SEISMIC RESPONSE OF LEVEL GROUND SUBJECTED TO EXTREME SHAKING

by

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ABSTRACT

Prediction of seismic site responses has been one of the most important tasks in geotechnical earthquake engineering. Since Kanai used the multiple wave reflection theory to compute horizontal ground movements against seismic shaking, a number of researchers have extended the basic concept proposed by Kanai. Performance of seismic site response methods, however, has always invited open questions for problems involving extreme seismic shaking and large deformation of soils due, for example, to liquefaction and lateral spreading. A new numerical method SRANG3D (Site Response Analysis of Non-linear Ground in 3 Dimensions) has been developed to improve our prediction capabilities for seismic site responses. SRANG3D computes seismic site responses that involve vertical propagation of two horizontally polarized S waves and one P wave. The most distinct feature of SRANG3D is that the stress-strain relationships of soil can be represented by a combination of various elasto-plastic constitutive soil models and discrete element models. This paper introduces the new site-response analysis method SRANG3D and the paper highlights results obtained from this new method. Our study demonstrated that SRANG3D yields improved predictions of the large-scale experimental data than currently available site-response analysis methods.

KEY WORDS: Site Responses
Earthquakes
Numerical Simulations

1. INTRODUCTION

Historically major earthquakes brought devastating damage to civil engineering structures, and prediction of seismic ground shaking has been one of the most important tasks in earthquake engineering. Since Kanai (1966) used the multiple wave reflection theory to compute horizontal ground movements against seismic shaking, a number

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of research studies have extended the basic approach adopted by Kanai. The one-dimensional site response method SHAKE (Schnabel et al. 1972), based on the equivalent linear method to incorporate non-linear stress-strain effects, has been the most widely accepted one in practice. Also, the site response methods that are based on effective stress approaches and various types of constitutive soil models are becoming increasingly popular. Performance of these one-dimensional seismic site response methods, however, has always invited open questions for situations involving extremely strong seismic shaking, significant degradation of soil stiffness and strength, and large soil deformation caused by liquefaction and lateral spreading. This is partly because the constitutive soil models used in these site response methods are not versatile enough over the wide strain range covering from 10^{-4} % up to 10 % and above.

A new numerical method SRANG3D (<u>S</u>ite <u>R</u>esponse <u>A</u>nalysis of <u>N</u>on-linear <u>G</u>round in <u>3</u> <u>D</u>imensions) has been developed to improve our prediction capabilities for seismic site responses. SRANG3D computes seismic site responses that involve vertical propagation of two horizontally polarized S waves and one P wave. One of the most distinct features of SRANG3D is that the stress-strain relationships of soil can be represented by a combination of various elasto-plastic constitutive soil models and discrete element models. This feature is expected to yield improved prediction capabilities for problems involving large soil deformation and liquefaction/lateral spreading under extreme seismic shaking.

This paper first introduces the new site-response analysis method SRANG3D. The paper then highlights the stress-strain responses obtained from the DEM models in SRANG3D and the seismic soil responses obtained from SRANG3D. This study demonstrated that the proposed new methods yield improved predictions of seismic soil responses than currently available methods.

2. NEW SITE-RESPONSE METHOD

This section highlights the key features of the new site-response analysis method SRANG3D. SRANG3D originates from its one-dimensional version SRANG (Kagawa and Kraft 1981; Kagawa 1996), but SRANG3D has the following new distinct features (Tao 2000). Firstly, seismic excitation can consist of two horizontally polarized shear waves and primary waves that propagate in the vertical direction and, secondly, discrete element models can be used to represent the stress-strain relationships of soil.

The key motivation for this study was to realize a numerical simulation tool that can automatically reproduce non-linear stress-strain responses of sandy soils under complex multi-directional seismic loading conditions more realistically than currently available constitutive models. This original version of SRANG3D incorporates the DEM models readily available today. More advanced DEM models, of course, may be easily adopted into the program when such models become available.

Figure 1 schematically shows the numerical model employed by SRANG3D. Foundation soils are assumed horizontally layered. Each soil layer interface has three degrees of freedom; i.e., two horizontal and one vertical degree of freedom. Rotational (i.e., torsional and rocking) degrees of freedom could also be included in the model, but no information is available about the contribution of such motions to soil-structure responses. Therefore, only translational degrees of freedom exist in SRANG3D. Seismic shaking is applied to the base of the soil column in the form of acceleration time histories. Similar one-dimensional column systems have been adopted for seismic site-response analyses by various researchers (Ghaboussi and Dickmen 1979; Borja et al. 1999).

In SRANG3D, DEM models involving assemblies of spherical and/or ellipsoidal elastic particles can be used to reproduce the stress-strain relationships of soil layers. Physical properties of the particle assemblies (i.e., number of particles, particle shapes and properties, porosity, and etc.) can be different from one soil layer to another. Some soil layers, however, may be modeled as continuum media with specified constitutive soil models such as cyclic non-linear stress-strain models and plasticity-based constitutive soil models. The equations of motion of the entire soil layers are numerically integrated using the Newmark's β method. SRANG3D has a provision for performing equilibrium iterations to minimize numerical integration errors when suitable soil models are used.

SRANG3D includes a standard consolidation model to evaluate the effects of dissipation and redistribution of excess pore-water pressures. Therefore, the program can assess liquefaction potential of and its effects on deformation of level ground.

The base rock for the soil layer system can be either perfectly rigid or compliant. When the base rock is rigid, seismic input motions are specified at the base rock and no wave energy is transmitted down to the base rock. When the compliant base rock option is used, however, the base rock is considered to be an elastic half space. Therefore, input seismic motions will be assumed as incident seismic motions to the soil layers. Reflected waves from the soil layers are absorbed by the compliant base rock. The option for a compliant base rock is useful to eliminate the resonance phenomena induced by imposing an artificial rigid base in a soil layer system.

The program SRANG3D was developed using the FORTRAN-90 language. The program runs on CRAY supercomputers and UNIX workstations by taking advantage of parallel processing options. The program also runs conveniently on fast PC's. Incidentally, the results presented in this paper were generated on PC's.

3. DEM STRESS-STRAIN MODEL

(1) Overview

To provide the stress-strain relationships needed by SRANG3D, we developed new computer programs GEN3D and DemSS. GEN3D prepares soil specimens (i.e., assemblies of particles) and consolidates the specimens to a set of desired stresses. DemSS provides the stress-strain relationships of the specimen for a given loading condition. These programs are DEM codes with the implementation of spherical and/or ellipsoidal elastic particles in a three-dimensional periodic space. The programs maintain most of the key concepts found in the original programs ELLIPSE3 (Ng 1994) and TRUBAL (Strack and Cundall 1979). These key concepts include periodic space to remove boundary effects, grid marking to identify particle neighbors, and linked list data structure for storing particle neighbors and contact detection and information. In the DEM, equilibrium contact forces and displacements of a stressed assembly of particles are found through a series of calculations tracing the movements of individual particles. An explicit integration scheme is acted on the Newton's second law to obtain the translational and rotational movements of particles. These movements are the results of propagation through the medium of the disturbances imposed by specified loading.

Three major tasks are executed in GEN3D. Firstly, assembly (or specimen) of spherical or ellipsoidal elastic particles is formed according to a user-specified number of required particles with desired particle characteristics. The specimen is then compressed by reducing the grid sizes of the periodic space. Thirdly, the specimen is consolidated to the desired initial stress condition and density. Isotropic and an-isotropic consolidation can of course be achieved. Also, the process of normal or over-consolidation can be simulated. Results from GEN3D (i.e., consolidated specimens) are stored in a binary form as input to programs DemSS and SRANG3D.

When using the program DemSS, two input data files are needed, one file containing the DEM soil specimens generated by GEN3D and another file containing information about loading (i.e., time variations of strains or stresses). DemSS can apply any combinations of stress- and strain-controlled applications of six components of stresses and/or strains to a soil specimen. DemSS also can handle extremely low or high confining pressures. Experiments involving such conditions may not be feasible in physical laboratory tests. Therefore, virtually any advanced geotechnical laboratory shear tests (e.g., monotonic, cyclic drained, cyclic undrained tests, and etc.) can be simulated by DemSS.

The entire process of constructing a specimen and testing resembles physical sample preparation and testing in a geotechnical laboratory. A series of “digital specimens” were generated to build a specimen database. The database may be readily used to make a seismic site response analysis without knowing the details of the discrete element method and techniques for specimen preparation.

The stress-strain responses of the soil specimens obtained by DemSS are highlighted below.

(2) Stress-Strain Responses under Drained Conditions

Numerical experiments were performed employing a strain-controlled cyclic simple shear condition with vertical stresses kept constant and no lateral normal strains. The void ratio of the specimens ranged from 0.57 to 0.74 and the vertical stress ranged from 0.003 to 79.0 kgf/cm^2. Figure 2 summarizes the small-strain shear moduli (G_{max}) obtained from the drained cyclic simple shear tests. The small-strain shear moduli are normalized by f(e):

$$f(e) = \frac{(2.17 - e)^2}{1 + e} \quad (1)$$

where e is void ratio. These results are in good agreement with laboratory static and cyclic test results for much smaller range of consolidation stresses (e.g., Seed and Idriss 1970; Hardin and Drnevich 1972; Iwasaki et al. 1976).

Figure 3 summarizes the shear modulus reduction curves and hysteretic damping curves obtained from DemSS. The general features of these curves agree well with those obtained from laboratory element tests on sandy soils.

In addition to the “standard” one-directional cyclic simple shear tests, two-directional cyclic simple shear tests were numerically simulated for the two conditions shown in Fig. 4. The first situation is of importance when considering seismic site responses involving propagation of two horizontally polarized shear waves, and the second type of loading needs to be considered for ground motions involving rotational components. Our study indicates that application of the second cyclic shear stress tends to increase the hysteretic damping of the specimen while the modulus reduction curves are not very much affected by the second shear stress.

(3) Stress-Strain Responses under Undrained Conditions

Undrained cyclic stress-strain responses were simulated with the volume of the periodic space kept constant. The change in the mean total normal stresses on the soil specimen represented the excess pore-water pressure. Figures 5 and 6 show typical stress-strain and excess pore-water pressure responses computed by DemSS for a loose and a dense specimen.

Figure 5 shows the results for the dense case. The void ratio and the vertical consolidation stress of the dense specimen were 0.597 and 15.79 kgf/cm^2. Due to strong dilatancy tendency of the dense specimen, negative excess pore-water pressures developed when the specimen was loaded with cyclic shear strain amplitude of 1.0 %.

Figure 6 shows results for the loose specimen. Due to the volume decrease tendency of the loose specimen, positive excess pore-water pressures developed. When the specimen was loaded with the shear strain amplitude of 0.1 %, excess pore-water pressure accumulated gradually with increase in number of cycles of loading. The specimen, however, liquefied during the first load cycle when the shear strain amplitude was 1.0 %. These observations are commonly seen in laboratory undrained cyclic tests.

4. EXAMPLE ANALYSES

A series of numerical simulations have been made using SRANG3D to confirm the performance of the new method and to study seismic site responses affected by the soil non-linearity under strong shaking. A hypothetical soil site in Fig. 7 was used for this analysis. The site consists of the fill layer underlain by four DEM layers that are supported by stiff cohesive layers. Cyclic non-linear models were used to represent the stress-strain relationships of the fill and stiff cohesive layers. The first example involves four DEM layers prepared at a dense dry condition and the second example involves four DEM layers prepared at a loose saturated condition. Each DEM model had approximately 400 particles and it was K_o consolidated. The dense model had a void ratio of about 0.68 and the loose model had a void ratio of about 0.99. In both cases, the soil columns were excited at the base by a sinusoidal shaking with a frequency of 2 Hz and the peak acceleration amplitude of 200 cm/sec^2.

Figures 8 and 9 show the results for the dense dry condition of the four DEM layers. Figure 8 presents acceleration responses of the soil layers. Virtually no amplification of acceleration responses is observed due to the strong intensity of shaking applied to the base. Also, the acceleration time histories in the soil layers show strongly distorted waveforms due to non-linearity of the stress-strain relationships of the soils. These features have been commonly observed in our large-scale shaking table tests. Figure 9 shows volumetric strains in the four DEM layers. Volume of the DEM models tends to decrease in the early stage of shaking, but it generally increased towards the end of shaking due to strong dilatancy tendency of the dense DEM specimens.

Figures 10 and 11 show the results for the loose saturated DEM layers in an undrained condition. During the early stage of shaking, excess pore-water pressures quickly build up in the DEM layers. This results in dramatically reduced soil stiffness in the DEM layers and small energy transmission to upper layers. Small soil stiffness in the liquefied and nearly liquefied DEM layers gradually produces large soil strains to start mobilizing dilatancy. The sudden regains in soil stiffness due to dilatancy are responsible for sharp peaks in the acceleration time history of the DEM layer. Similar peaks have been observed in recorded acceleration time histories from the historically major earthquakes such as the Kobe earthquake. The major features of our numerical simulations agree very well with various field observations and the results from our large-scale shaking table tests (Tao et al. 1998a and 1998b).

The examples shown above were run on PC’s. Specimen preparation and consolidation by GEN3D and DemSS typically took 3 to 60 hours and the site response computations by SRANG3D involving 40,000 integration steps took approximately 100 hours on 850 MHz systems. Computation time, however, drastically reduces if a parallel processing option of supercomputers and high-end workstations is used.

5. CONCLUDING COMMENTS

A new numerical method for seismic site response analyses is proposed in this paper. The most important feature of this method is its capability of incorporating DEM models to reproduce the stress-strain responses of sandy soil layers. Many sophisticated constitutive soil models have been proposed by a number of researchers around the world to simulate the stress-strain-strength responses of sand in the last decade or two. Such soil models are based on observations of soil responses under a limited number of stress-strain loading conditions. Therefore, extrapolation of such soil models to situations involving more general stress-strain conditions is always uncomfortable. DEM modeling, on the other hand, is conceptually straightforward. The stress-strain-strength responses of an assembly of elastic particles with a given set of parameters could be computed for any type of loading conditions. The numerical methods developed in this study are stable for a very wide range of stresses and strains. Therefore, the methods are suited to problems involving large soil strains due to extremely high level of seismic shaking and liquefaction and subsequent large lateral soil movements.

However, the DEM is not fully developed at present. For example, particle shapes are limited to simple geometry such as spheres and ellipsoids; dynamic interaction between particles and pore fluid is not explicitly taken into account; and crushing and wearing of particles are not considered. Therefore, rigorous quantitative evaluation of the results from SRANG3D is rather difficult. The results of this study, however, demonstrated that the proposed new numerical methods are able to reproduce the key features of the observations in our large-scale shaking table tests and that our numerical simulations agree very well with measured responses.

6. REFERENCES

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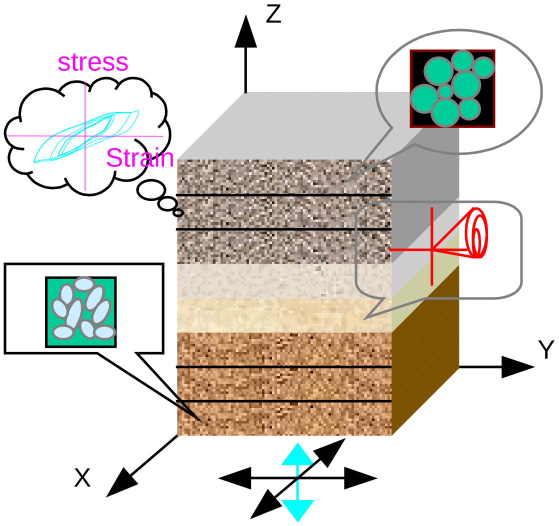


Fig. 1 Numerical Model for SRANG3D

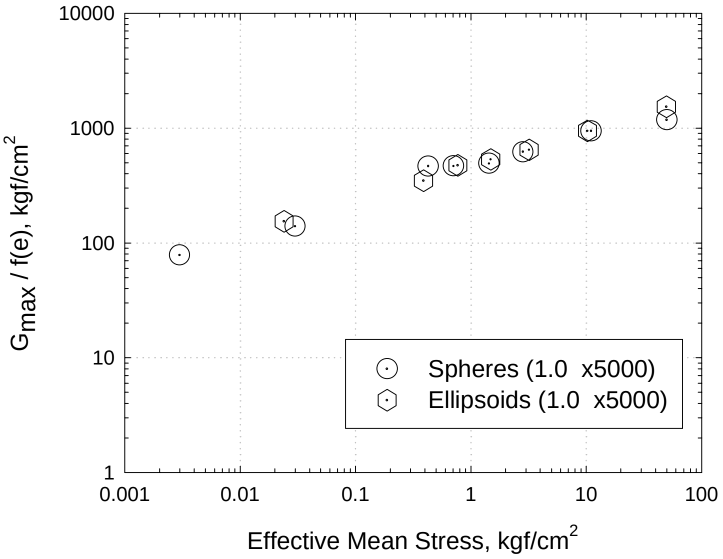


Fig. 2 Small-Strain Shear Moduli

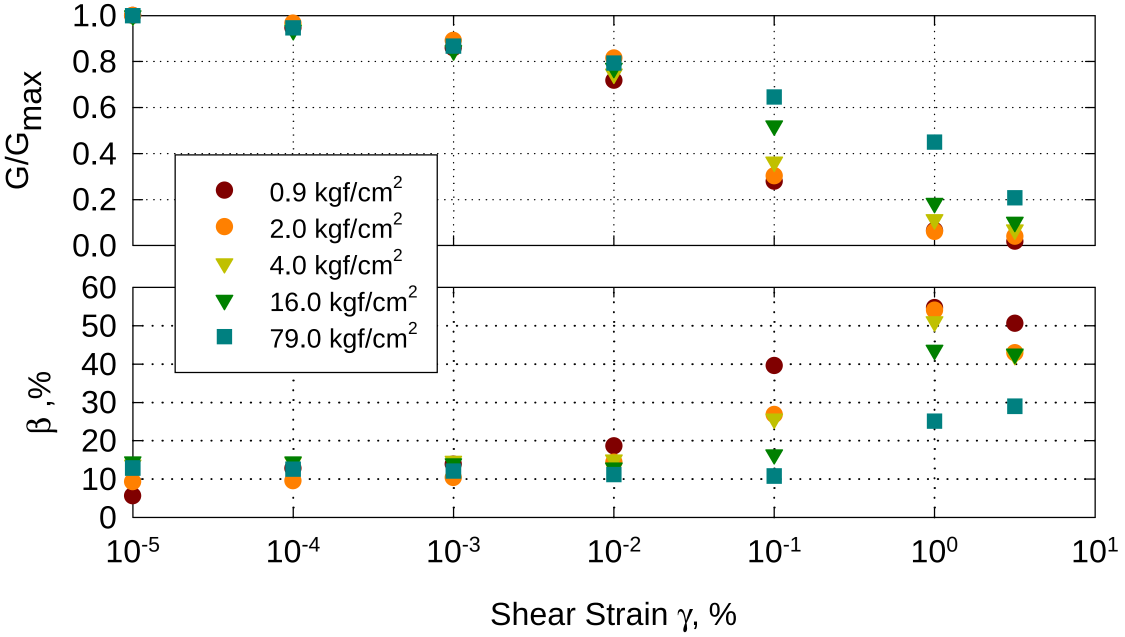
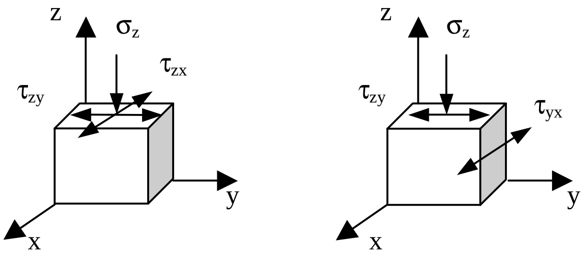


Fig. 3 Shear Modulus and Damping Curves



(a) 2-D (Circular) Simple Shear (b) 2-D Simple Shear

Fig. 4 Two-Directional Cyclic Loading

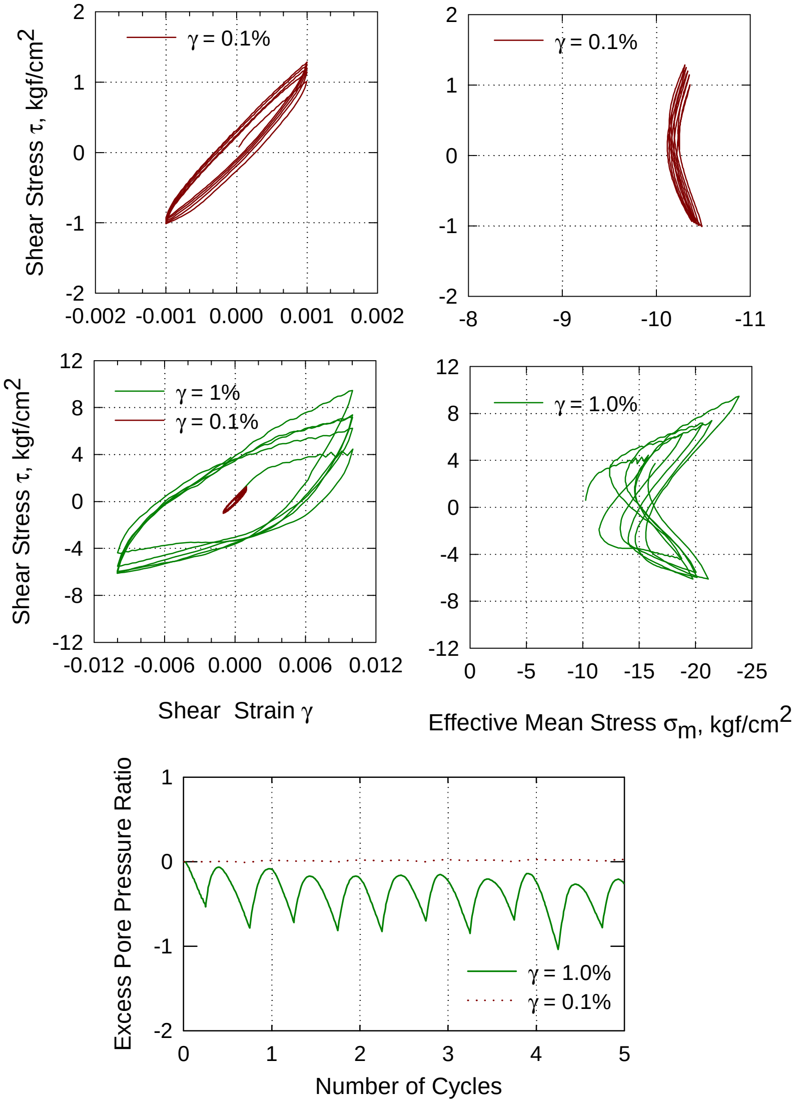


Fig. 5 Cyclic Responses for Dense Case

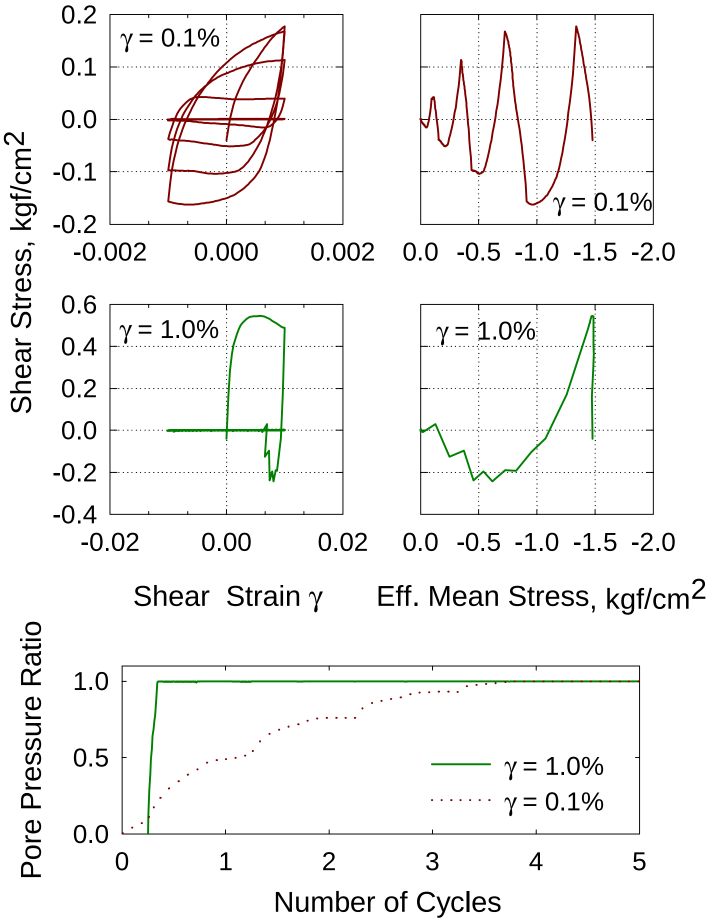


Fig. 6 Cyclic Responses for Loose Case

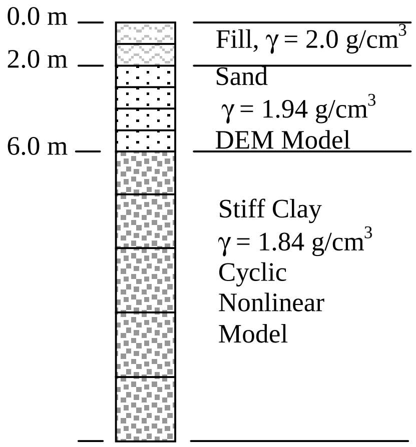


Fig. 7 Soil Profile for Example Analysis

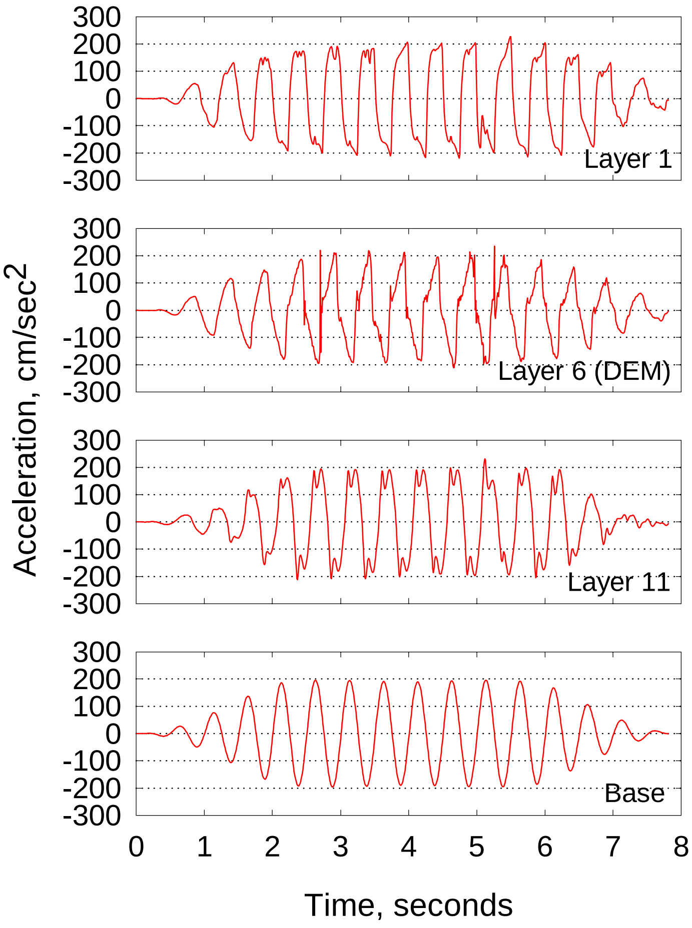


Fig. 8 Acceleration for Dense Case

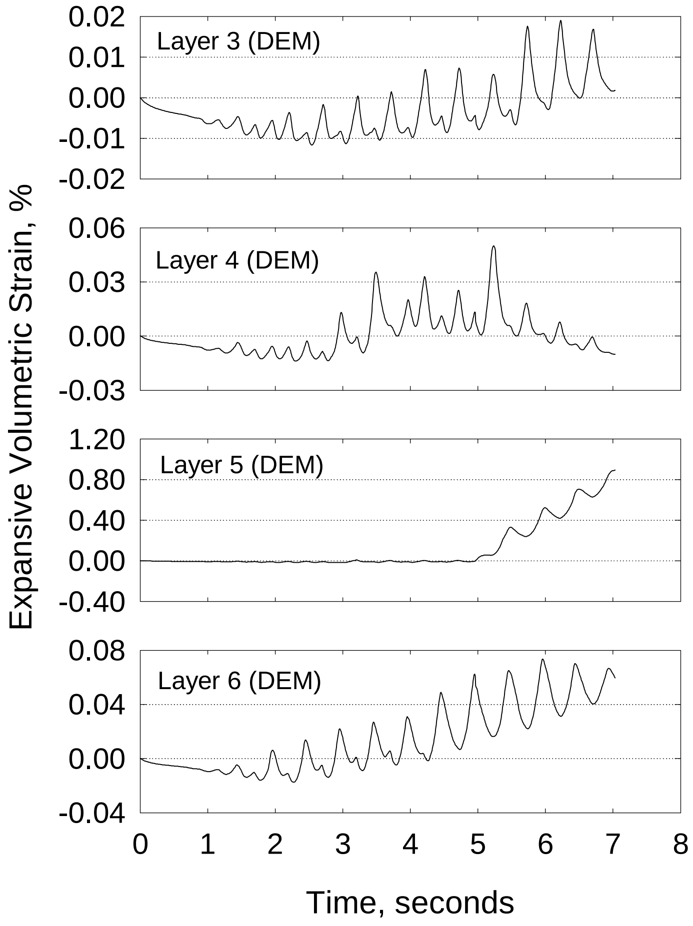


Fig. 9 Volume-Change for Dense Case

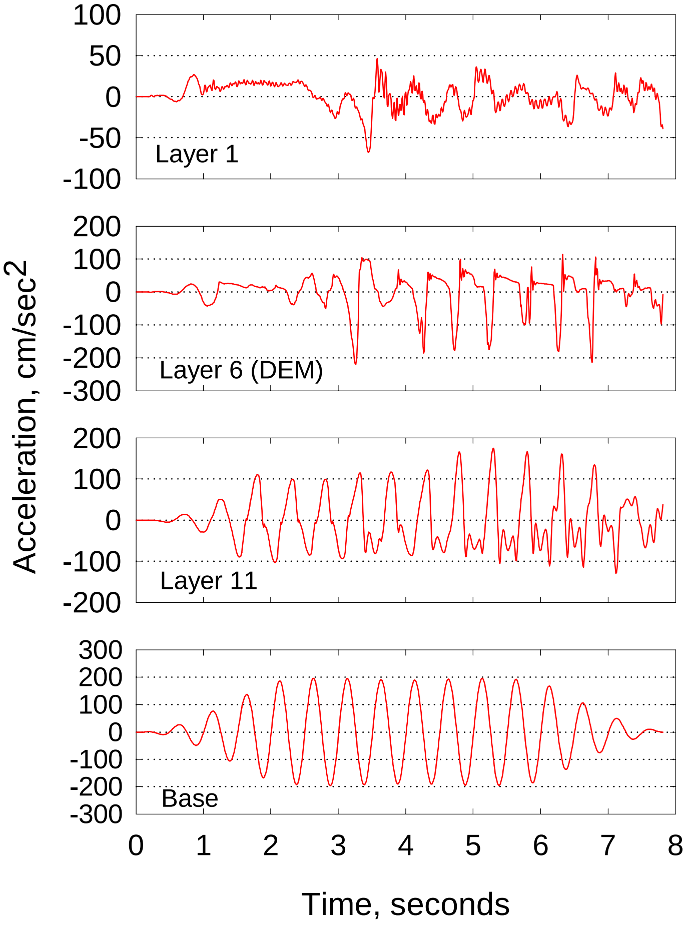


Fig. 10 Acceleration for Loose Case

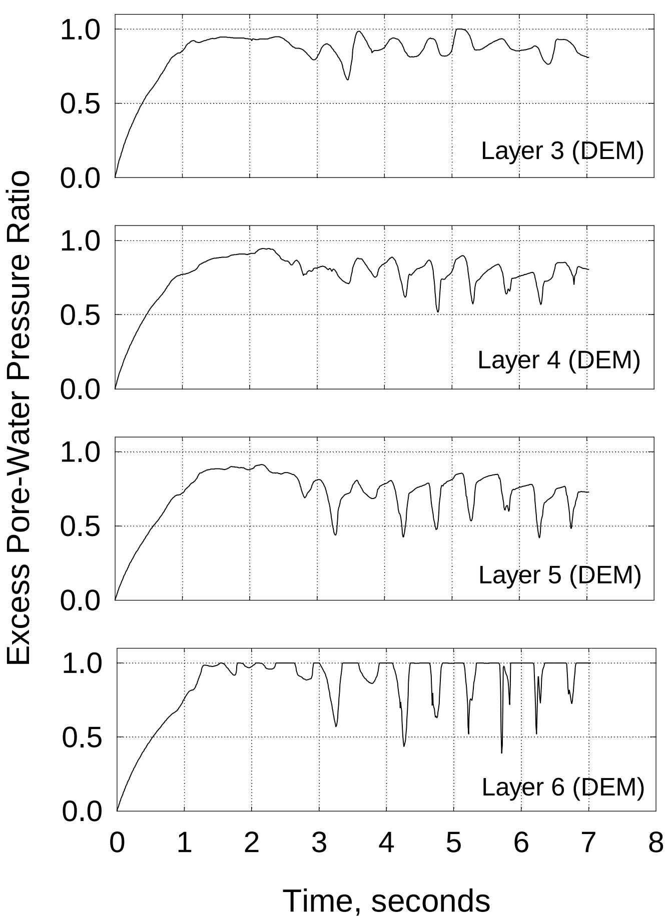


Fig. 11 Pore Pressure for Loose Case