A FUNDAMENTAL STUDY ON THE SEISMIC RESPONSES OF GROUND

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SUMMARY

A new approach to the evaluation of seismic site responses is proposed in this paper. The proposed method involves integration of the distinct element method (DEM) into a soil column model with each soil layer capable of transmitting horizontally polarized S waves and vertically propagating P waves. The motivation for the development was rather straightforward; all existing site response methods have some shortcomings and limitations. The major shortcomings are in most cases related to the constitutive models employed; most constitutive soil models have potential difficulties of reproducing the stress-strain relations of soils undergoing large strains and deformation. However, from the designer's viewpoint, such soil behavior is of most importance. The present study indicates the feasibility of the proposed new approach, although the method itself is extremely computing intensive.

INTRODUCTION

Site response analyses and evaluation of the potential for liquefaction may be two of the most important tasks a geotechnical engineer must perform in a geotechnical engineering project located in a seismically active region. A site response analysis has been made using the computer program SHAKE or the equivalent in many cases. These programs are based on so-called equivalent-linear method, which approximates successively the nonlinear stress-strain relations of soils using secant shear moduli and equivalent viscous damping ratios through iterations on these soil parameters. These equivalent-linear methods are known to provide reasonable predictions of acceleration responses of ground for majority of site conditions and seismic events. These methods, however, are insufficient especially when the site involves deep soft soils and when seismic shaking is very strong. Seismic responses of ground involving liquefaction are typical examples of the situations where such equivalent-linear approach shows weakness.

Alternative site-response analysis methods involve nonlinear cyclic stress-strain models. These methods employ step-by-step integration methods. Therefore, the methods are more time-consuming compared to the equivalent-linear methods. This shortcoming is of no importance today since the computers available to us are sufficiently powerful. However, the key shortcoming of these nonlinear cyclic stress-strain approach lies in the fact that most nonlinear stress-strain models are based on continuum theories. Therefore, such models are potentially incapable of simulating the soil responses controlled by discontinuous nature.

With the considerations outlined above, a new type of site response method has been developed. The proposed method integrates a series of discrete element models into a site response analysis method. The key function of the discrete element models is to generate "more realistic" stress-strain responses of soils for wide range of situations involving extreme conditions produced by liquefaction and associated large deformation of soils.

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SEISMIC SITE RESPONSES FROM LARGE-SCALE EXPERIMENTS

Fundamental aspects of seismic site responses have been studied using the world-largest laminar shear box fabricated for the EDUS project (Kagawa et al, 2000). The findings have been used to calibrate the reliability of the proposed numerical method. The large-scale laminar shear box has a height of 6 m, and it provides excellent opportunities for observing the seismic responses of soils under a reasonable range of overburden stresses. A typical experimental set-up using the large-scale laminar shear box is shown in Fig. 1. Shaking-table tests were conducted using dry sand layers and saturated sand layers. Responses of acceleration and pore-water pressures in sand were measured at a series of depths in the sand layer. Findings from these two types of tests are highlighted below.

Seismic Responses of Dry Sand *Dry sand layers were subjected to sinusoidal shaking. The stress-strain loops of the dry sand at various depths were obtained from the acceleration time histories measured in sand. It is interesting to note that the stress-strain loops in the beginning of shaking with low acceleration levels have shapes similar to what we usually assume in most site response analyses; i.e., their shapes may be approximated comfortably by hyperbolic or Ramberg-Osgood backbone curves. But, the shapes of the stress-strain loops towards the end of shaking with acceleration amplitudes on the order of 0.6g are considerable different from what we normally expect. Secant shear moduli and equivalent viscous damping ratios were estimated from such stress-strain loops. Results are shown in Fig. 2 together with those implied by the empirical formulae proposed by Iwasaki et al (1978) and Ishibashi and Zhang (1993). Figure 2 demonstrates that the secant shear moduli and damping ratios thus obtained are shown to be reasonably consistent with those from the empirical formulae.*

Figure 3 shows comparisons between measured and computed responses of the sand layer. Numerical evaluation of the responses of the sand layer was made using the computer program SRANG (Kagawa, 1996). Figure 3-a compares the acceleration time histories of the sand layer near the top obtained from the test and from our numerical analysis, and Figure 3-b compares the profiles of peak accelerations in the sand layer. The comparisons in Fig. 3 tend to confirm the validity of a nonlinear site response analysis method such as SRANG for dry sand cases.

Seismic Responses of Saturated Sand *Figure 4 shows responses of acceleration and pore-water pressures in a saturated sand layer. High excess pore-water pressures developed, and the sand layer liquefied during shaking. Therefore, the stiffness of the sand layer gradually degraded until complete liquefaction. The acceleration time history at the shallowest location clearly shows the effects of such phenomenon. In addition, the dilatant behavior of the liquefied sand is also shown in this acceleration time history. The computer program SRANG was also used to simulate the responses of this saturated sand layer. The computed acceleration time history at the shallowest location is compared with the measured response in Fig. 5. Since SRANG has a pore pressure generation and dissipation model, overall features of acceleration responses of the sand layer are reproduced reasonably well. However, it was very difficult to achieve reasonable agreements between the measured and computed displacement responses of the sand layer.*

The findings highlighted above suggest potential shortcomings of the existing site response methods. Immediate improvements of the existing site response methods could be accomplished if these methods employ improved constitutive relations of soils. One way of accomplishing such improvement may be to integrate a series of discrete element models into a site response analysis method.

3-D SITE-RESPONSE ANALYSIS USING THE DEM

The majority of the one-dimensional site response methods currently available were not developed to evaluate large deformation of soils due for example to liquefaction. Therefore, they are based on the theories for continuum medium. Unfortunately, however, soils undergoing large deformation are often not governed by the laws for continuum medium. The numerical methods such as the distinct element method are potentially better suited to such situations. In addition, the distinct element method is potentially capable of incorporating the influences of micro mechanical parameters into the stress-strain responses of soils in explicit manner. Such parameters may include grading, particle shapes and sizes, fabrics, and stress-strain histories.

The proposed site response analysis model consists of horizontal soil layers. Each soil layer has three degrees of freedom, two horizontal displacement components and vertical displacement. The dynamic equilibrium equations of the soil layers are generated by the finite element method. The stress-strain relations of the soil layers could be represented by using nonlinear cyclic stress-strain models or the DEM models. The soil layers represented by the nonlinear cyclic stress-strain models are suited to implicit solution schemes, while the DEM is based on an explicit integration solution. Therefore, the time interval required to obtain stable solutions in the DEM is usually significantly smaller than that required by an implicit integration method. In addition, it is not very convenient numerically to perform equilibrium iterations to maintain full dynamic equilibrium at all time steps in the DEM. Therefore, such equilibrium iterations are only made for the soil layers involving the nonlinear cyclic stress-strain models.

The new computer program SRANG3D (Site Response Analysis of Nonlinear Ground in 3 Dimensions) has been developed that incorporates the key features discussed above. The program is based on SRANG (Kagawa, 1996), which can perform an effective-stress based, one-dimensional site response analysis in the time domain. Various stress-strain models including elasto-plastic constitutive models and the hyperbolic and Ramberg-Osgood models are used. Figure 7 schematically shows the flow of numerical computing tasks involved in SRANG3D. In SRANG3D, partial or the entire soil layers can be represented by arrays of elastic spherical and/or ellipsoidal particles. The properties of the arrays (e.g., porosity, contact number, and particle size and distribution) can be different from one soil layer to another. Also, each DEM layer is consolidated to desired consolidation stresses before seismic site responses are computed.

The DEM is extremely computing intensive, and many researchers are exploring possibilities of improving its numerical efficiency. In this study, SGI/Cray supercomputers were mainly used to compute responses of soil layers subjected to seismic shaking. Two types of enhancement of computing speeds have been employed; vectorization and parallelization.

CONCLUDING COMMENTS

A new numerical method for seismic site responses has been in this paper. The method employs the DEM to reproduce the stress-strain relations of soil layers, and it computes vertical propagation of two horizontally polarized S waves and P waves. This study showed that the proposed method provides us with an alternative way of computing the responses of level ground subjected to three components of earthquake shaking.

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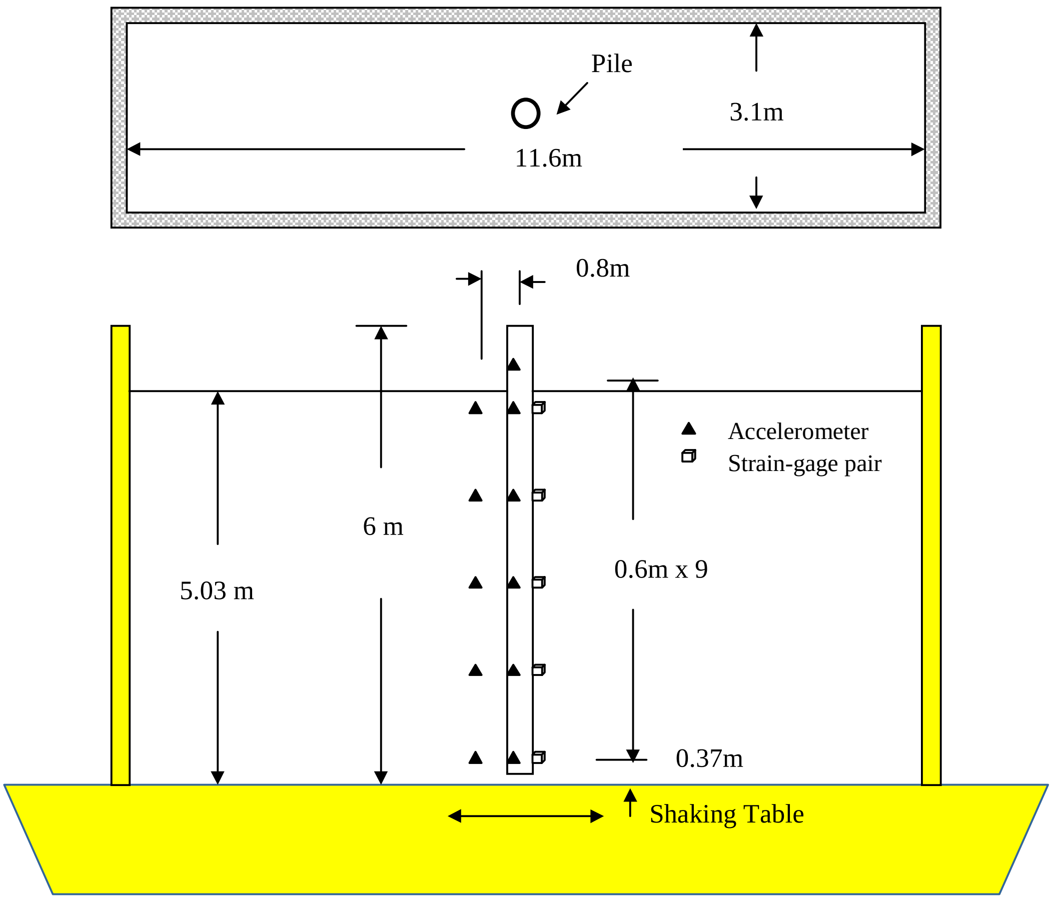


Fig. 1 Large-Scale Shaking-Table Test Set-up

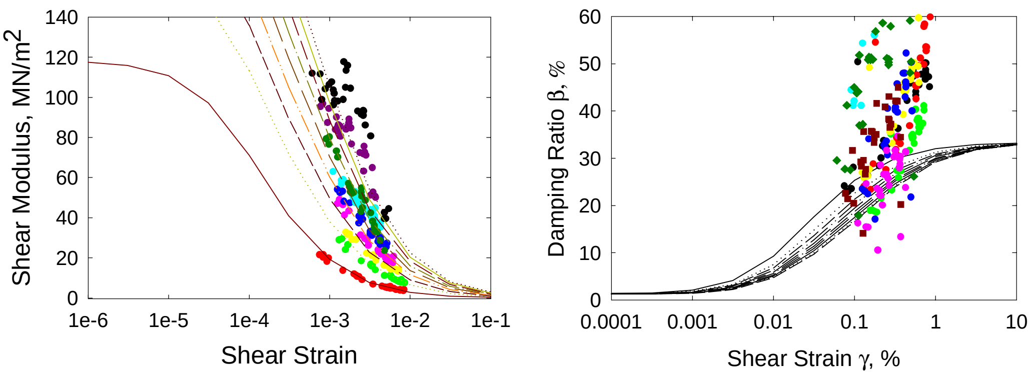
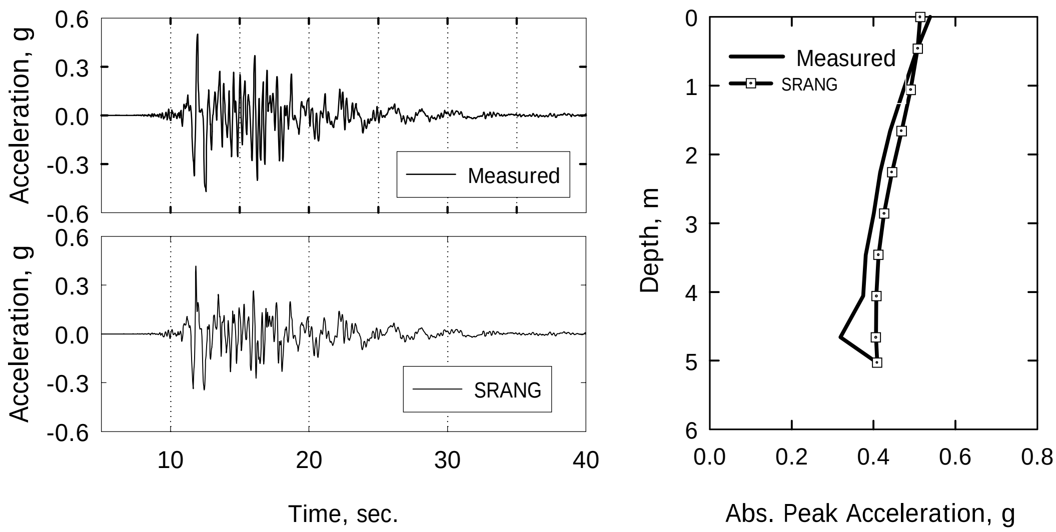


Fig. 2 Shear Moduli and Damping Ratios from Large-Scale Tests



a) Acceleration Histories **b) Profiles of Peak Acceleration**

Fig. 3 Measured and Computed Acceleration Responses of Dry Sand Layer

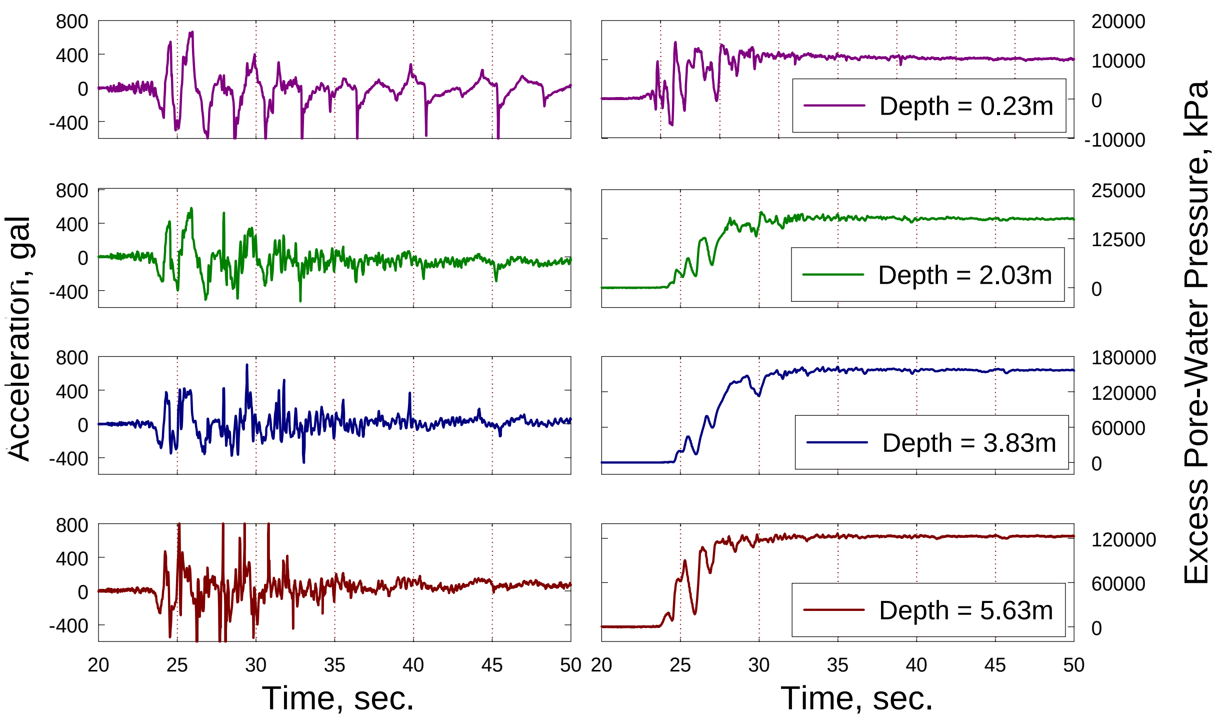


Fig. 4 Measured Responses of Saturated Sand Layer in Large-Scale Test

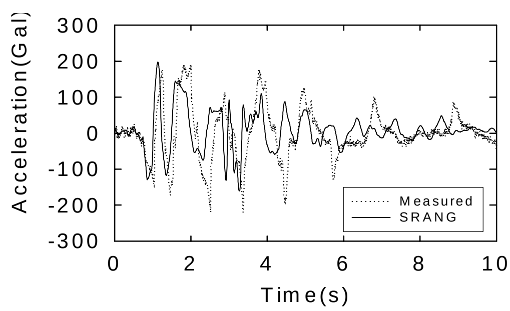
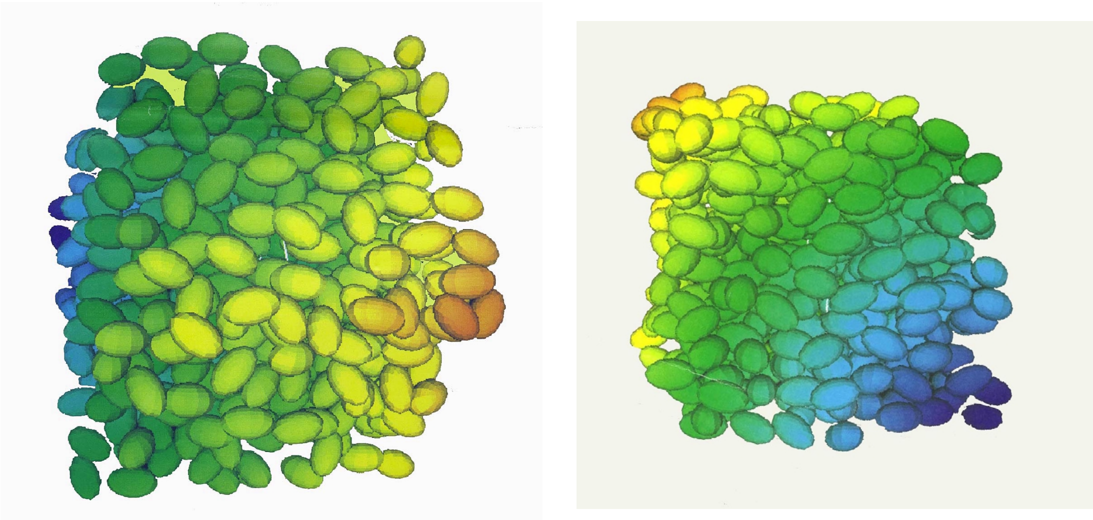


Fig. 5 Measured and Computed Acceleration



a) After Random Packing **b) After Consolidation to In-Situ Stresses**

Fig. 6 Assembly of Ellipsoidal Particles

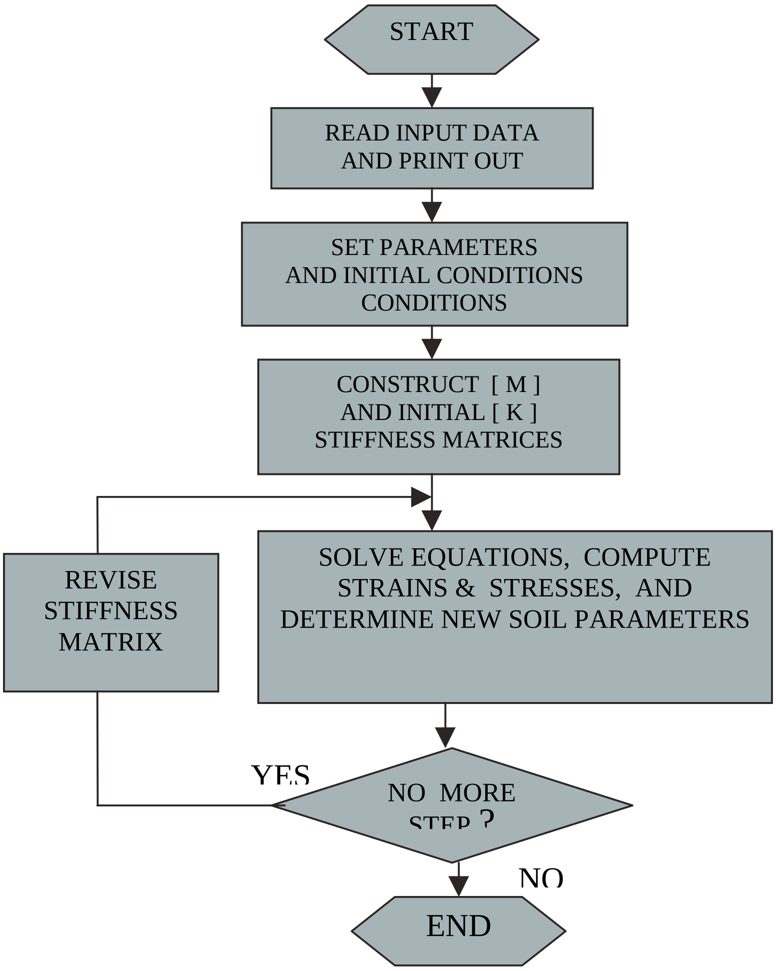


Fig. 7 Flow of the Major Computational Tasks in SRANG3D