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Liquefaction analysis of stratified soil layers: A verification of coupled stress-flow approach

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Abstract: A fully coupled stress-flow approach was used to predict the results of two different centrifuge tests. In the first case, the centrifuge simulation of a "homogeneous sand layer" excited by simulated earthquake motions was selected as a bench mark problem to verify the ability of the approach to predict the pore water pressure and acceleration time histories within the sand layer. In the second case, it was shown that the method is able to predict the behavior of stratified soil layers composed of a sand layer overlain by a silt layer with a permeability of about two orders of magnitude less than that of the sand layer.

1 INTRODUCTION

The state of the practice in the determination of stresses and displacements is to use the equivalent linear stress-strain behavior in total stress-based approaches. This method cannot be applied to evaluate the ground response and deformation of soft soil sites especially where a liquefiable layer exists. Hence there has been a major research effort in recent years to develop and implement effective stress based nonlinear numerical procedures using elastio plastic constitutive models.

Following extensive research work in soil liquefaction at the University of California, Davis (Arulanandan, Anandarajah and Abghari, 1983; Arulanandan and Muraleetharan, 1988), Muraleetharan adopted the Zienkiewicz u-U formulation (Zienkiewicz and Shiomi, 1984), to develop a two-dimensional coupled stress flow code (DYSAC2) incorporating bounding surface plasticity models for cohesive (Dafalias and Herrmann, 1986) and non-cohesive soils (Yogachandran, 1990).

The objectives of this paper are: 1) to verify the computer code (DYSAC2) utilizing centrifuge model tests, 2) to explore the importance of initial state on the seismic response of soil deposit (k_0 condition) and 3) to investigate whether a dynamic interface element is necessary for the prediction of pore water pressure in horizontally layered systems.

2 SIMULATION OF LIQUEFACTION IN A HOMOGENEOUS COLUMN OF SAND

The coupled stress-flow (CSF) approach was applied to predict the pore water pressure and acceleration time histories of saturated loose sands in a homogeneous system.

The centrifuge test results (Figs. 1, 2, 3) obtained on saturated fine Nevada sand in a laminar box (Hushmand et al. 1987) are predicted using DYSAC2. Two of the properties of the sand determined (Hushmand, et al. 1987) from the laboratory test are: (1) minimum and maximum unit weights, from compaction tests of 13.82

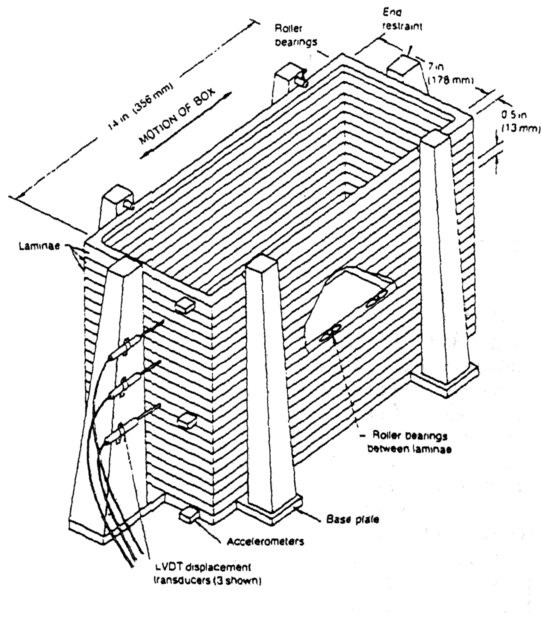

Figure 1. Laminar simple shear box for centrifuge experiments (After Hushmand et al., 1988)

kN/m^3 (88 pcf) and 17.44 kN/m^3 (111 pcf), respectively; and (2) permeability, $k = 1 \times 10^{-5}$ m/sec; and specific gravity $G_s = 2.67$. The average height of the sand column was about 22.86 cm (9 inch). Some

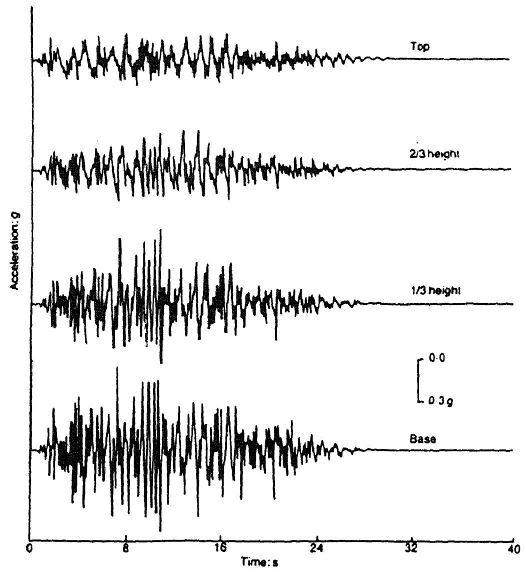

Figure 2. Recorded accelerations at various depths in the centrifuge (After Hushmand et al., 1988)

additional properties of sand column are also presented in Table 1.

Table 1. Homogeneous sand test data [Hushmand, et al. 1987]

Initial Void Ratio	Relative Density, D_r	Total Unit Weight, γ_{sat}, kN/m^3	Buoyant Unit Weight, γ, kN/m^3
0.72	44%	19.33	9.52

The test was carried out at a centrifuge acceleration of 50 g. The saturated sand model was subjected to shaking with a base input acceleration corresponding in frequency content and duration to the NS component of the 1940 El Centro accelerogram. The maximum amplitude of the input base acceleration during the test was 0.55 g. This amplitude was about 50% higher than the peak acceleration in the actual El Centro record. The duration of strong shaking was about 22 seconds (Hushmand, et al. 1987).

Initial application of DYSAC2 to predict the pore pressure and acceleration time histories of homogeneous sand deposit was not successful due to: (1) not considering the properties of soil at very low effective stresses and (2) not taking into consideration the actual initial state of the soil.

Based on a bounding surface plasticity concept, Yogachandran developed a constitutive model for non-cohesive soils (Yogachandran, 1990). In applying this model for solving boundary value problems, the shear modulus is assumed as a constant input parameter or as

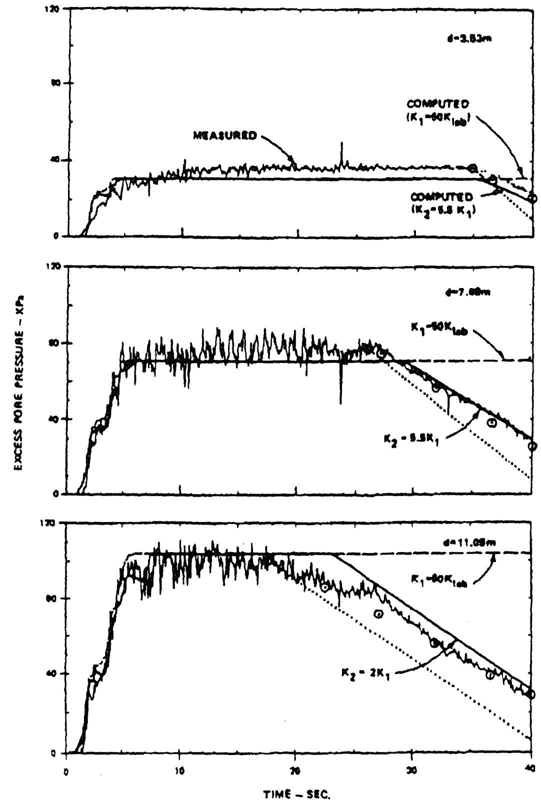

Figure 3. Pore pressure measured at various depths (d) in saturated sand during centrifuge test versus pore pressures (dashed and solid lines) computed by program "DESRA" using two different permeability profiles (K_1 & K_2).

an "effective mean stress" dependent parameter which is calculated as:

$$\text{Shear Modulus } G = \text{Bulk Modulus } \times \frac{(1.5)(1-2\nu)}{1+\nu}$$

$$= \frac{1 + e_{in}}{3\kappa} \times (\langle I - I_L \rangle + I_L)$$

where:
- ν = Poisson ratio
- I_L = transitional pressure (see Dafalias and Herrmann, (1986) for details)
- e_{in} = initial void ratio
- κ = rebounding modulus in e-ln$p$ curve

Because the constant G could not be a proper choice for sands under cyclic loading, it was customary to use ν = 0.3 and I_L = 30 kpa for Nevada fine sand. Although incorporation of I_L in the program is useful to avoid numerical difficulties near zero effective stress condition, selection of this parameter should be such that the model takes into account the residual strength of sand.

Additionally, the assumption of an isotropic stress condition made the sand stiffer (higher I, higher G modulus) than its actual stiffness and caused the propagation of shear waves up to the ground surface. In addition, by using a large I_L, material was able to transmit the shear waves even after occurrence of initial liquefaction in part of the sand column.

To overcome these difficulties, DYSAC2 was modified to simulate the initial state of stress in the sand column automatically. In order to simulate this initial state, it is necessary to increase the gravity level acting on the finite element model incrementally. In addition, shear modulus calculation in the program was modified to use the following empirical relationship for cyclic behavior of sands (Silver and Seed, 1972).

$$G = k\,(\sigma_m)^{1/2}$$

$$\sigma_m = \frac{1 + 2k_o}{3}\,\sigma_v$$

where: k = 4000 to 9000 (very loose to very dense sands)

σ_m = mean effective stress

k_o = horizontal to vertical stress ratio

Applying these two modifications and using the model parameters shown in Table 2, we are able to predict the pore pressure (Fig. 4) and acceleration time histories (Fig. 5). Good agreement of the predicted results with the experimental results is seen to exist (Figs. 4-5).

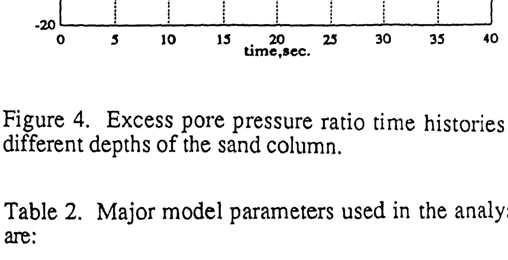

Figure 4. Excess pore pressure ratio time histories at different depths of the sand column.

Table 2. Major model parameters used in the analysis are:

$\lambda = 0.022$, $\kappa = 0.0036$, $M_c = 1$

$M_e/M_c = 0.9$, $\delta^* = 4.92$, $H_u^* = 10.$, $\gamma_u^* = 1.0$

*see Yogachandran (1990) for details

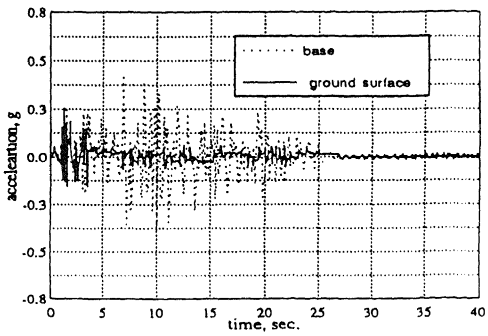

Figure 5. Comparison of acceleration time history at the base and the top of the sand column.

3 SIMULATION OF LIQUEFACTION IN A LAYERED SYSTEM OF SOIL

Using the same procedure as described in Section 2, the CSF approach was applied to predict the pore pressure and acceleration time histories of a layered system of soil. To explore the ability of the procedure, the centrifuge test results (Kitazume and Arulanandan, 1989) were used for the prediction purposes.

Kitazume and Arulanandan (1989) conducted a centrifuge test to investigate the response of stratified layers of soil when subjected to the earthquake loading. The centrifuge model consisted of a fine Nevada Sand layer overlain by a layer of silica flour as shown in Fig. 6(a). The initial void ratios of Nevada Sand and silica flour were 0.72 and 0.96, respectively. The model instrumentations are also shown in Fig. 6(a). The model was placed in the centrifuge and was consolidated for 5 minutes at 30 g centrifugal acceleration. While the centrifuge was spinning at 30 g, the model was subjected to 20 cycles of approximately sinusoidal base motion of magnitude 14 g at a frequency of 30 Hz (see Fig. 6(b).

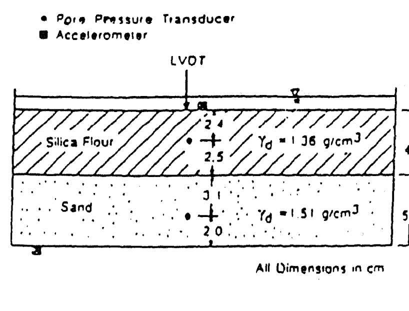

Figure 6(a). Schematic representation of stratified layer.

The excess pore pressure time histories measured in the mid point of the sand and silica layers are shown in Fig. 6(c) and the acceleration time history at the surface of the model is shown in Fig. 6(d).

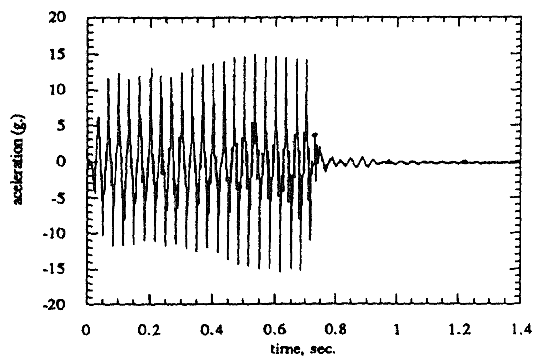

Figure 6(b). Input base acceleration for stratified layer in model scale.

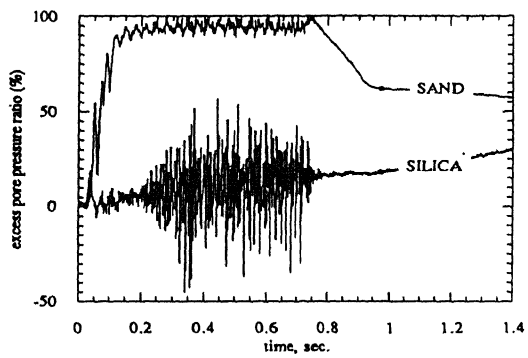

Figure 6(c). Excess pore pressure ratios measured at the sand and silica flour layers.

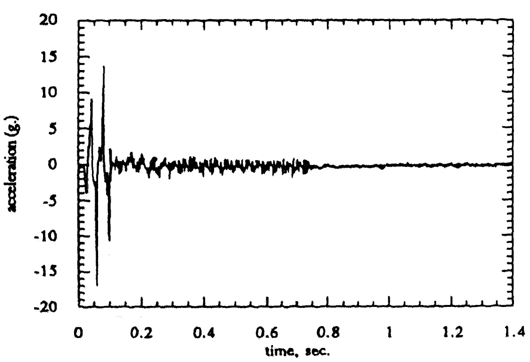

Figure 6(d). Measured surface acceleration.

There are two major observations which need to be considered:

1. The excess pore pressure ratio in the sand layers reached 100%, but the excess pore pressure in the silica flour remained under 30% of the initial effective stress at the measured point. This shows that the sand layer liquefied but the pore pressure of the silica layer was alternating around the base line during the application of the base motion. The pore pressure rose to 30% of the initial effective stress only after the base motion stopped.

2. Acceleration time history at the top of the silica layer showed some amplification of base motion in the first 0.1 sec. After that, however, it damped out considerably. Considering the excess pore pressure time history at the mid point of the sand layer, we can see that during the first 0.1 sec, the excess pore pressure ratio reached 80%. This shows that the sand layer liquefaction and the damping of the surface acceleration occurred simultaneously.

Yogachandran (1990) attributed the damping of the surface acceleration to the formation of a thin layer of water at the interface of the sand and silica layers. He assumed that this layer of water prevents the shear wave propagation through the silica layer, and developed a dynamic interface element (Yogachandran, 1990) to model the phenomena. According to Yogachandran, since the original version of DYSAC2 could not predict the pore water pressure time history in the silica flour layer, he introduced a dynamic interface element, to reasonably predict the excess pore pressure ratio reasonably. The acceleration time history prediction however was not in good agreement with the experimental results.

Using the same concept introduced in the second section of this paper, we could predict the excess pore water pressure and acceleration time histories without using an interface element. In fact, the shear modulus reduction occurring as a result of the significant decrease of confining pressure in the sand layer, will automatically prevent shear wave propagation through the silica layer. Figures 7 and 8 show the predicted time histories of excess pore pressure ratio and acceleration at the relevant points, respectively.

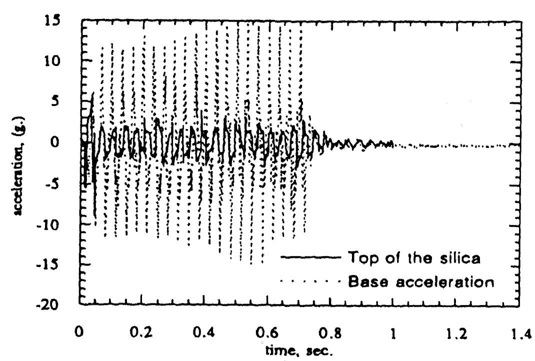

Figure 7. Computed acceleration time history at the top of the silica flour layer.

4 CONCLUSION

Using the coupled stress-flow approach, we attempted to predict the excess pore pressure and acceleration time histories for a homogeneous and a layered system of

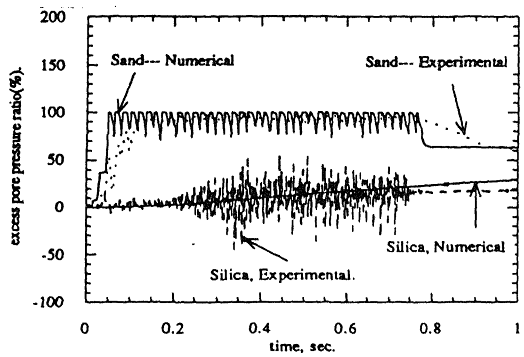

Figure 8. Comparison of computed and measured excess pore pressure time histories at the middle of the sand and silica layers.

soil subjected to earthquake motion. It was shown that a good agreement with the experimental results can be achieved by proper consideration of the material properties and the initial state of stress.

5 ACKNOWLEDGEMENT

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