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SEISMIC ANALYSIS OF SOIL EMBANKMENTS

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ABSTRACT

An Analysis of stresses and deformations in a model soil embankment during a simulated earthquake excitation is presented. It is shown that the response of the embankment can be simulated with a good accuracy using a coupled stress-flow formulation with a plasticity model representing the stress-strain behavior of the soil.

KEYWORDS

Earthquake; Large deformation; Liquefaction; Plasticity; Soil

INTRODUCTION

Earthquake has always been one of the major sources of natural hazards to mankind. During the past few decades, many sever ground shakings have occurred in different parts of the world. Only in the past 5 years, more than 50,000 people were killed due to the 1995 Kobe, 1994 Northridge, and 1990 Manjil Earthquakes in Japan, United States, and Iran, respectively. Financial losses in these earthquakes amount to billions of dollars. These casualties were mostly due to the collapse of residential buildings, urban structures, and civil infrastructure systems shaken by a sever ground motion.

In order to reduce the possibility of catastrophic failures of buildings, bridges, power plants, and other important structures the current design procedures should be continuously revised to accommodate the lessons learned from recent earthquake-caused failures in the urban areas. Due to scarcity of the data gathered from such failures, however, they are not sufficient to thoroughly investigate the mechanisms involved in these failures. Simulation studies using physical (scaled) models in the laboratory and numerical modeling using advanced computational and analytical techniques are found useful in uncovering mechanisms involved in the failure of infrastructure systems.
It is believed that physical and numerical modeling are becoming two major tools to study the validation of current design procedures as safe and economic measures against earthquake loading.

Main components of the current research in study of stability of civil infrastructure systems are:
1) *Physical Modeling in order to understand the underlying failure mechanisms*
2) *Constitutive Modeling of Materials*
3) *Numerical Modeling*

In this paper, an example of the use of the above components in the analysis of seismic stability of soil embankments is presented.

PHYSICAL MODELING

Centrifuge modeling is one of the most elaborate physical modeling techniques available to study the mechanisms involved in the earthquake-caused failures of infrastructure systems. It has been used to study the seismic response of buildings, earth-structures, and soil-structure systems. Figure 1 shows a model embankment tested in centrifuge to simulate realistic stress levels occurring in real-life soil embankments (Arulanandan et al., 1993). Several pore pressure transducers, accelerometer, and displacement transducers (LVDT) monitor the time histories of the response of this model to a simulated earthquake. Figure 2 shows the time history of the base motion.

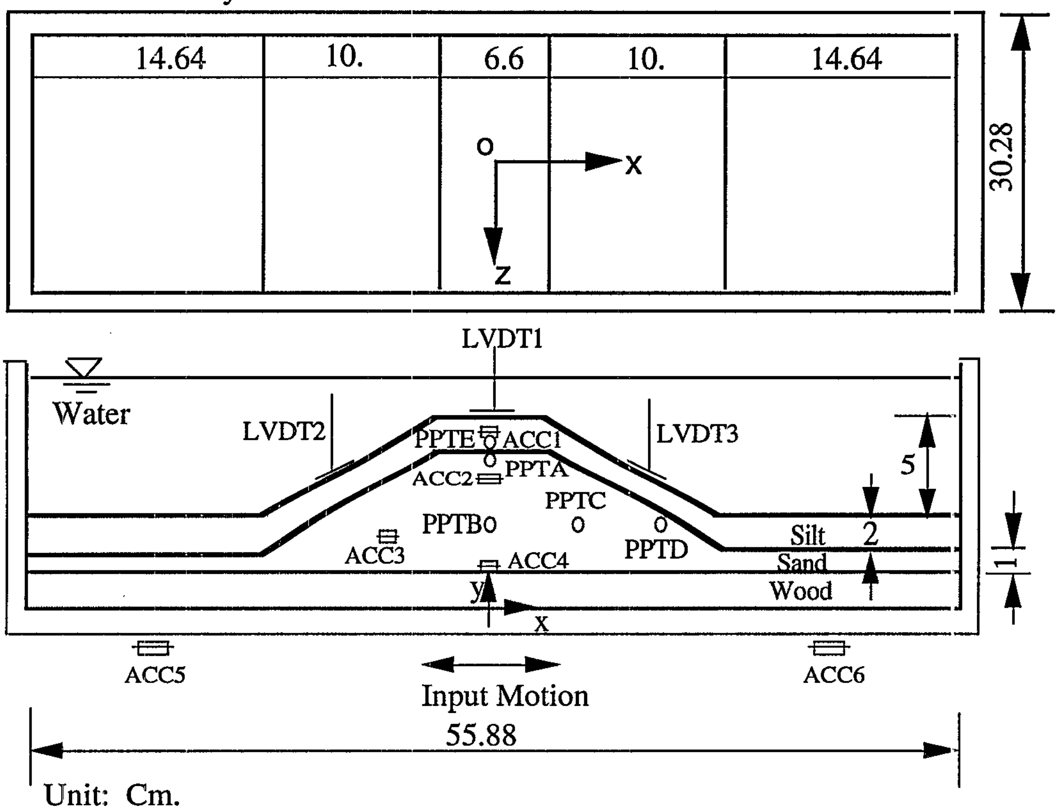

Figure 1 - Plan and Cross Sectional View of the Flow Failure Centrifuge Model.

In order to monitor the time history of pore pressure generation and dissipation during and after shaking phase, five pore water pressure transducers were used at different locations of sandy core and silt layer. A quasi-static analysis showed a high value of shear stress ratio for all of the transducer locations except for the PPTB; Shear stress ratio varies from 0.54 for B to 0.66 for C and 0.74 for D. This means that a higher potential of pore pressure generation exists at B than at other pore pressure transducers. In fact, due to the high initial shear stress ratios at D and A which are close to the interface between the sandy core and the silt layer, dilative behavior is expected at these points. Experimental results (Arulanandan et al., 1993) confirmed the expected trends at different pore pressure transducers except for PPTE which developed a high excess pore pressure ratio some 12 seconds after the start of shaking. This may be attributed to the sinking of the pore pressure transducer at E after liquefaction of its foundation soil. A large negative pore water pressure measured at PPTD reveals a very important mechanism involved in the response of the model embankment. It signifies the development of dilation in the zone of high stress ratio. Such a negative pore water pressure would prevent the failure of the embankment while a positive pre water pressure of same magnitude would induce a catastrophic failure.

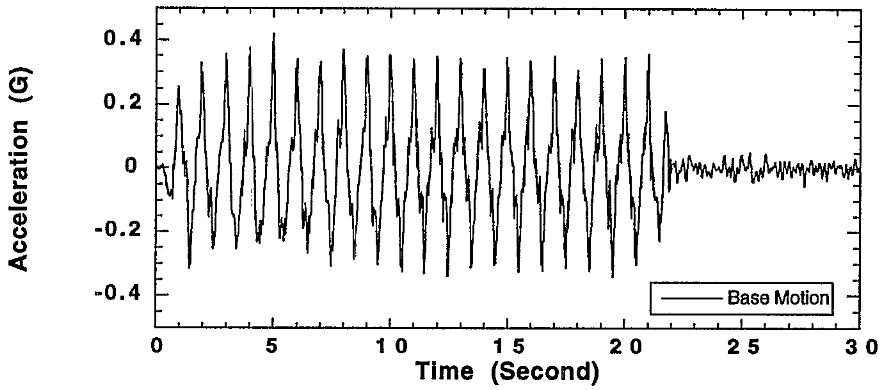

Figure 2 - The Achieved Horizontal Acceleration Recorded at the Base of the Centrifuge Model

CONSTITUTIVE MODELING OF SOIL STRESS-STRAIN BEHAVIOR

One of the major components of a numerical procedure for analyzing the stability of geo-structure is the constitutive models which represent the stress-strain behavior of soil or other material involved with the structure. The author is working to develop comprehensive constitutive models which can simulate the stress-strain behavior of cohesive and non-cohesive soils. A recently developed model by Manzari and Dafalias (1996) is shown to accurately simulate the monotonic as well as cyclic stress-strain behavior of sands (e.g., Figures 3). The outcome of this research is particularly significant due to peculiar behavior of sands in cyclic loading and impact of this behavior on soil liquefaction during earthquake loading. Liquefied layers of sands have been observed to be the major causes of instability of geotechnical infrastructure systems in reclaimed areas (e.g., Kobe earthquake, Loma Prieta Earthquake).

NUMERICAL MODELING, AN EFFECTIVE STRESS APPROACH

The centrifuge model shown in Figure 1 is a heterogeneous embankment of small height with a slope angle of approximately 26.56 degrees. One of the major steps encountered in any elasto-plastic analysis of a boundary value problem is determination of initial state of stresses and internal variables used in the constitutive model. In the case of the present centrifuge model, a quasi static analysis was conducted to compute the state of stresses and pore water pressures in the model just before the shaking phase starts. The actual time history of centrifugal acceleration during the spinning phase was simulated by applying the gravity field as a function of time in a quasi-static manner. The centrifugal acceleration was gradually increased from 1g to 50g during 10 minutes and was maintained constant for another 20 minutes before the shaking phase started. Results of a quasi-static analysis of the embankment during the centrifuge spinning showed that 30 minutes of spinning of the centrifuge at 50g is nearly sufficient for a complete dissipation of the excess pore pressure. However some parts of the soil in the central core still maintain some 10 percent of their initial excess pore pressures.

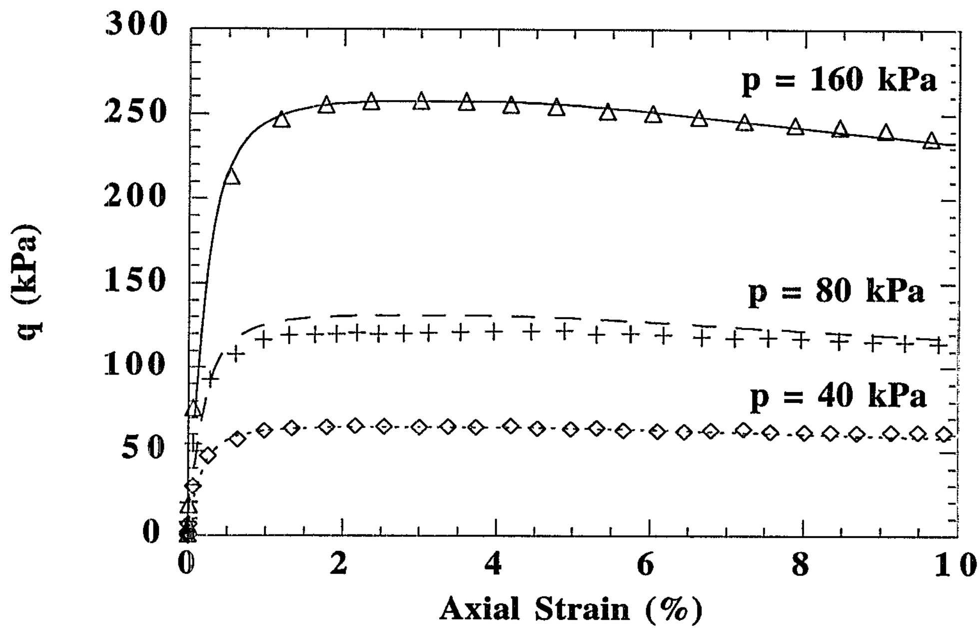

Figure 3a - Simulated Response of Dense Nevada Sand versus Experimental Results

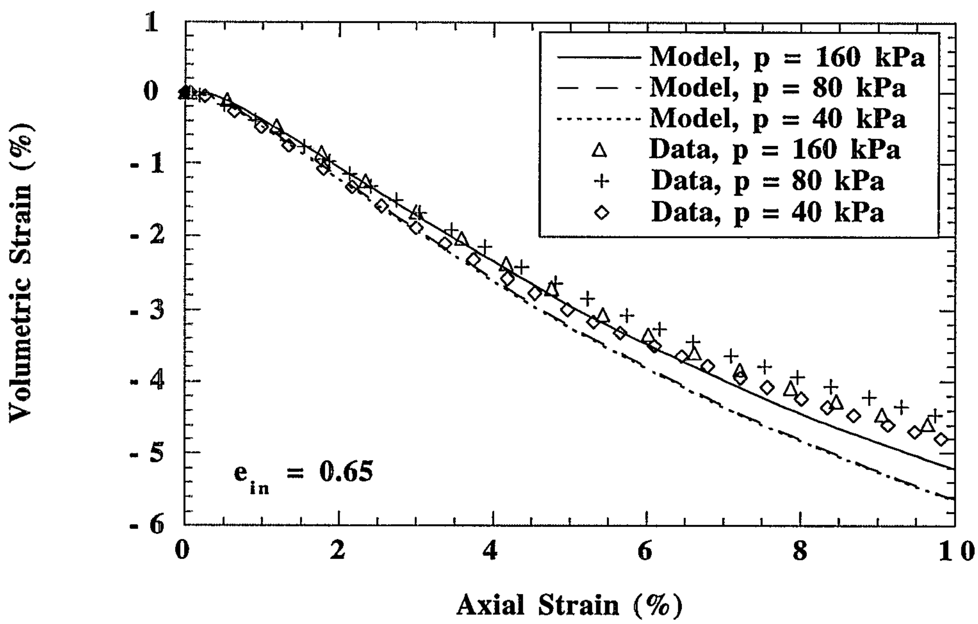

Figure 3b - Simulated Response of Dense Nevada Sand versus Experimental Results

Figures 4 and 5 show the distributions of vertical and horizontal effective stresses inside the embankment. Figure 6 shows distribution of the initial shear stresses inside the embankment. The quasi static analysis also shows that the maximum vertical effective stress inside the embankment is less than 40 kPa.

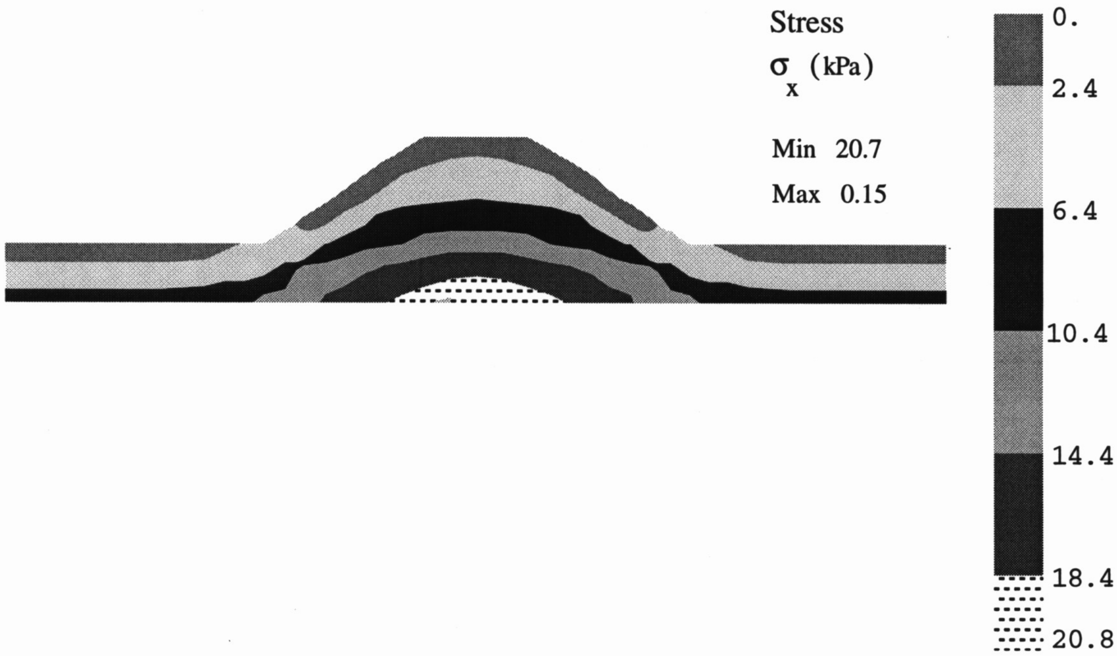

Figure 4 - Distribution of the Initial Horizontal Effective Stresses inside the Model Embankment just before the Shaking Phase.

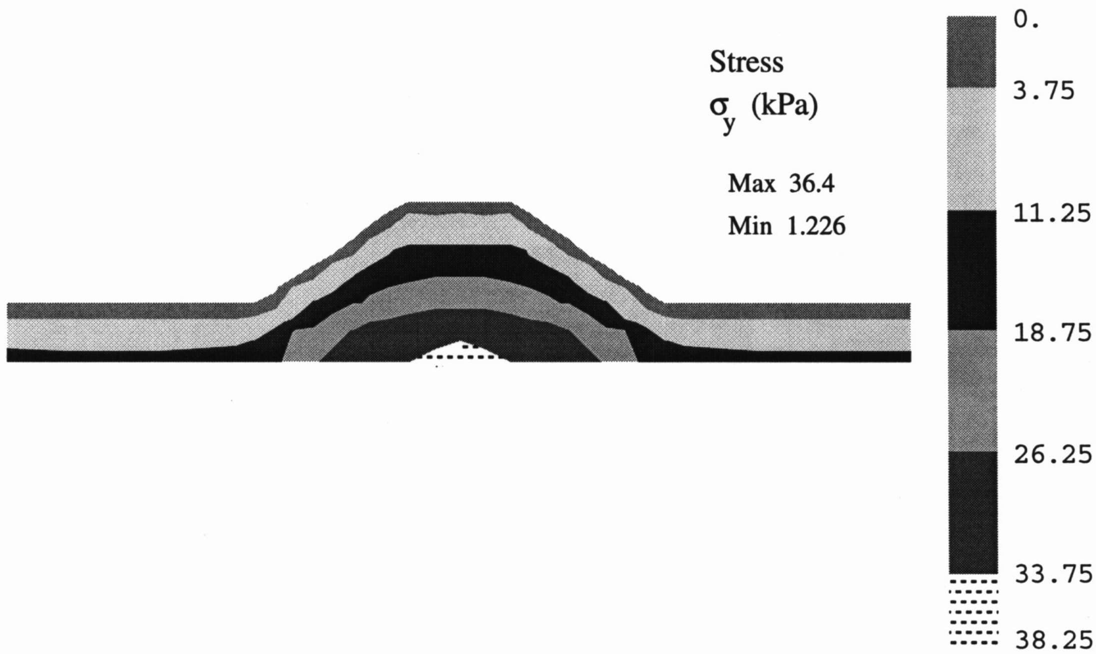

Figure 5 - Distribution of the Initial Vertical Effective Stresses inside the Model Embankment just before the Shaking Phase.

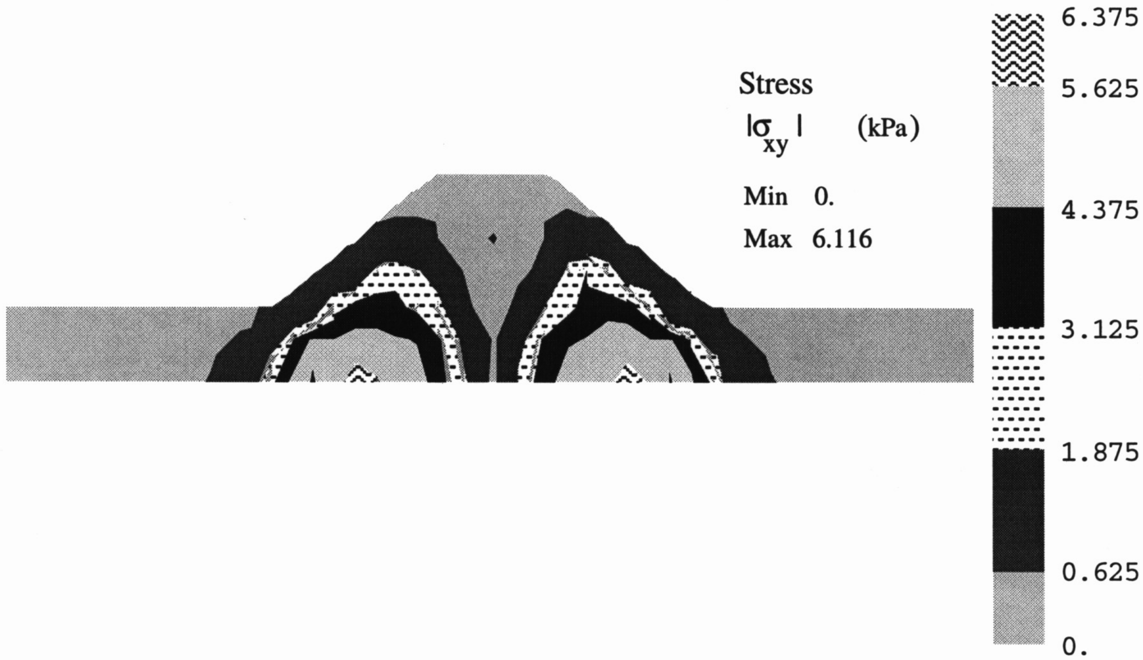

Figure 6 - Distribution of the Initial Shear Stresses inside the Model Embankment just before the Shaking Phase.

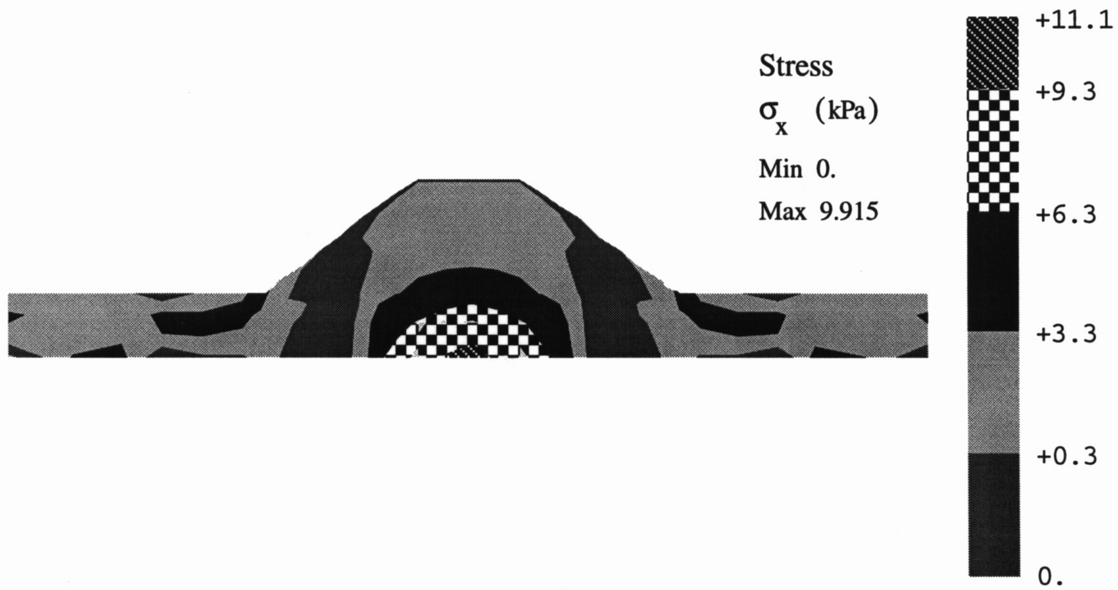

Figure 7 - Computed Distribution of the Horizontal Effective Stresses inside the Model Embankment a Few Seconds after the Shaking Phase Starts.

Even though there was no measurement of pore pressure at the silt layer, a dynamic analysis shows that (Figures 7 and 8) a few seconds after the start of shaking the silt layer is in a state of liquefaction and there is no shear strength to hold it on a slope of 26 degrees. Figures 7 and 8 clearly show that the vertical and horizontal effective stresses calculated in the model are nearly zero in the silt layer while the sandy core still maintains 40% of its initial effective stresses in the central part. Therefore, after this point, the silt is in a state of gravity flow over the sandy core. In other words LVDT2 and LVDT3 will fall down on the sandy core after the flow of silt removes the material from beneath these transducers.

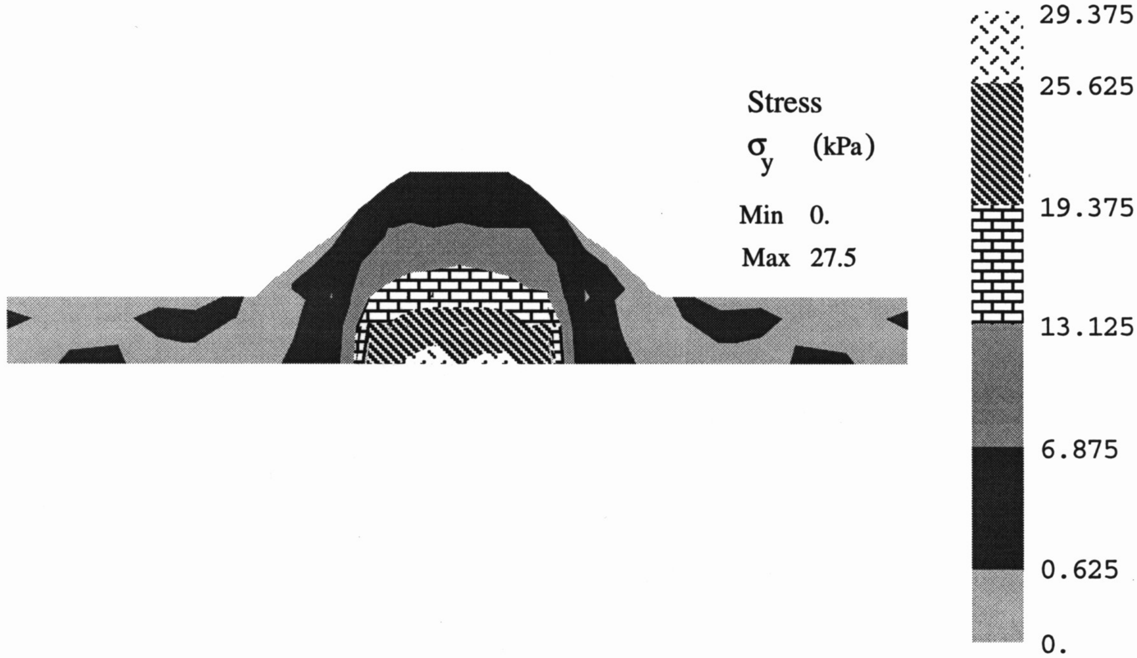

Figure 8 - Computed Distribution of the Vertical Effective Stresses inside the Model Embankment a Few Seconds after the Shaking Phase Starts.

Figure 9 shows the shear stress ratio computed at the end of shaking phase. This figure also confirms that the shear stress ratio at the silt layer is in state of failure, while a major portion of the central core has not reached the failure state. It is interesting to see that the sand and silt both have liquefied in the horizontal wings of the structure.

Figure 9 - Computed Distribution of Shear Stress Ratio inside the Model Embankment a Few Seconds after the Shaking Phase Starts.

One of the important observations in this centrifuge test was that the sandy core remained stable after the shaking while the silty core flowed off toward the toes of the embankment. Even though simulation of displacement of the silty layer after the flow is of little practical importance, it is important to simulate the stability of the main core. One of the major goals of this study was to investigate the capability of a finite deformation formulation in simulation of permanent deformations in a flow failure problem. Numerical simulations of deformations with a small strain formulation showed excessive displacements at the top of the embankment while the finite deformation formulation showed that the main core remained stable after the cease of shaking. This is in agreement with the observed behavior. Figure 10 show comparisons between the computed time histories of vertical displacement and those measured at LVDT1. As it can be seen the computed displacement time history at LVDT1 is in excellent agreement with the recorded displacement.

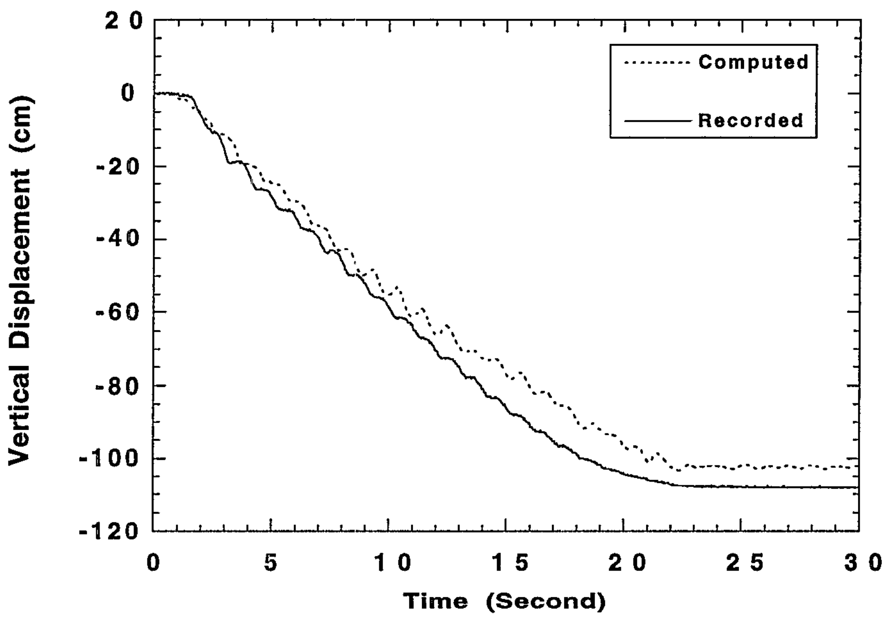

Figure 10 - Computed Time History of Vertical Displacement at Top of the Embankment versus the Displacement Time History Recorded at LVDT1.

CONCLUSION

An effective stress approach is shown to be useful in predicting the seismic stability of a saturated soil embankment. A large deformation analysis is essential when a flow slide occurs in a soil embankment containing liquefiable soils.

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