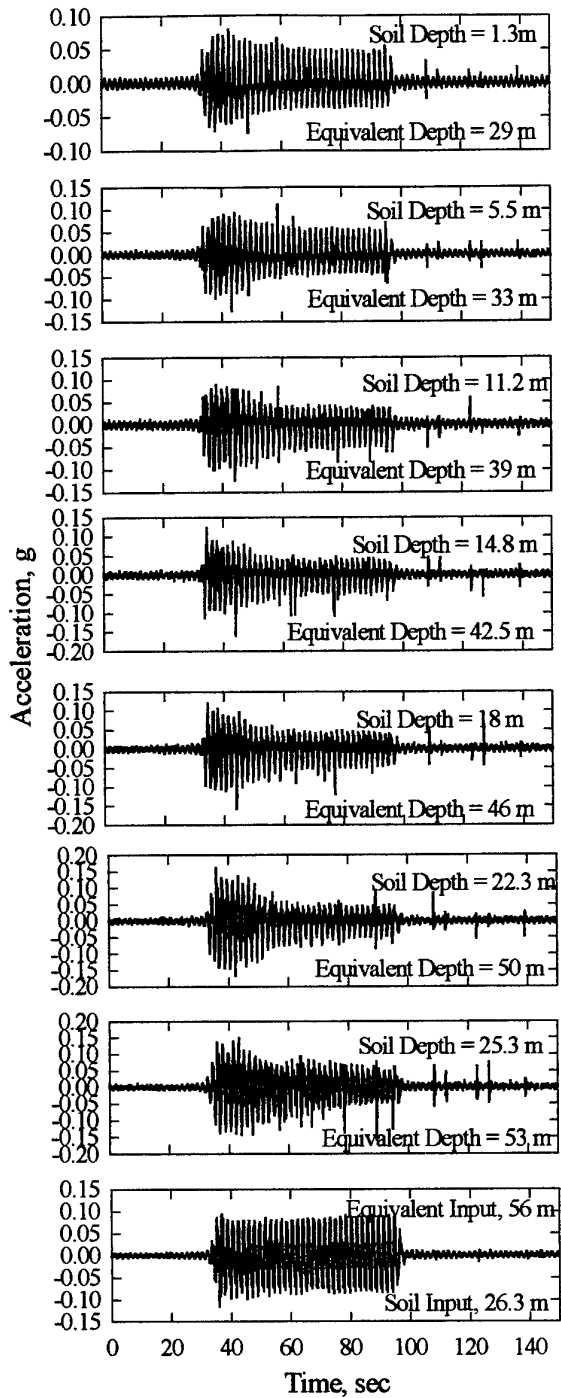


Model 4l-eq1

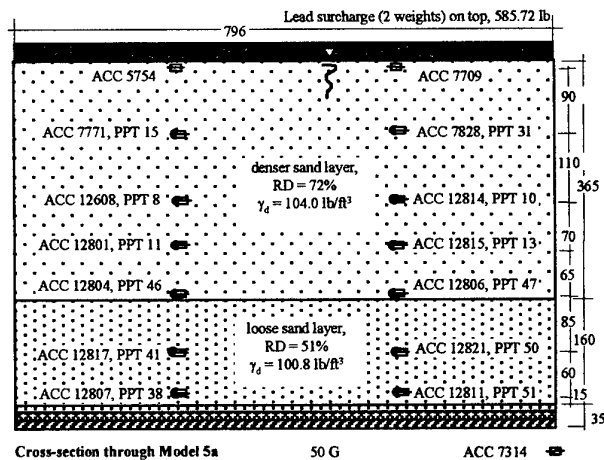
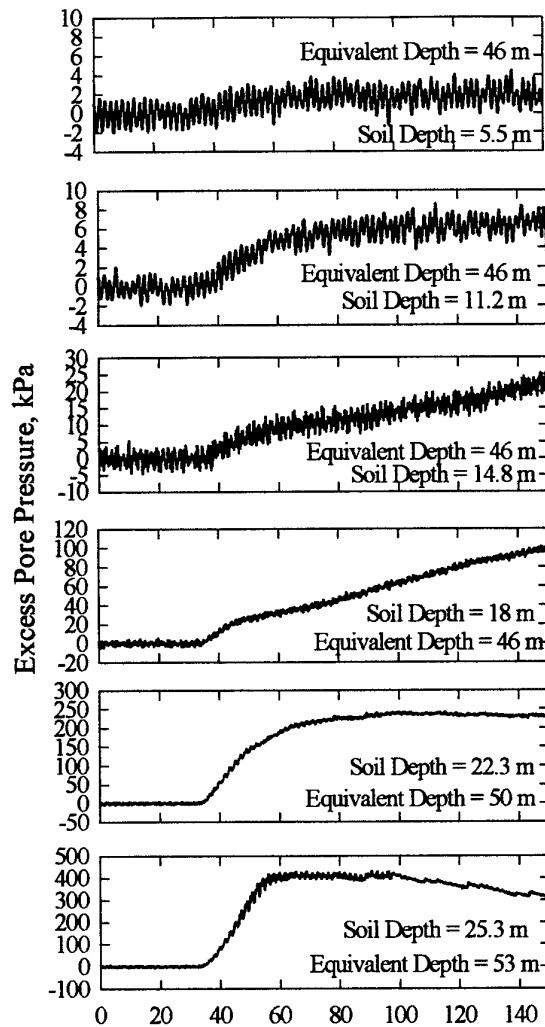
Cyclic Shear Stress, kPa

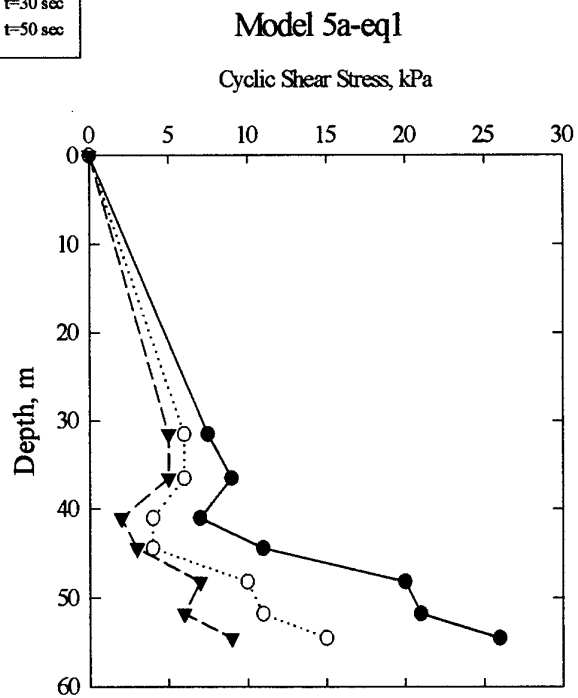
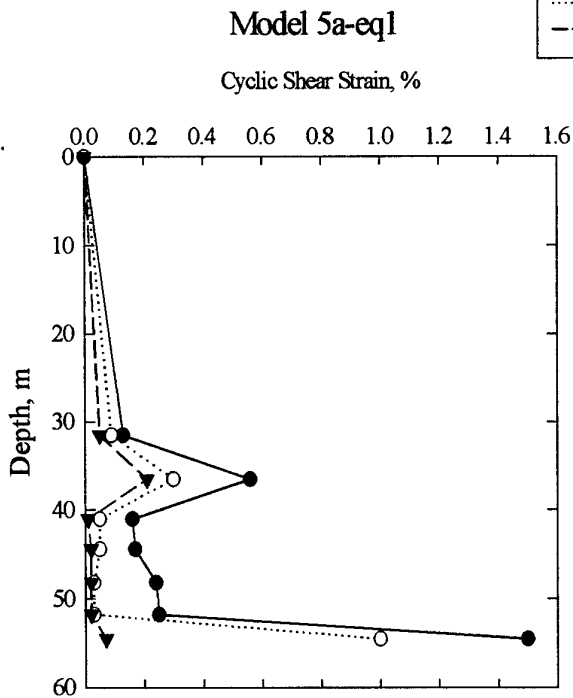
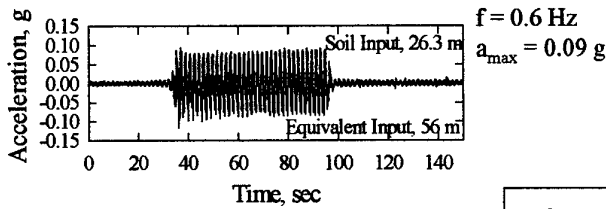
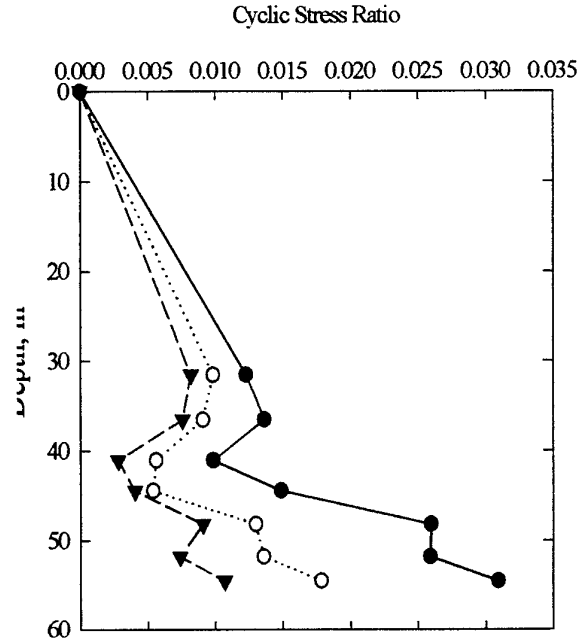
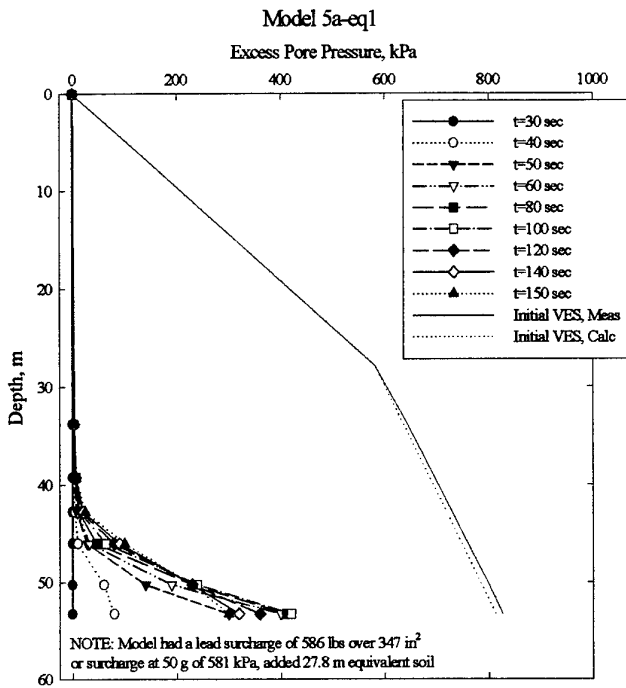


Model 4l Stress and strain isochrones

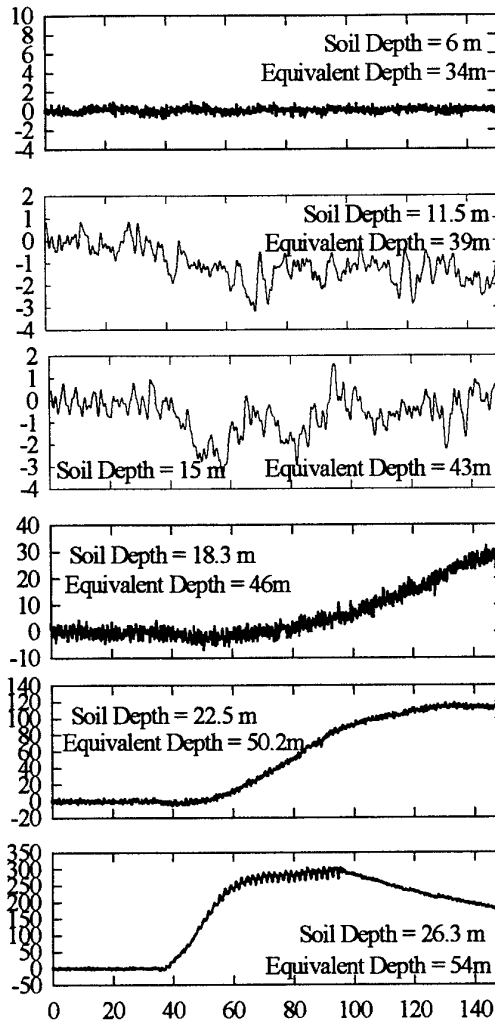
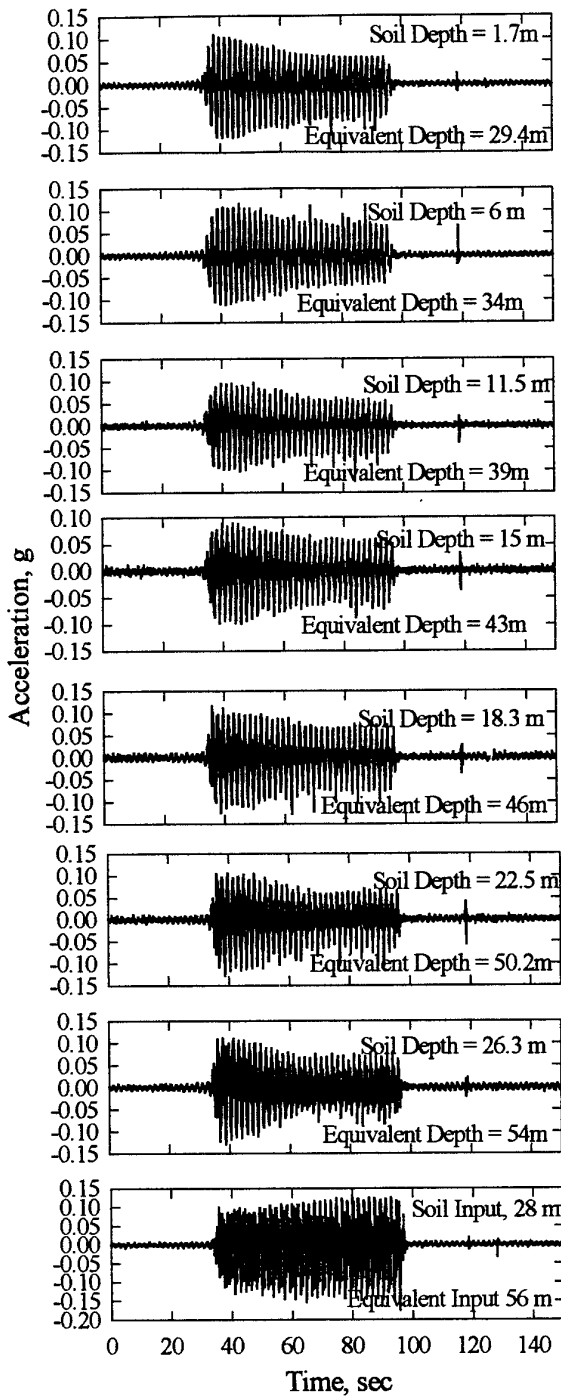


Model 5a

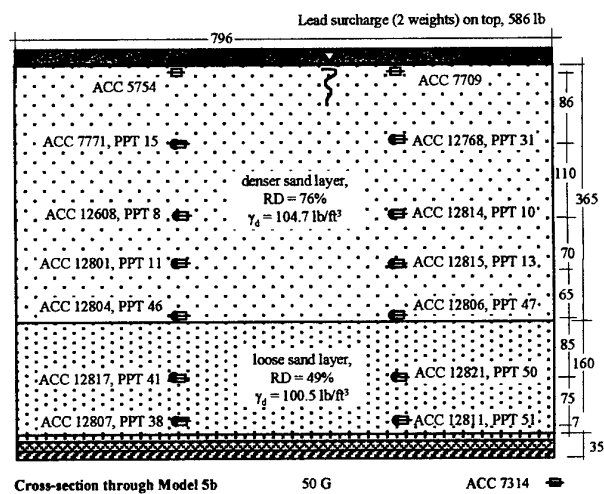


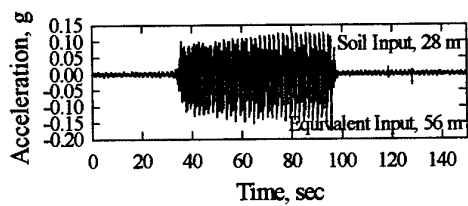
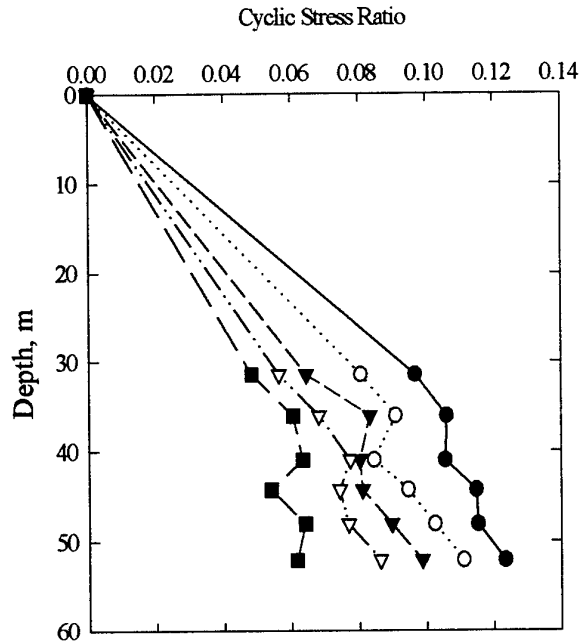
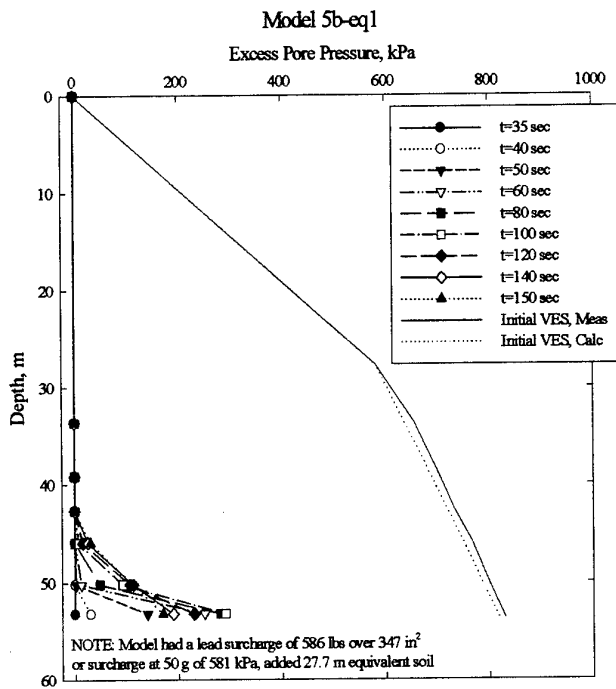


Model 5a Stress and strain isochrones

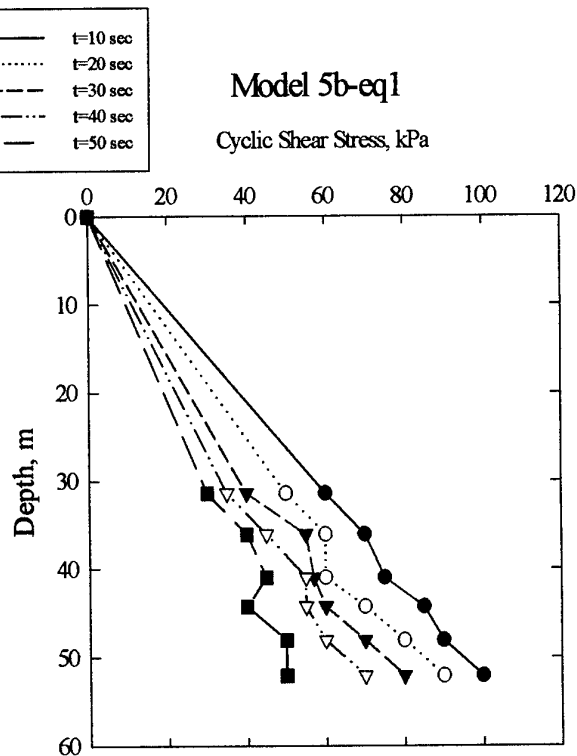
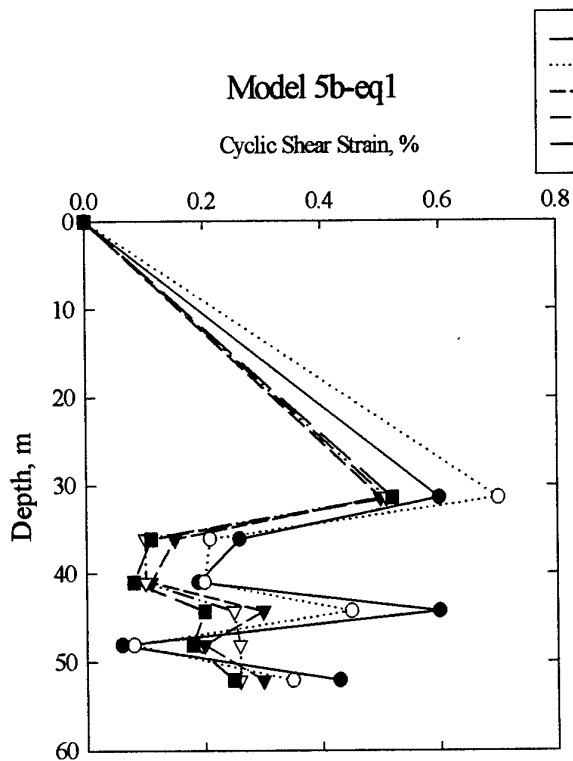


Model 5b





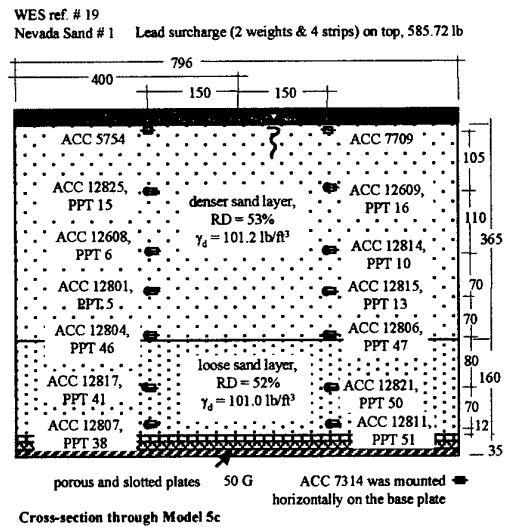
$f = 0.6 \text{ Hz}$
 $a_{\text{max}} = 0.12 \text{ g}$

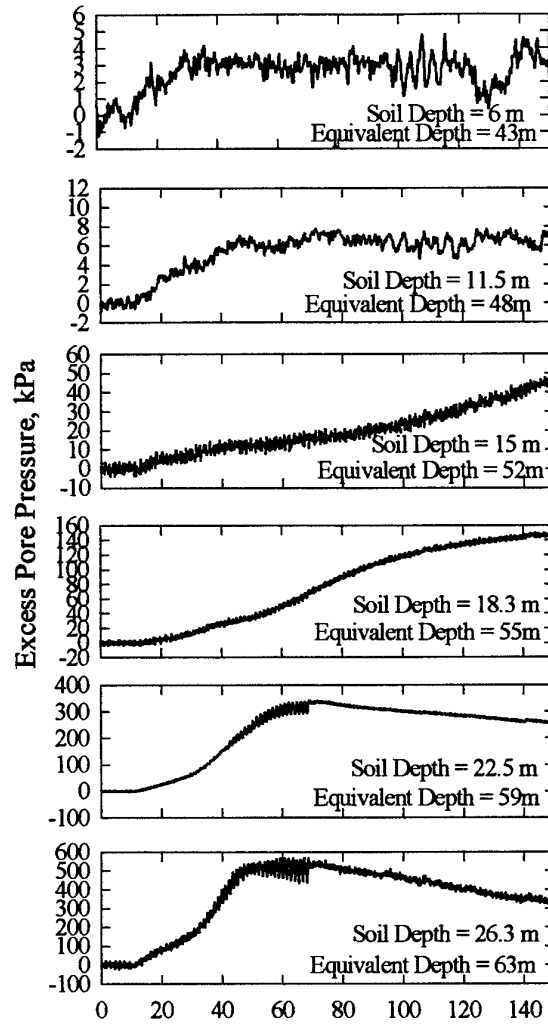
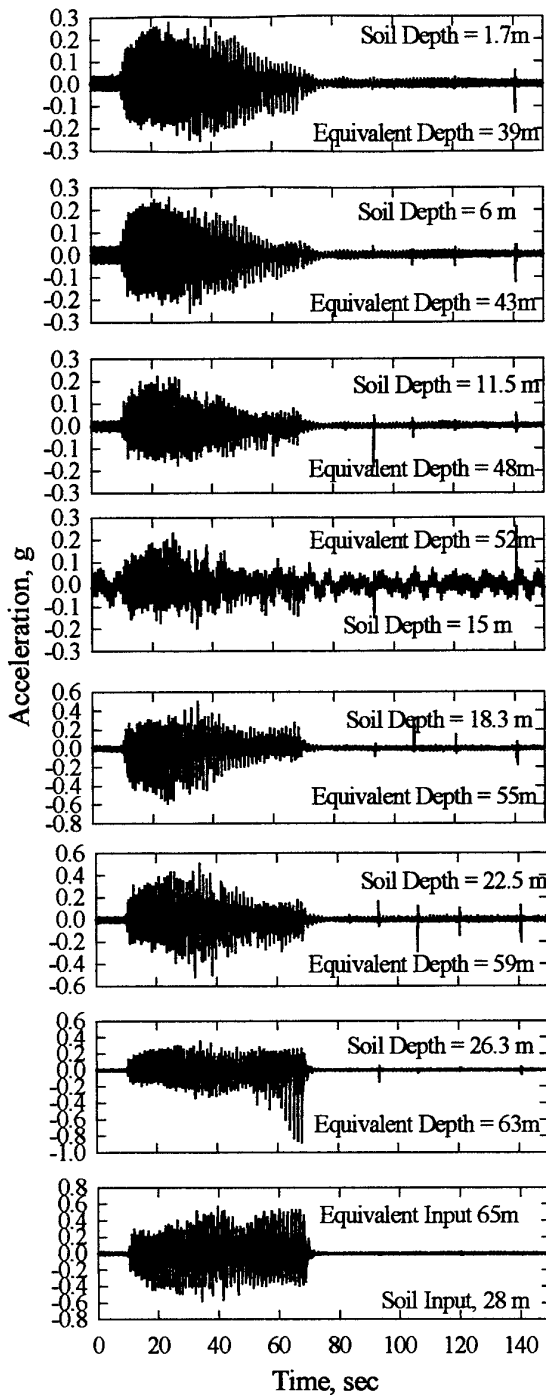


Model 5b Stress and strain isochrones

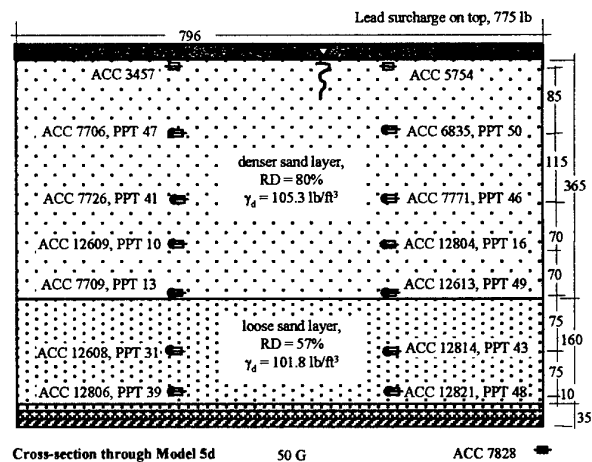
This test generated no useable data, Eq1 and 2 were particularly poor, Eq3 may have produced some information.

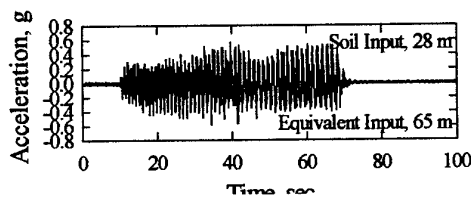
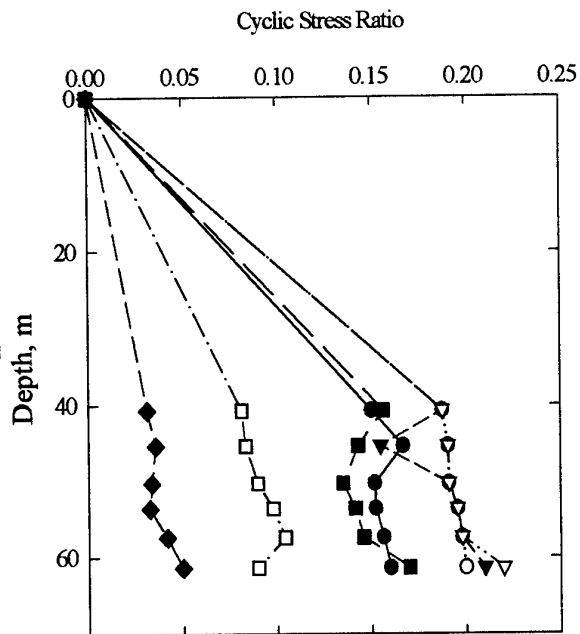
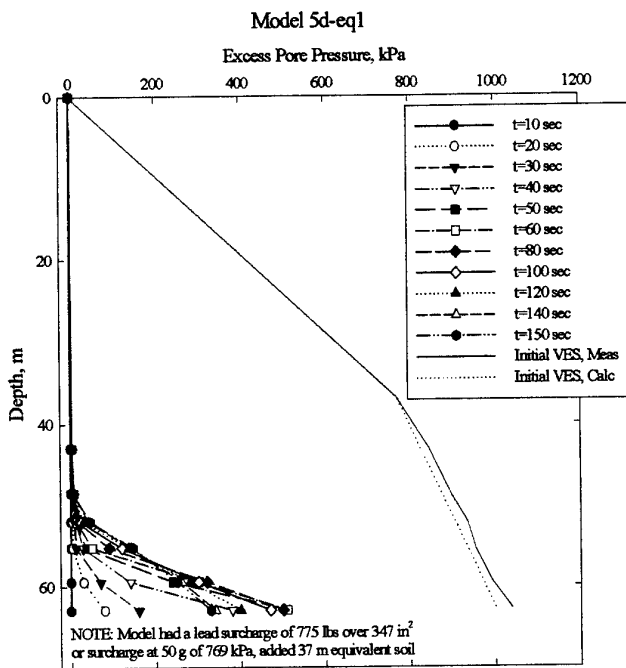
Model 5c



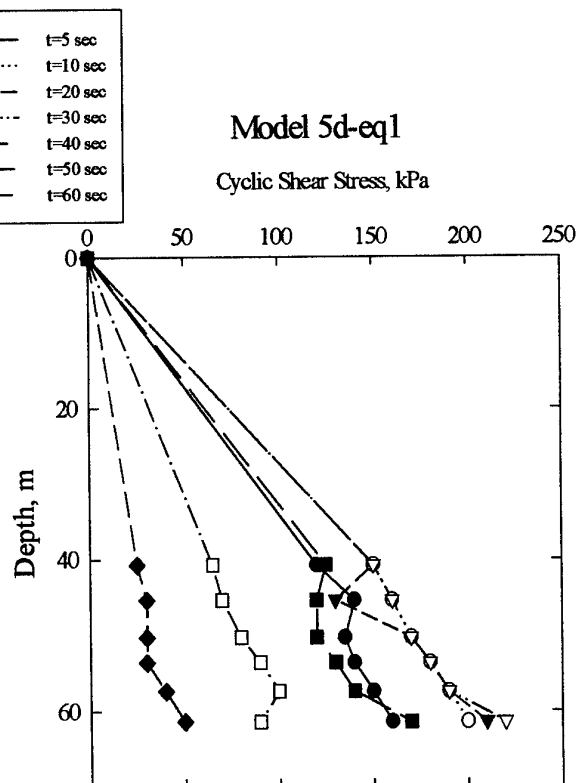
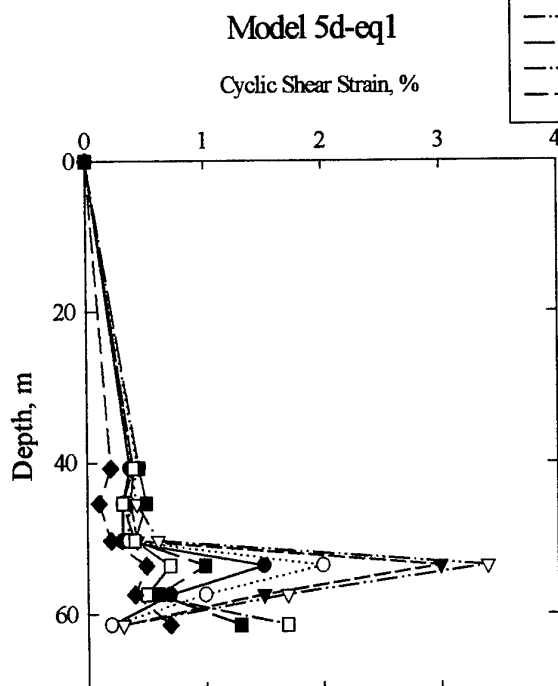


Model 5d

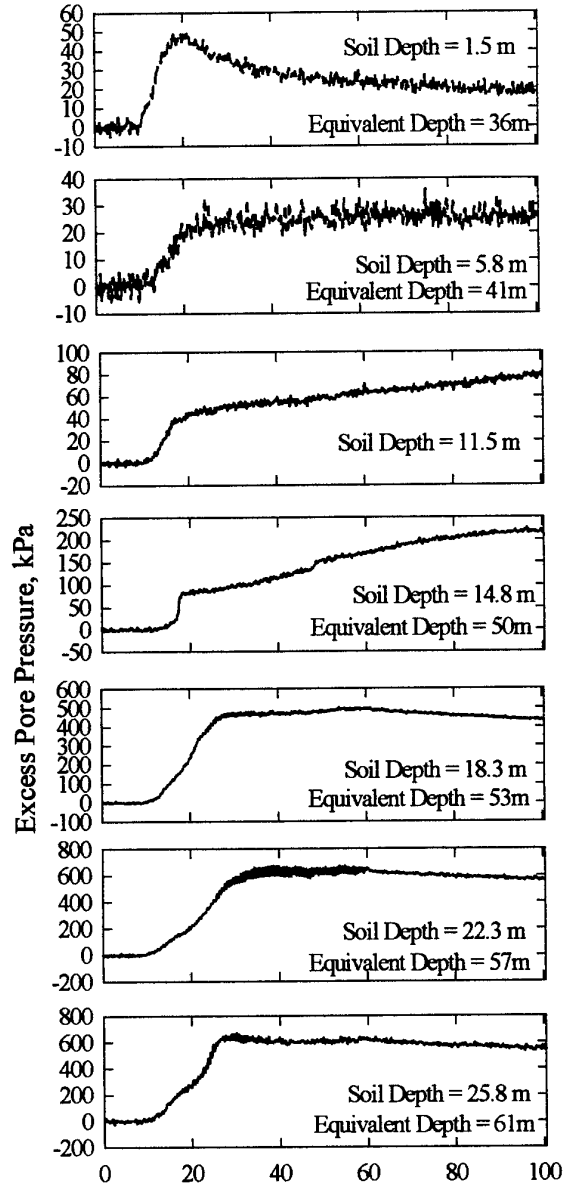
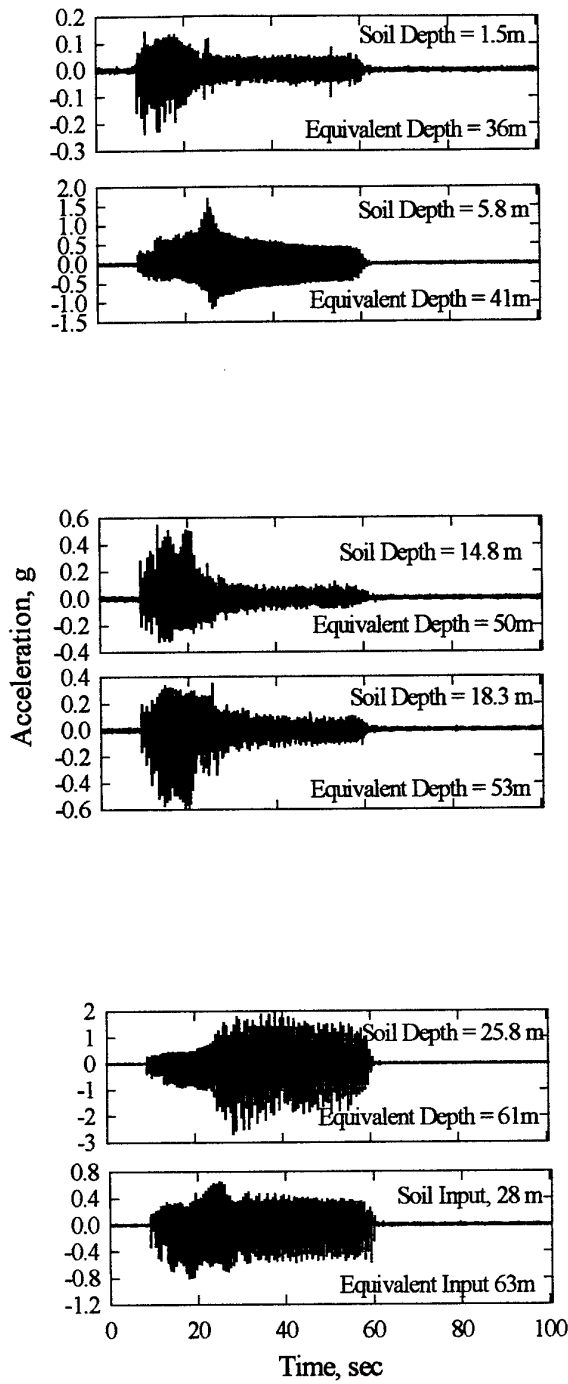




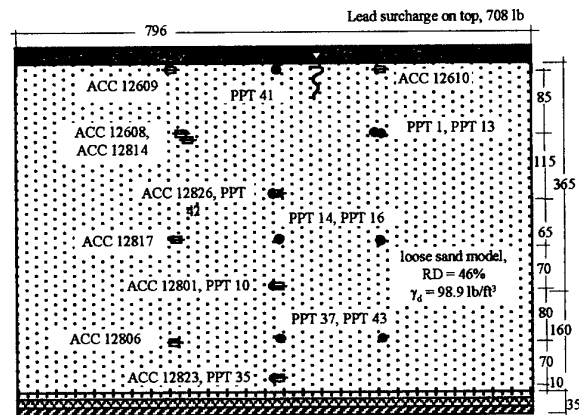
$f = 1.6 \text{ Hz}$
 $a_{\text{max}} = 0.5 \text{ g}$



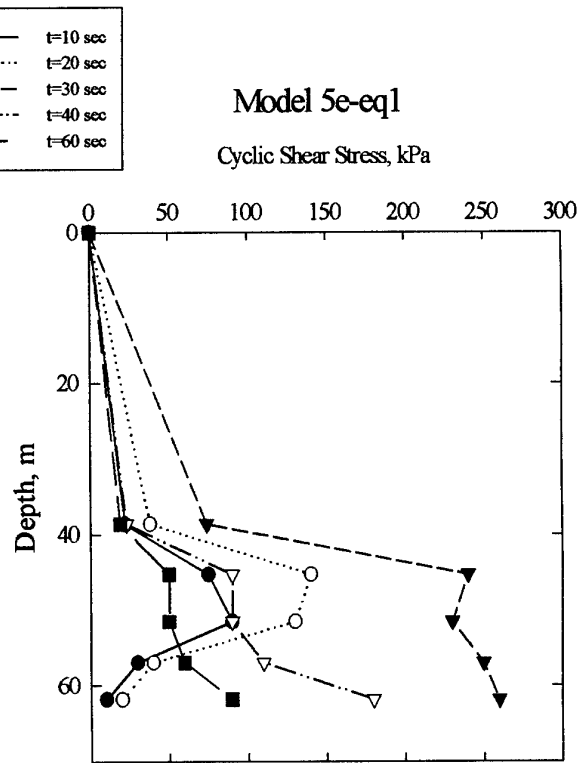
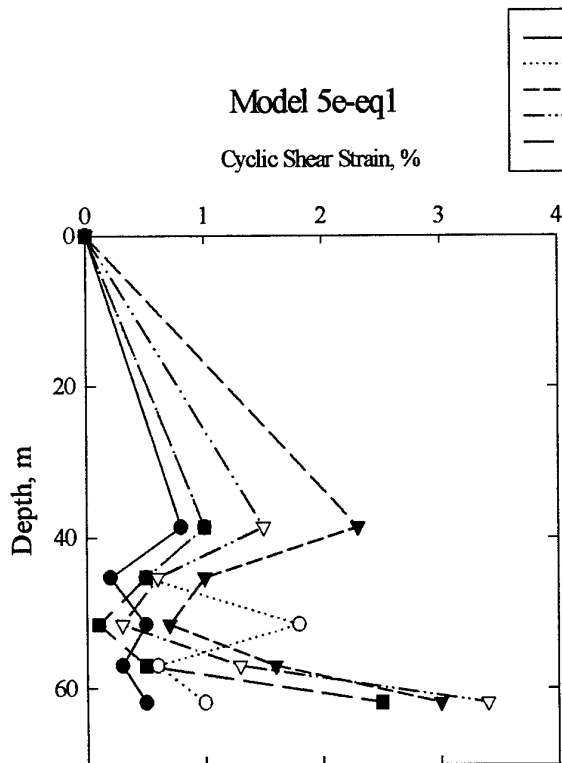
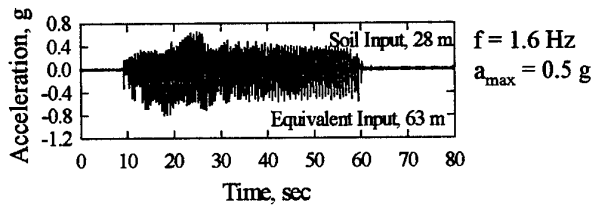
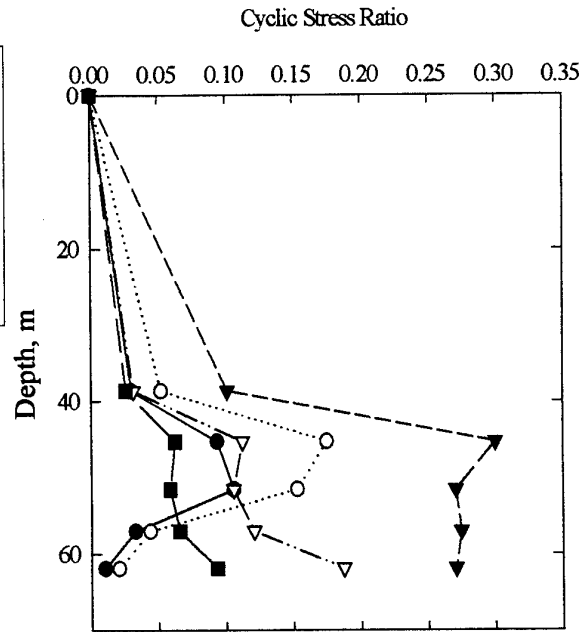
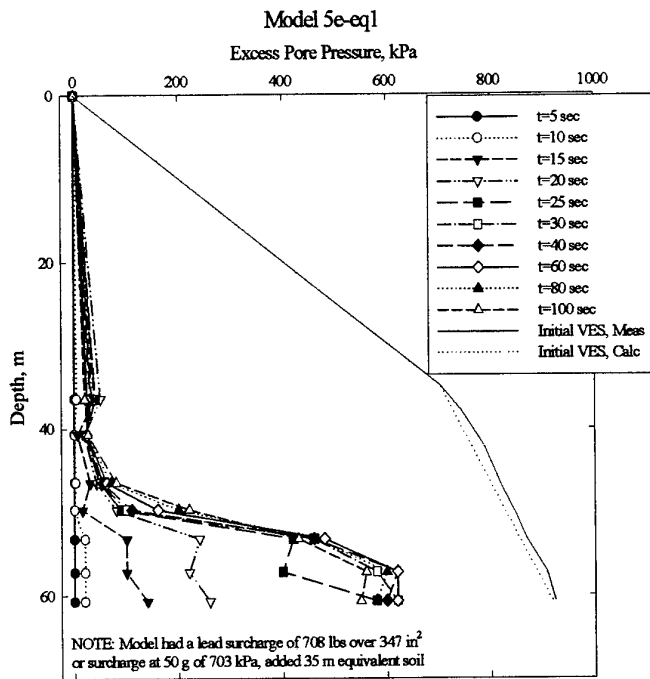
Model 5d Stress and strain isochrones



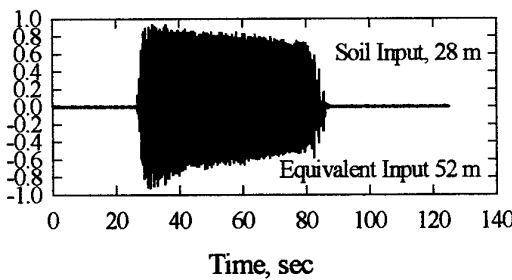
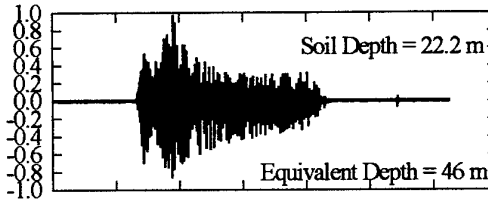
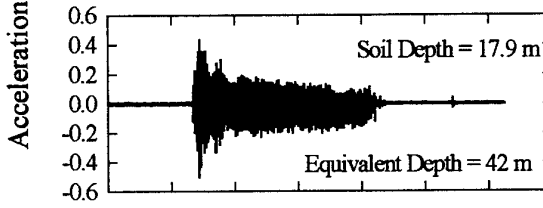
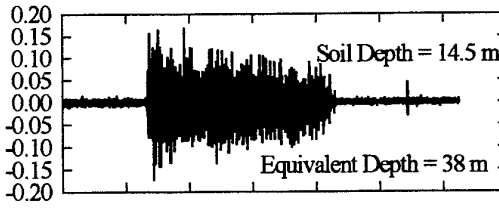
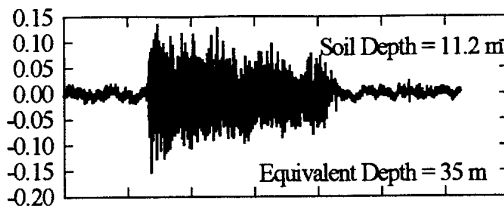
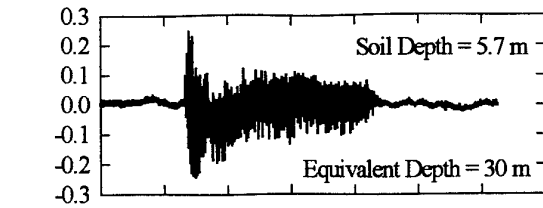
Model 5e



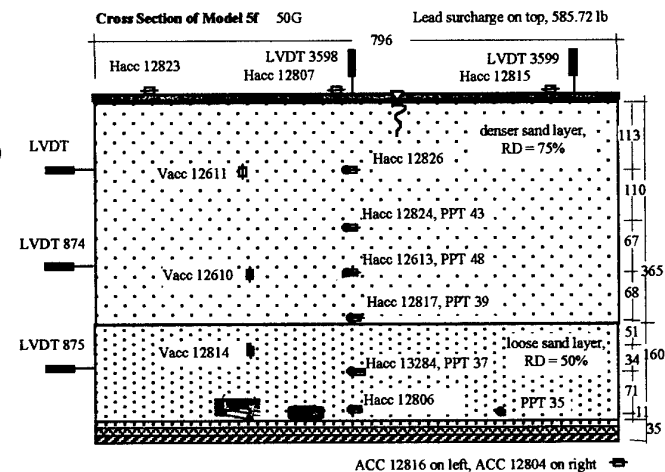
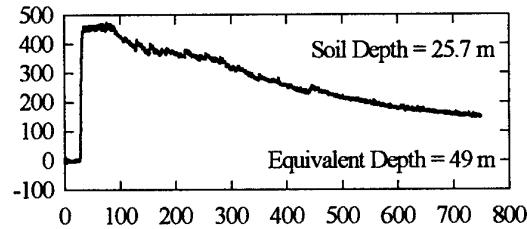
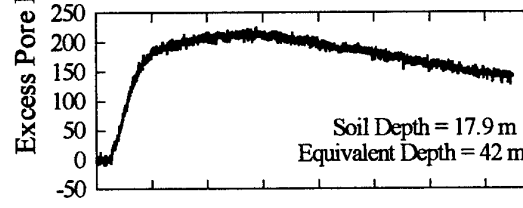
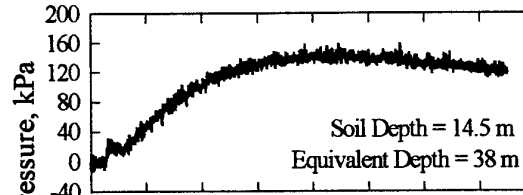
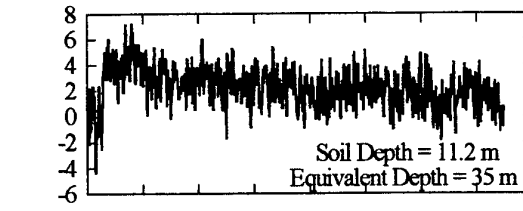
Cross-section through Model 5e 50 G ACC 12821 left, ACC 12807 right

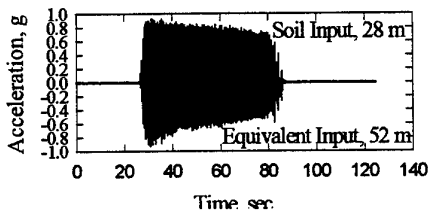
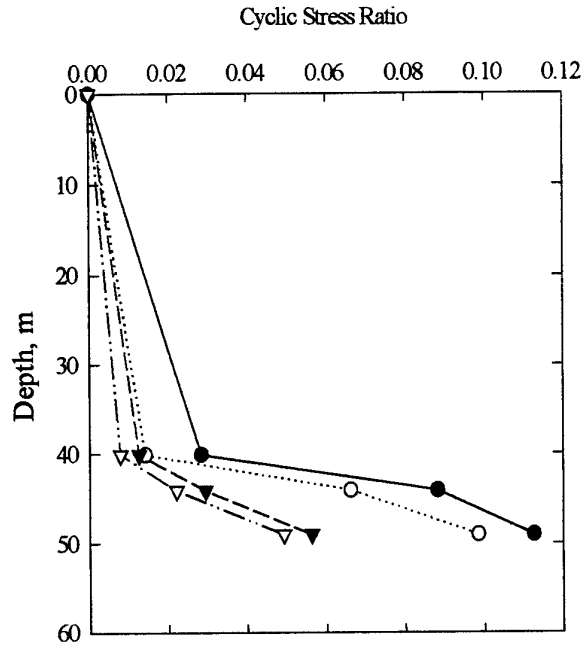
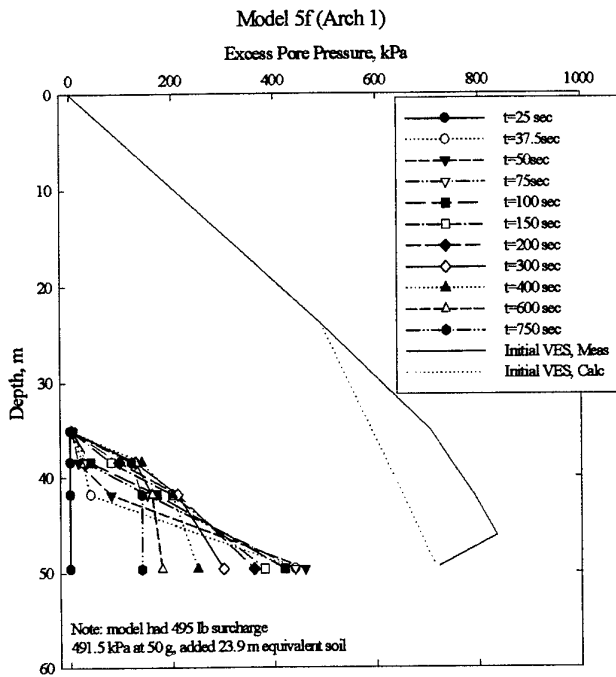


Model 5e Stress and strain isochrones



Model 5f

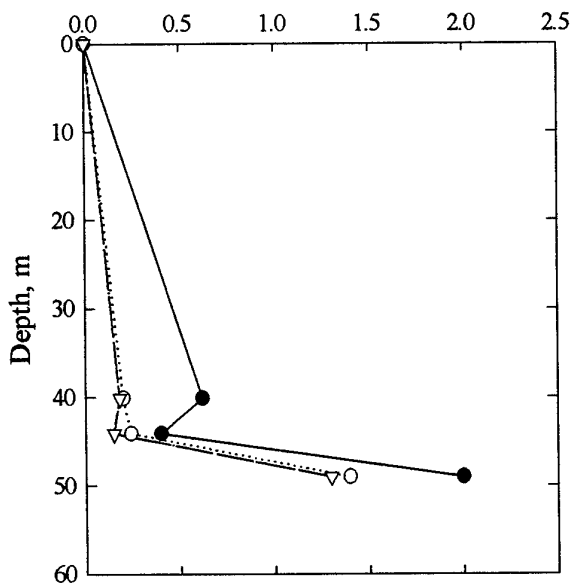




$f = 1.6 \text{ Hz}$
 $a_{\text{max}} = 0.8 \text{ g}$

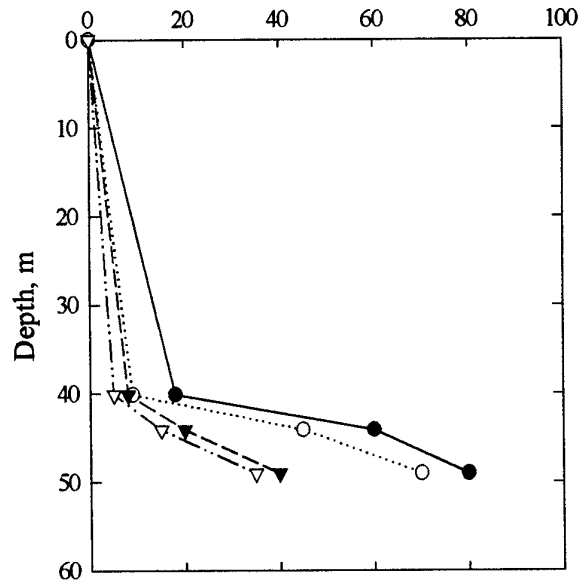
Model 5f-eq1

Cyclic Shear Strain, %

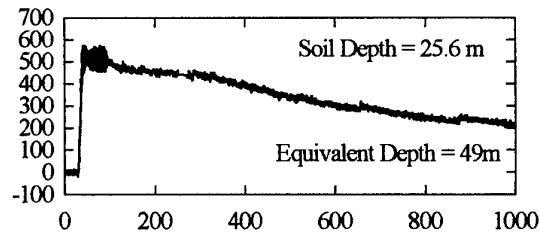
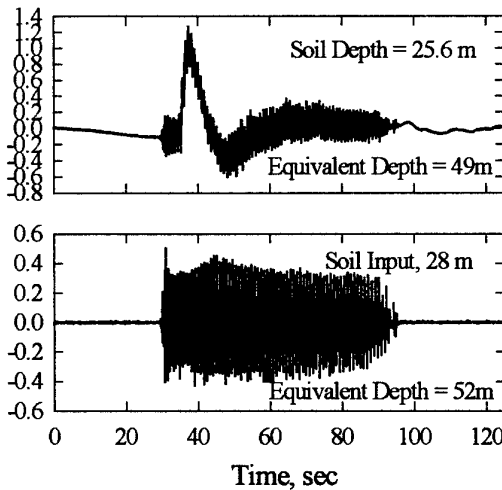
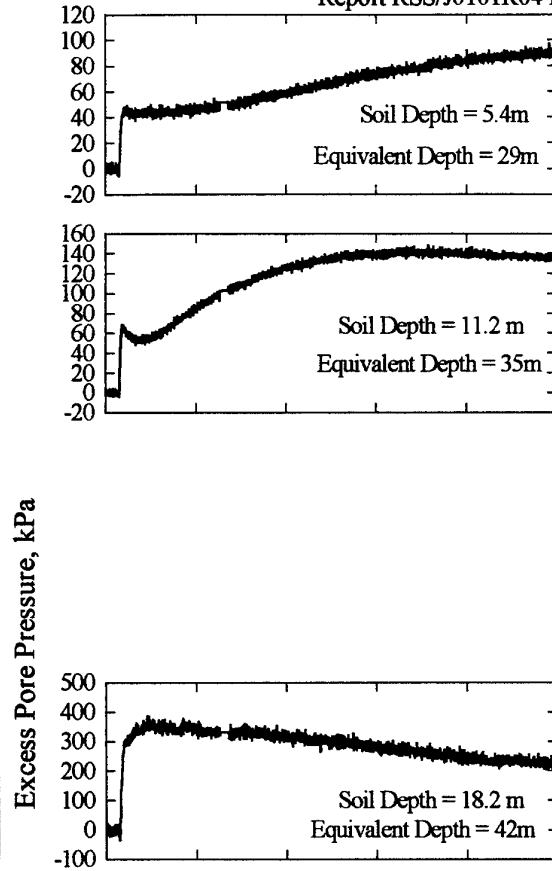
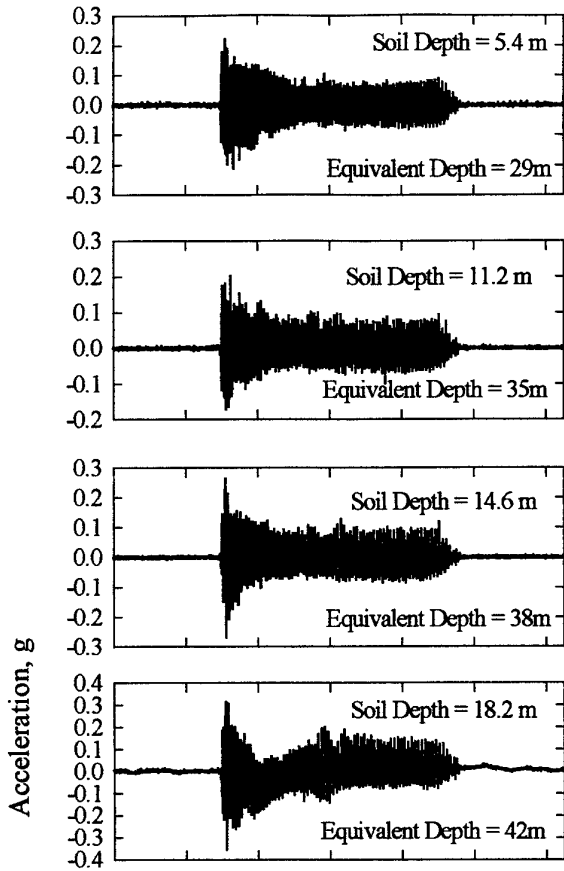


Model 5f-eq1

Cyclic Shear Stress, kPa

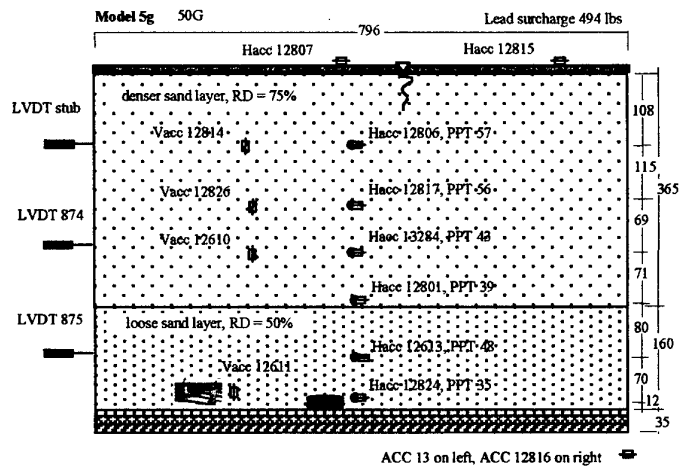


Model 5f Stress and strain isochrones

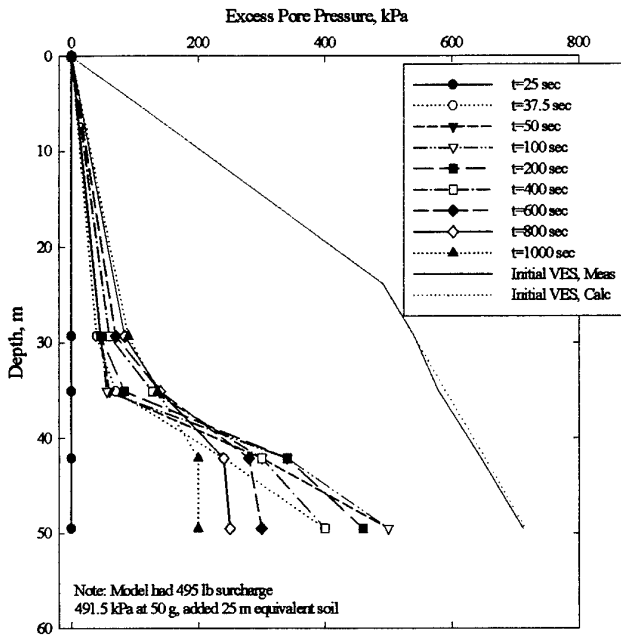


Model 5g

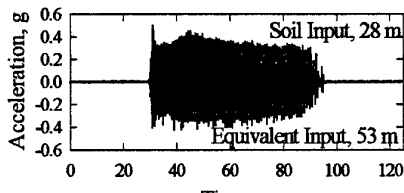
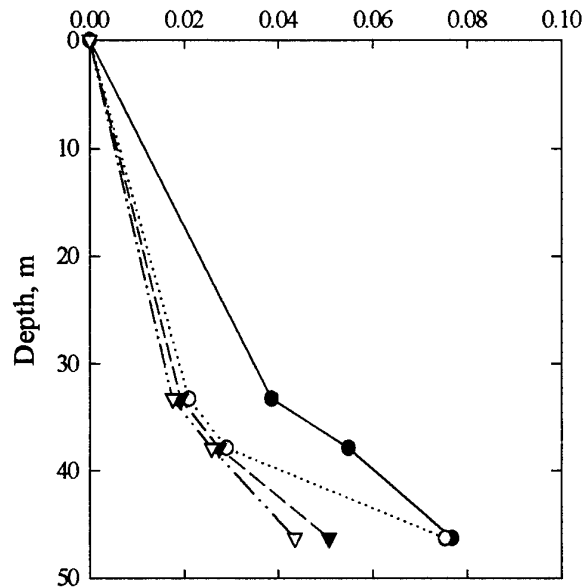
B-60



Model 5g (Archtest 2b, with weight)



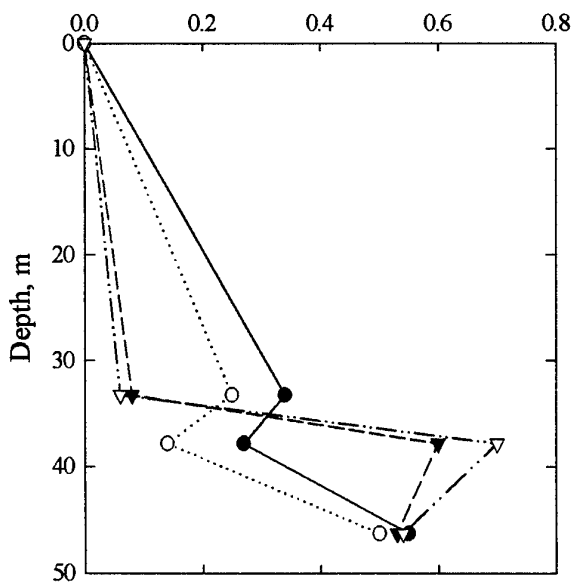
Cyclic Stress Ratio



$f = 1.2 \text{ Hz}$
 $a_{\text{max}} = 0.4 \text{ g}$

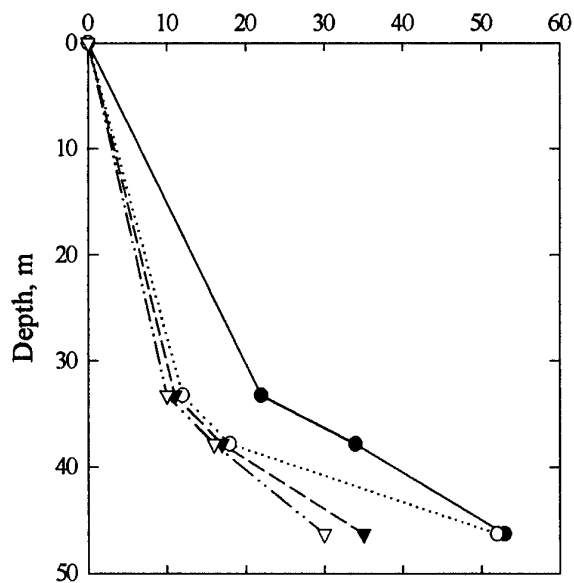
Model 5g-eq1

Cyclic Shear Strain, %

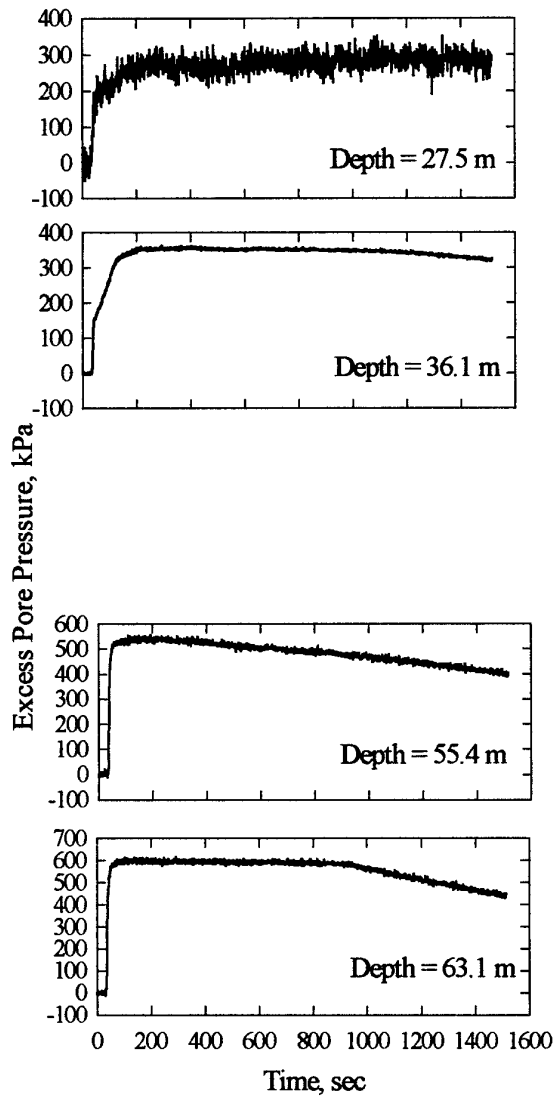
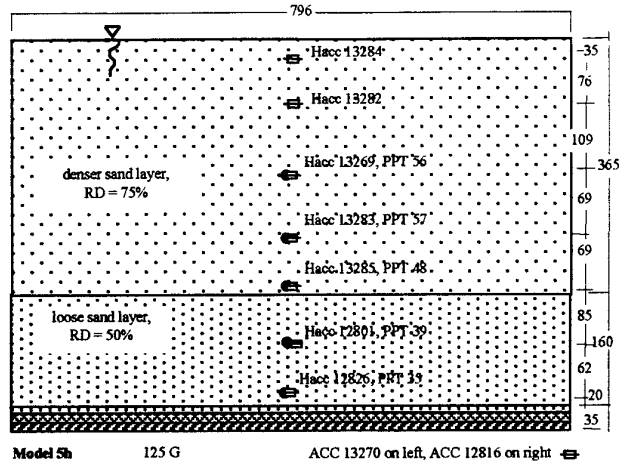
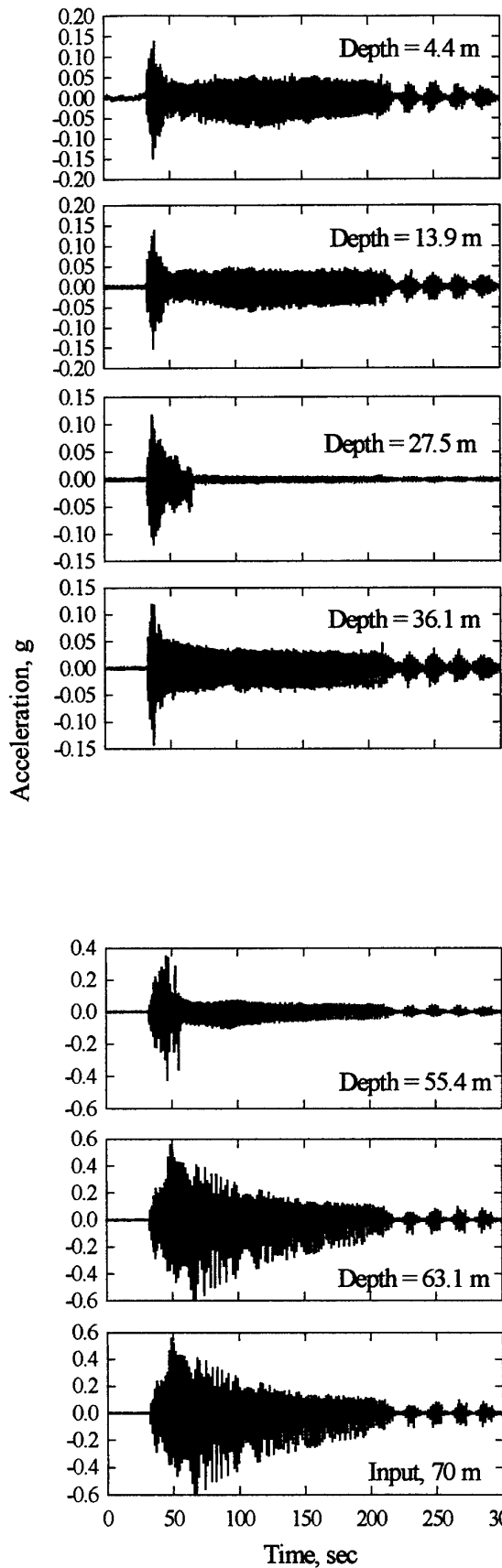


Model 5g-eq1

Cyclic Shear Stress, kPa

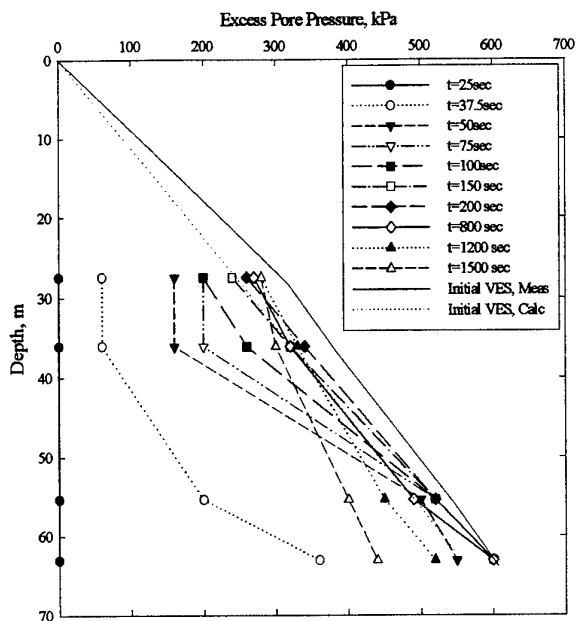


Model 5g Stress and strain isochrones

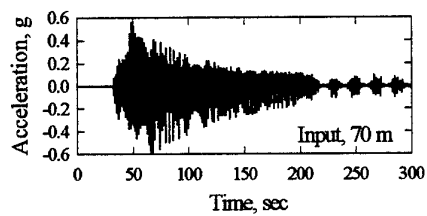
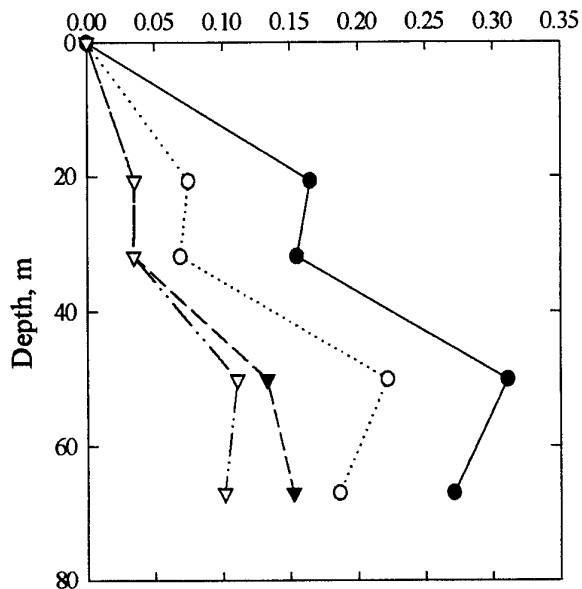


Model 5h

Model 5h (No Weight 125g)

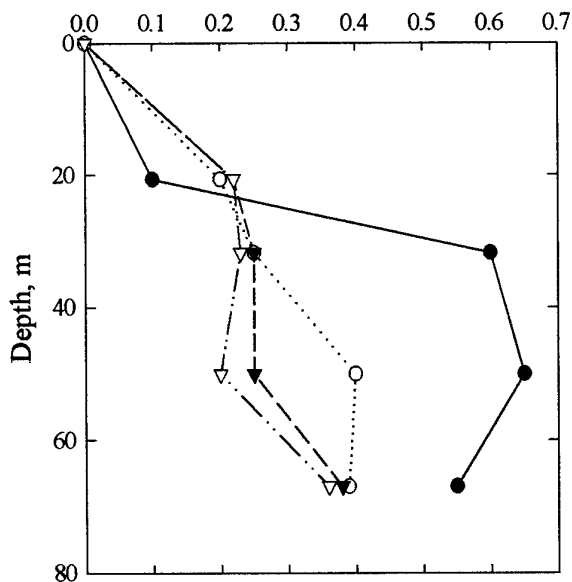


Cyclic Stress Ratio



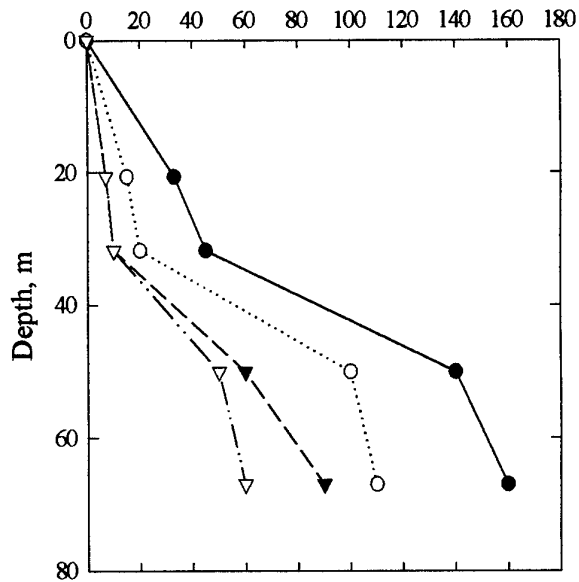
Model 5h-eq1

Cyclic Shear Strain, %

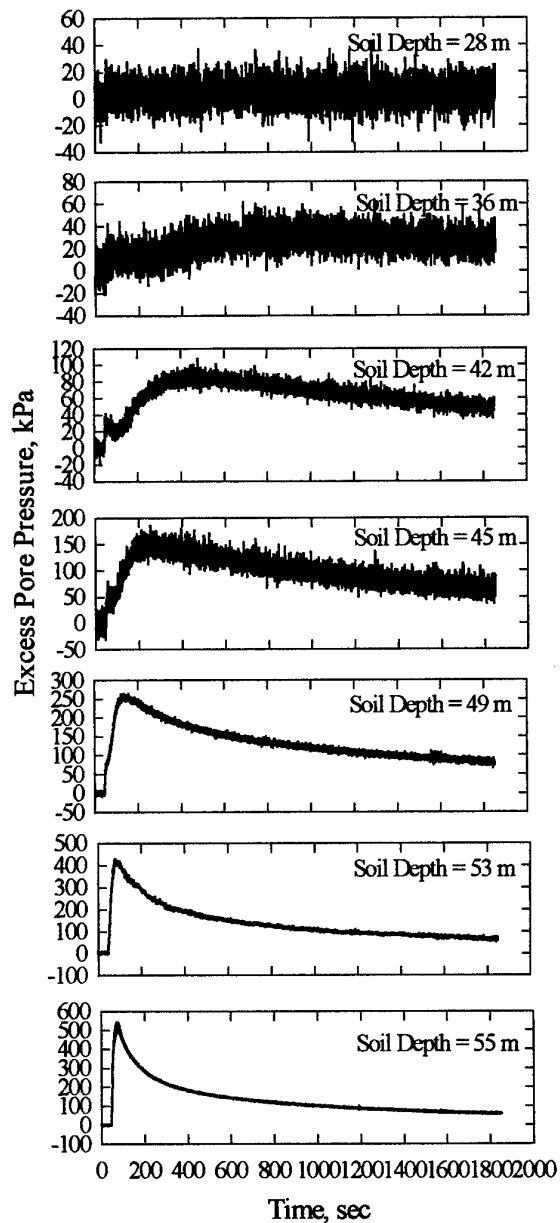
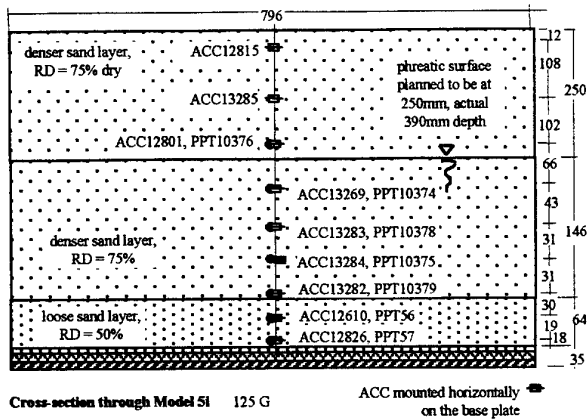
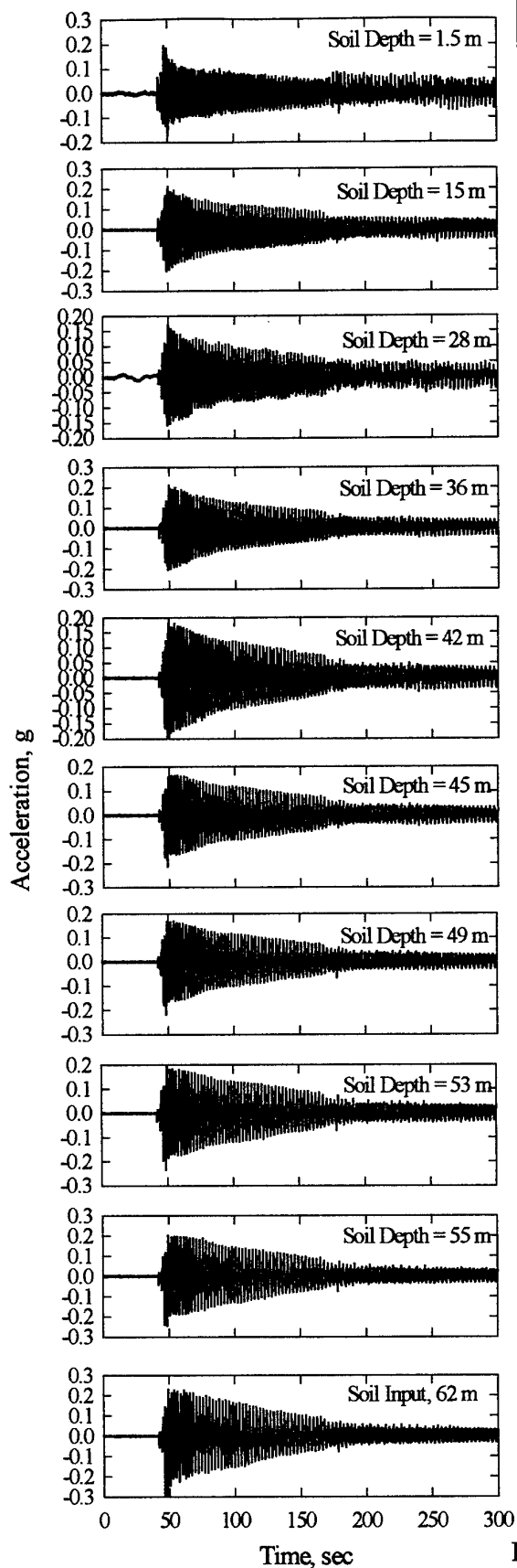


Model 5h-eq1

Cyclic Shear Stress, kPa

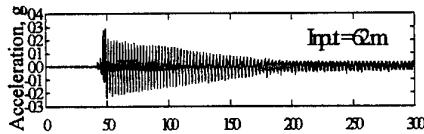
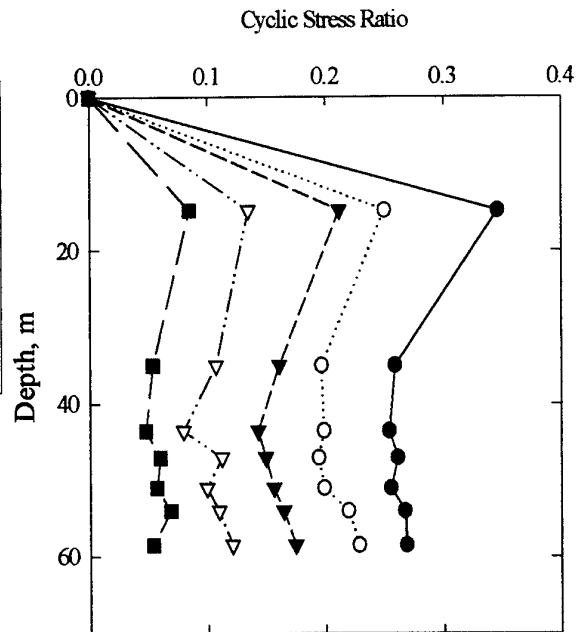
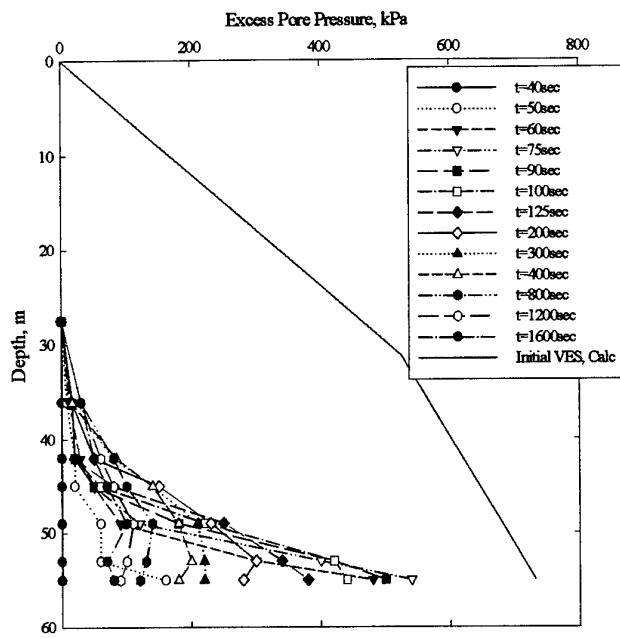


Model 5h Stress and strain isochrones



Model 5i

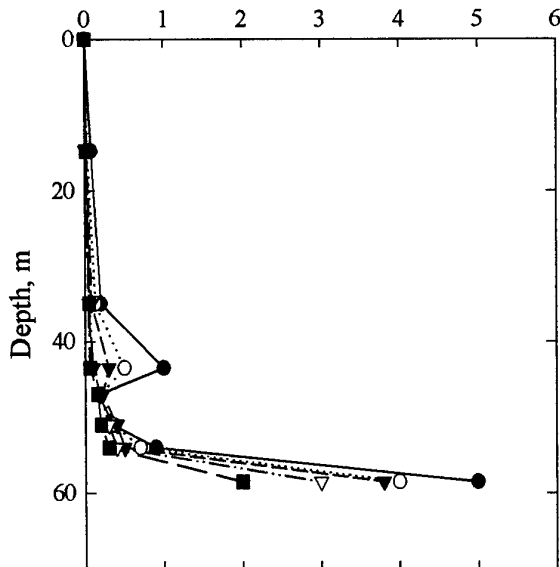
Model 5i (Dry Surcharge 125g)



$f = 0.43 \text{ Hz}$
 $a_{\text{max}} = 0.22 \text{ g}$

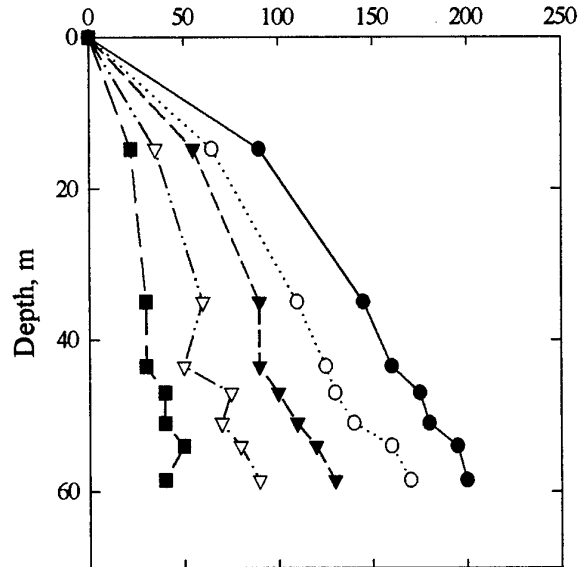
Model 5i-eq1

Cyclic Shear Strain, %



Model 5i-eq1

Cyclic Shear Stress, kPa



Model 5i Stress and strain isochrones