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Pelin Tohumcu Özener
Yıldız Technical University, Turkey

I. Kutay Özaydın
Yıldız Technical University, Turkey

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NUMERICAL MODELING OF LIQUEFACTION IN LAYERED AND SILT INTER LAYERED SANDS

Pelin Tohumcu Özener
Yıldız Technical University, Davutpaşa Campus,
Department of Geotechnical Engineering, 34210,
Esenler-İstanbul/ TURKEY

I. Kutay Özaydın
Yıldız Technical University, Davutpaşa Campus,
Department of Geotechnical Engineering, 34210,
Esenler-İstanbul/ TURKEY

ABSTRACT

In this paper, the pyhsical model tests which were carried out in the laboratory on uniform sand columns, silt inter layered sand columns and two layered sand columns deposited at various relative densities and subjected to different input accelerations are numerically modelled. The numerical analyses are performed by using Towhata-Iai liquefaction model in a finite element program called DIANA and the excess pore water pressures computed from the numerical analyses are compared with the experimental results. The numerical analyses have shown that the development of excess pore water pressures is highly influenced by the relative density of the sand and the presence of a less permable soil layer within the sand deposit. The numerical modeling of silt interlayered sand tests showed that there is an abrupt increase in the r_u values below the silt seam demonstrating the accumulation of pore water pressures due to the presence of silt layer. The results of the numerical analyses also revealed that a constitutive model coupled with a ground water flow analysis must be used to simulate the generation of excess pore water pressures especially in layered sand deposits.

INTRODUCTION

Site investigations show that natural sand deposits in the field usually contain stratified sands in different relative densities and some silt seams which are more impervious relative to sand. Especially the presence of the low permeable interlayers can have significant effect on development of pore water pressures which might lead to liquefaction as well as to the after effects of liquefaction such as lateral spreading and slope instability during earthquakes.

In recent years, the behaviour of stratified sands during liquefaction has been investigated numerically and experimantally by several researchers. Scott and Zuckerman (1972), Huishan and Taiping (1984), Liu and Qiau (1984), Elgamal et al. (1989), Adalıer (1992), Kokusho (1999, 2002) and Tohumcu Özener et.al (2006, 2007 and 2009) investigated the response of stratified sands in small scale shaking table tests and showed that the presence of silt/clay soil interlayer may result in a water film entrapped beneath the less permeable soil layer. Similiar research works carried out with dynamic centrifuge experiments performed by Liu and Dobry (1993), Arulanandan and Scott(1993), Fiegel and Kutter (1994), Balakrishnan and Kutter (1999) Haigh and Madabhushi (2002), Brennan and Madabhushi (2005) also pointed out the effect of stratification and inhomogenity in soil properties (permeability) on liquefaction. The behaviour of dense sand layers underlaid by loose sand layers was experimentally investigated by Steedman and Sharp (1995), Steedman(2001) and Tohumcu Özener (2007) and it was observed that dense overlying sand layers are also capable of liquefying due to rapid transmission of excess pore pressures from the lower loose sand layers. There are also various numerical modeling studies which were performed to simulate the behaviour of stratified soil systems during earthquakes including Yoshida and Finn (2000) and Yang and Elagamal (2002). In these studies, the influence of permeability on the behaviour of layered soil systems and liquefaction-induced shear deformations were numerically investigated.

This paper presents the results of numerical analysis of shaking table model tests which were carried out in the laboratory on uniform sand columns, silt interlayered sand columns and two layered sand columns. The numerical modelling of silt interlayered sand model tests showed that an abrupt increase in the r_u values can be expected below the silt seam demonstrating the accumulation of pore water pressures due to the presence of silt layer.

SHAKING TABLE MODEL TESTS

The shaking table model tests were carried out in a rigid wall cylindrical container mounted on a shaking table which is triggered by a frequency-controlled electric motor producing sinusoidal motions. All the test models are prepared by pouring dry sand into water in a plexiglass cylinder of 24cm in diameter and 60 cm in height. For the silt interlayered test models, a 1 cm thick silt seam is placed in the middle of the sand column. PDCR 81 (DRUCK) type pressure transducers are placed at three different depths of the sand deposit to measure time dependent variation of excess pore water pressures during dynamic excitations. In Fig. 1, a uniform sand column model is shown with the pore water pressure transducer locations. The surface settlement and the water film thickness are measured by a digital video camera which is controlled by a computer program to record the images at 1 second time intervals. The grain size curves of the sand (D_{50}=0.31mm, e_{max}=0.88 and e_{min}=0.53) and silt used in the model tests are shown in Figure 2.

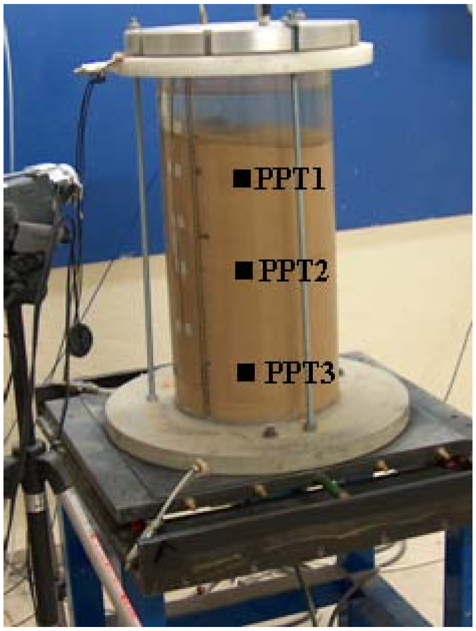


Fig.1. A uniform sand column model mounted on the shaking table

To investigate the liquefaction mechanism in layered soils, 3 series of shaking table tests which are summarized in Table 1 are carried out. The test models comprise uniform sand columns and various types of layered sand columns which correspond to different field situations. All the models are subjected to sinosodial base motions with 0.23g, 0.30g and 0.40g uniform accelerations.

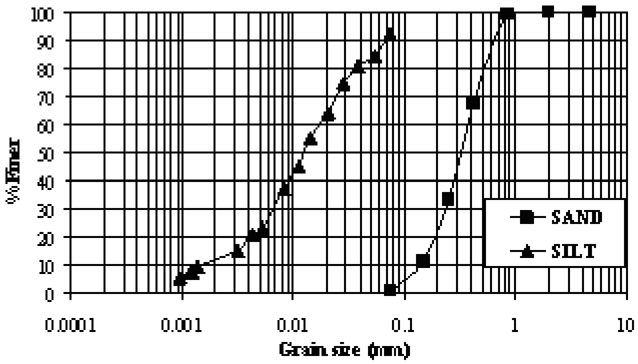


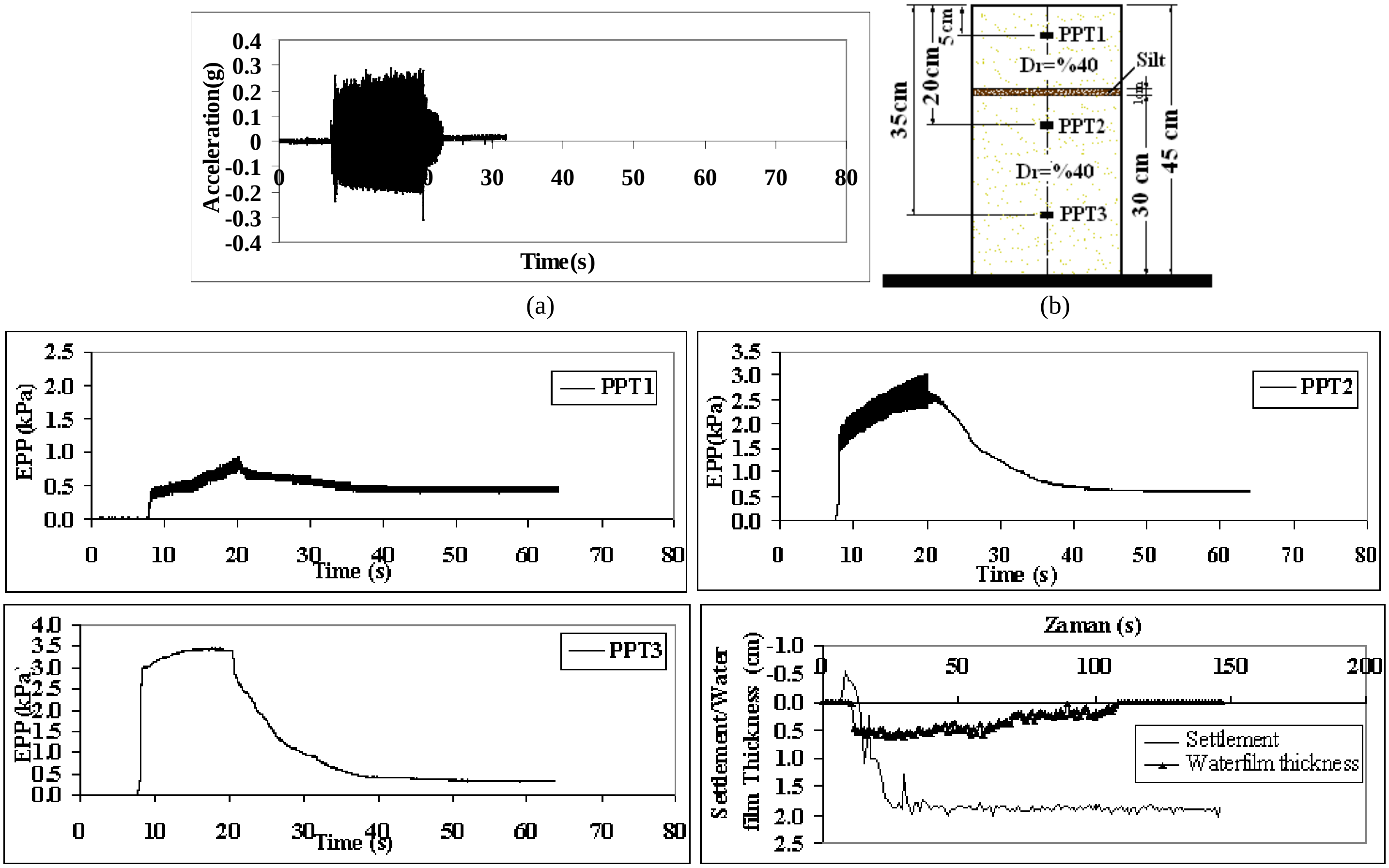
Fig.2. Grain size distribution curves of the sand and silt used in the experiments

Table 1. Summary of Shaking Table Model Tests

Model Series	Model Code	Model Height (cm)	Acceleration (g)	Relative Density (%)	
				Upper Layer	Lower Layer
Uniform Sand	U1A, U1B,U1C	45	0.23, 0.30, 0.40	40	
	U2A, U2B,U2C	45	0.23, 0.30, 0.40	72	
Silt Inter layered Sand	S1A, S1B, S1C	45	0.23, 0.30, 0.40	40	40
	S2A, S2B, S2C	45	0.23, 0.30, 0.40	72	72
	S3A, S3B, S3C	45	0.23, 0.30, 0.40	60	40
Layered Sand	L1A, L1B, L1C	45	0.23, 0.30, 0.40	72	40
	L2A, L2B, L2C	45	0.23, 0.30, 0.40	40	72
	L3A, L3B, L3C	45	0.23, 0.30, 0.40	60	40

The silt inter layered models (S1, S2, S3) were constructed to examine the effect of a less permeable soil layer within a liquefiable soil layer and its consequences on the generation of excess pore water pressures. In these models the 45 cm sand column had a 1cm thick silt seam in the middle. On the other hand, the behavior of layered sand deposits are investigated on layered sand columns (L1, L2, L3) comprising loose sand layers overlying dense sand layers and dense sand layers underlain by looser sand layers. In Fig.3. The time dependent variations of excess pore water pressures, thickness of water film and surface settlement measured in Model S1A are shown.

The experimental observations disclosed that the presence of a thin silt layer inhibits excess pore water pressure dissipation and the settlement of underlying loose sand layer results in formation of a water film beneath the silt seam. The water film developed beneath the silt seam is shown in Fig. 4.



(a) (b)

(c)

Fig.3. (a) Input base acceleration (b) The locations of the pwp transducers (c) excess pore water pressures and surface settlement measured in Model S1A

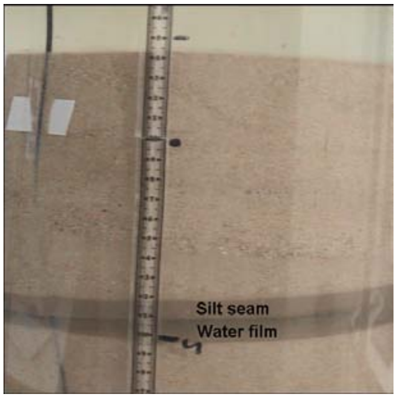


Fig. 4. The water film developed beneath the silt seam

NUMERICAL ANALYSIS BY DIANA

The physical model tests which are carried out under this research are numerically modelled in DIANA finite element program by using the Towhata-Iai liquefaction model (Towhata and Ishiara 1985, Iai et al. 1990) to analyse the dynamic behavior of uniform and layered sand columns. The constitutive model employed in the numerical analysis is based on a multiple shear mechanism in which the excess pore water pressure generation during cyclic loading is computed by using the liquefaction front parameter, S_0, which is a function of plastic shear work and shear stress ratio, r (Fig. 4).

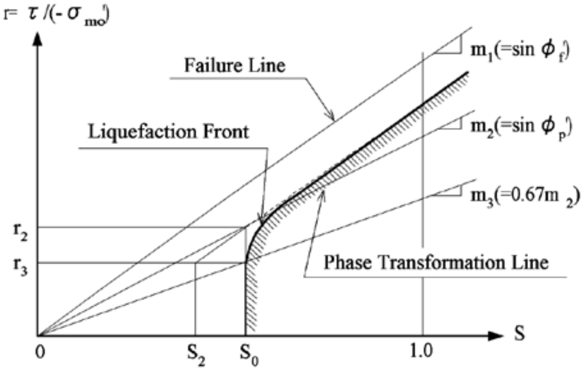


Fig.4. The pore water pressure generation implemented in Towhata-Iai liquefaction model (Iai, 1992).

The model parameters used in the analysis are outlined in Table 2. Here, ϕ_f and ϕ_p are the shear resistance angle and phase transformation angle of the soil, respectively and S_1, w_1, p_1, p_2, c_1 are dimensionless dilatancy parameters of the soil and h_{max} is the maximum damping factor. The details of the numerical model and the procedure to calibrate these parameters can be found in Iai et al. (1990) and Tohumcu Özener (2007).

Table 1. Model parameters for liquefaction analysis

Soil Type	Relative Density (%)	ϕ_f (°)	ϕ_p (°)	S_1	w_1	p_1	p_2	c_1	h_{max}
Sand	40	34	30	0.0005	2.0	0.75	0.72	1.8	0.24
	60	37	33	0.0005	5.0	2.0	0.72	1.8	0.24
	72	39	35	0.0005	15	4.0	0.72	1.8	0.24
Silt	-	37	33	0.0005	30	1.0	4.0	1.8	0.20

In order to study the dynamic response of sand columns, four-noded two dimensional quadrilateral plane strain elements are used and the finite element meshes of the experimental models are created to coincide with the locations of the pore water pressure transducers in the model tests. The finite element mesh is shown in Figure 5a for the uniform and two layered sand columns and in Figure 5b for the silt inter layered sand columns. As it is seen in Figure 5b, mesh refinement is applied in silt inter layered models to be able to compute the excess pore water pressures beneath the silt seam more precisely. To simulate the boundary conditions of the rigid container, base nodes are fixed both horizontally and vertically, and at two lateral boundaries, only lateral displacements are fixed.

Prior to the dynamic analysis a static analysis is performed to determine the initial stress and static equilibrium states. The resulting effective stresses and hydrostatic pressures are then used as initial conditions for the dynamic analysis. The recorded motion from the shaking table model tests are used as an input motion during the analysis.

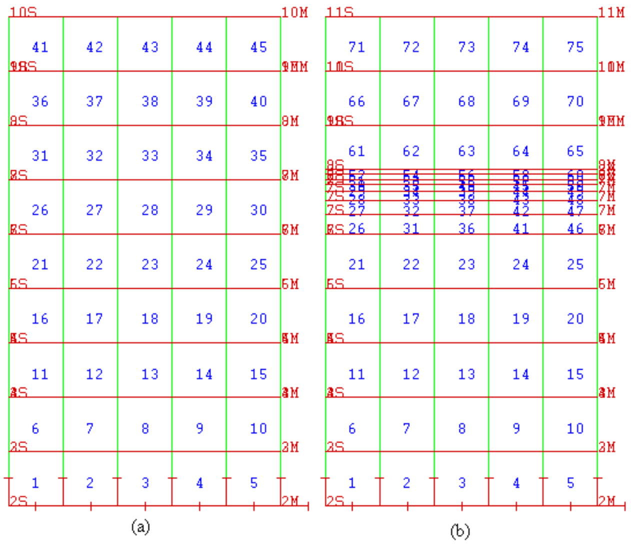


Fig.5. The finite element meshes a) for uniform and two layered sand models b) for silt inter layered sand models

Comparison of Measured and Computed Excess Pore Water Pressures

It is worth noting that the results and evaluations presented in this paper mainly discuss the effect of stratification on the computed excess pore water pressures. Therefore, detailed discussions and evaluations on the recorded excess pore water pressures, settlements and water film thicknesses during shaking table model tests are not covered herein. The detailed evaluations of the experimental results can be found in Tohumcu Özener (2007, 2009).

As a result of the numerical analyses, the excess pore water pressure time histories are computed for the test models and compared with the experimental results. The computed and measured time histories of excess pore water pressures are shown in Figure 6 for the uniform sand column at 40% relative density. The variation of computed and measured excess pore water pressures with depth for layered sand column model L3 and silt inter layered sand column S3 are shown in Fig. 7 and Fig. 8, respectively. The numerical simulation of excess pore water pressure development is seen to be comparable with the experimental results except the one measured in the shallow depth of model U1B. This inconsistency is which is observed at some physical models is thought to be due to the disturbance of the sand at very low confining stress levels.

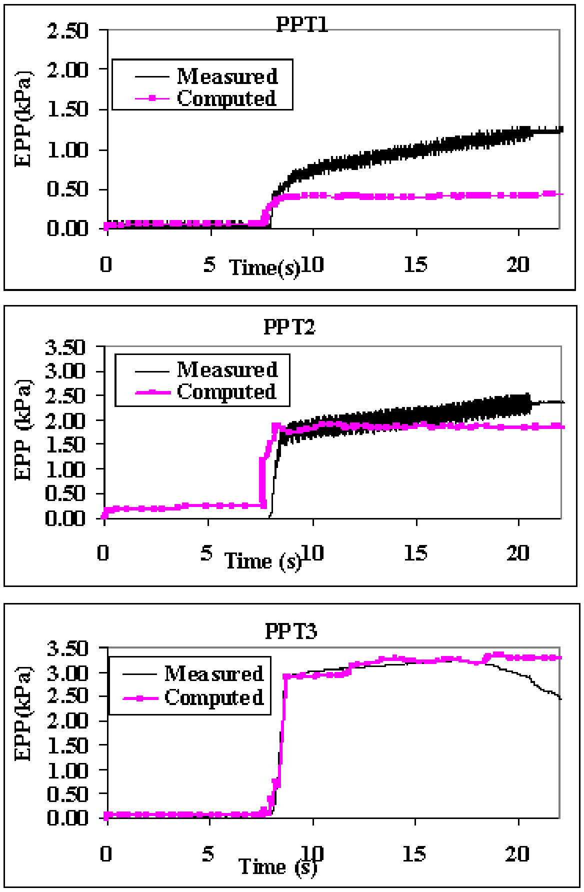


Fig. 6. The time histories of computed and measured excess pore water pressure in uniform sand model (U1B)

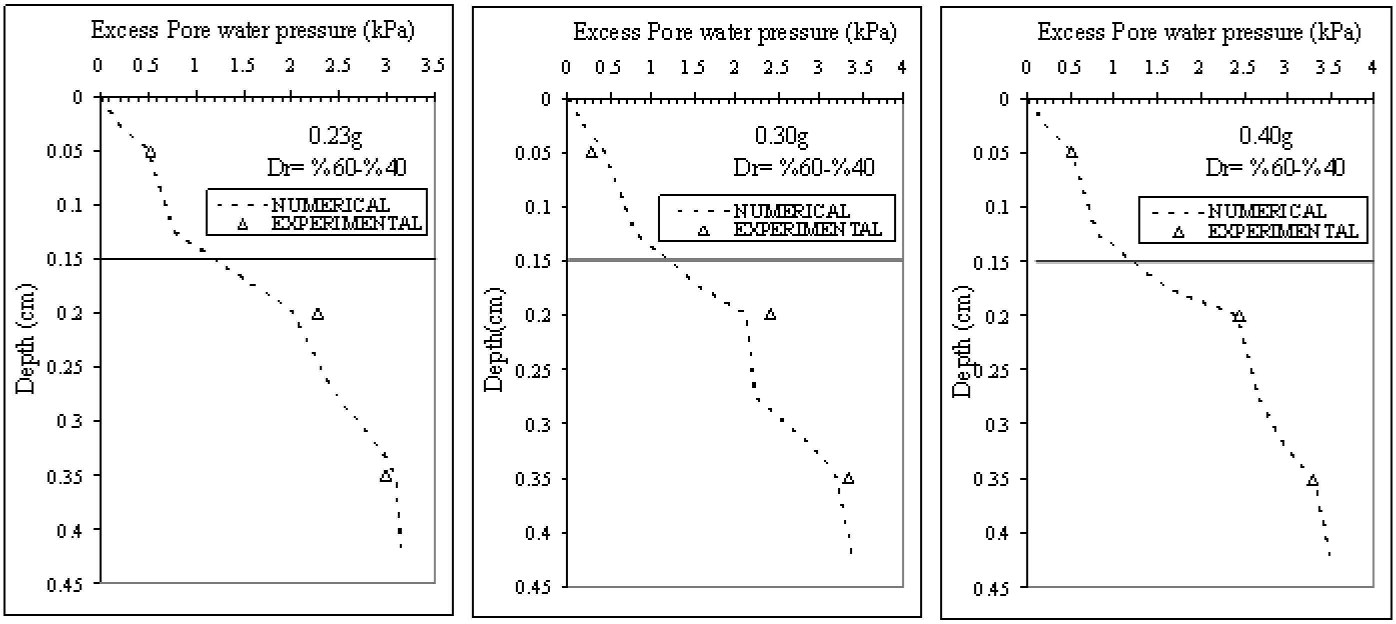


Fig. 7. The comparisons of variation of computed and measured excess pore water pressures with depth for layered sand column model L3

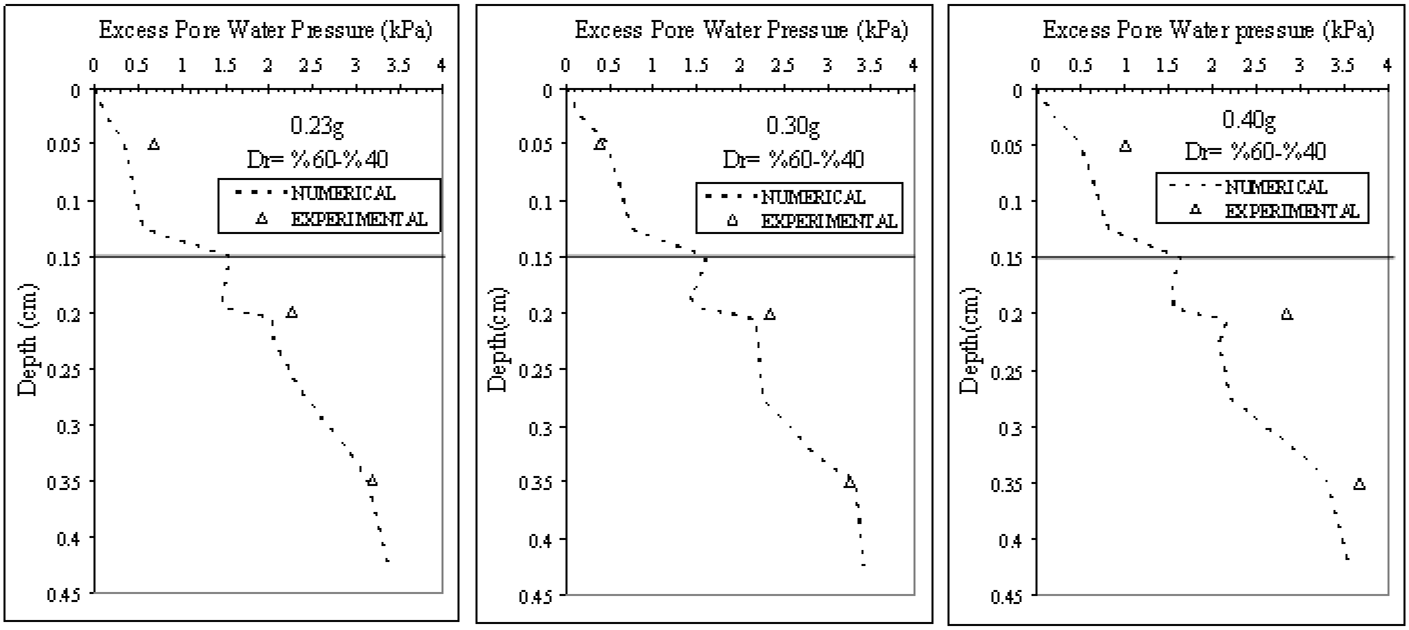


Fig. 8. The comparisons of variation of computed and measured excess pore water pressures with depth for layered sand column model S3

Results of Numerical Analysis For Silt Inter Layered Sands

The existence of less permeable silt layer in a sand deposit is also simulated by Towhata-Iai numerical model and compared with the numerical results of uniform sand models. In Figure 9, the variation of computed excess pore water pressure ratios with depth for the cases representing silt inter layered sand column is compared with the values computed for uniform sand model at 40% relative density and Figure 10 illustrates the comparisons of variation of excess pore water pressure ratios in the layered sand column (L3) with the silt inter layered sand column (S3).

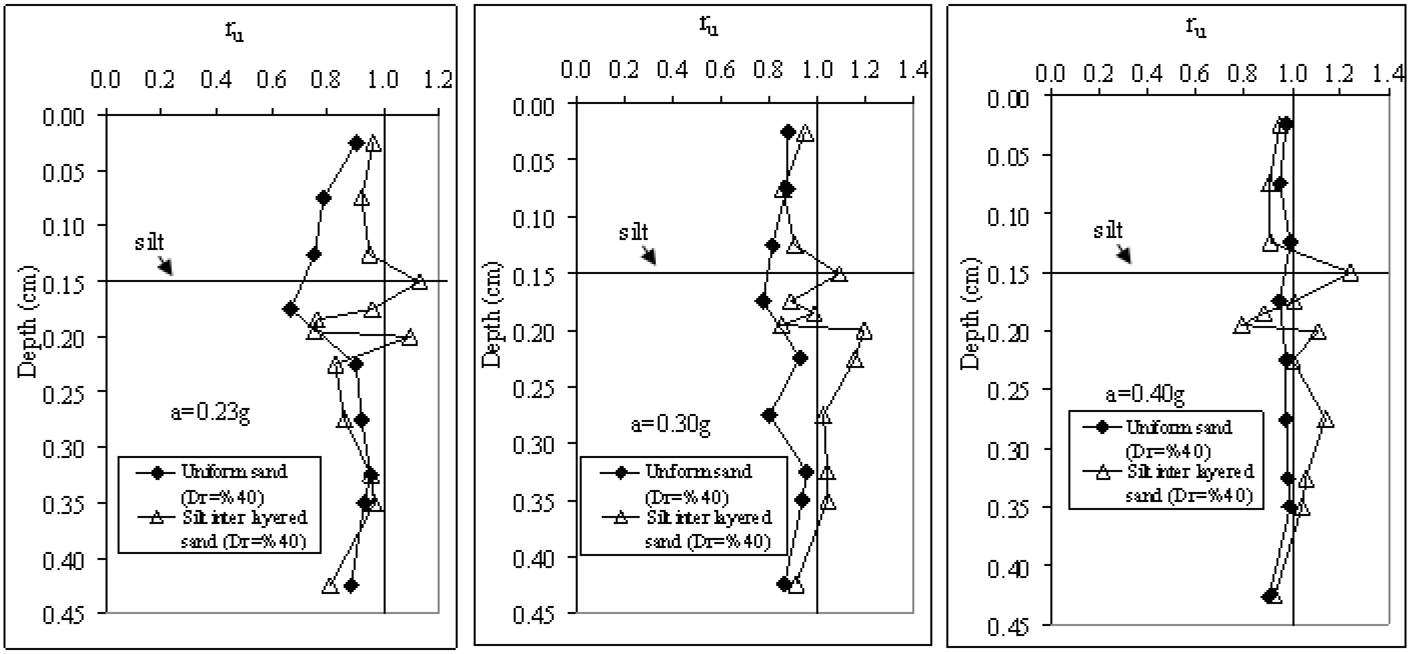


Fig. 9. Comparison of variation of computed r_u values with depth for the silt inter layered sand model (S1) and uniform sand model (U1)

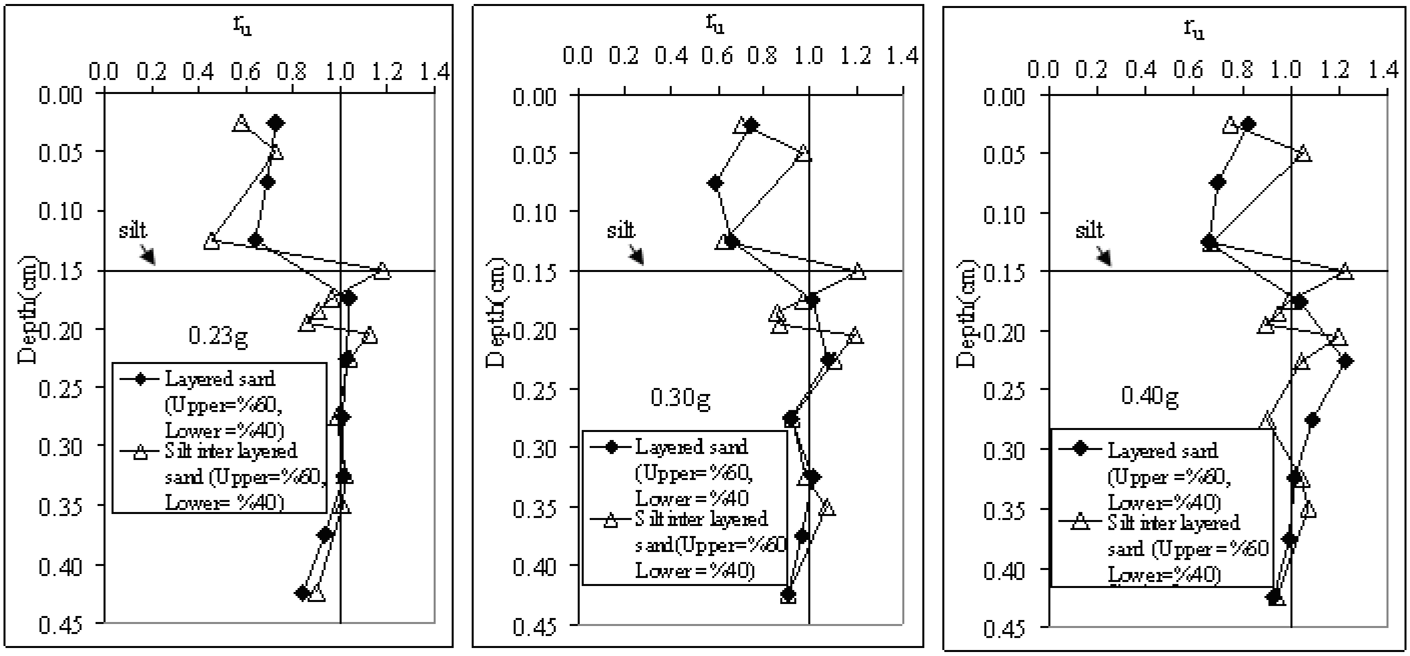


Fig. 10. Comparison of variation of computed r_u values with depth for the silt inter layered sand model (S3) and layered sand model (L3)

As seen in these figures, there is a small amount of increase in computed r_u values for silt inter layered sand below the silt seam demonstrating the accumulation of pore water pressures at that depth due to the presence of silt seam.

Results of Numerical Analysis For Layered Sands

The behavior of dense sand layers overlying loose sand layers and dense sand layers overlaid by loose sand layers are numerically investigated to study the generation of excess pore water pressures in layered sands during earthquakes. For

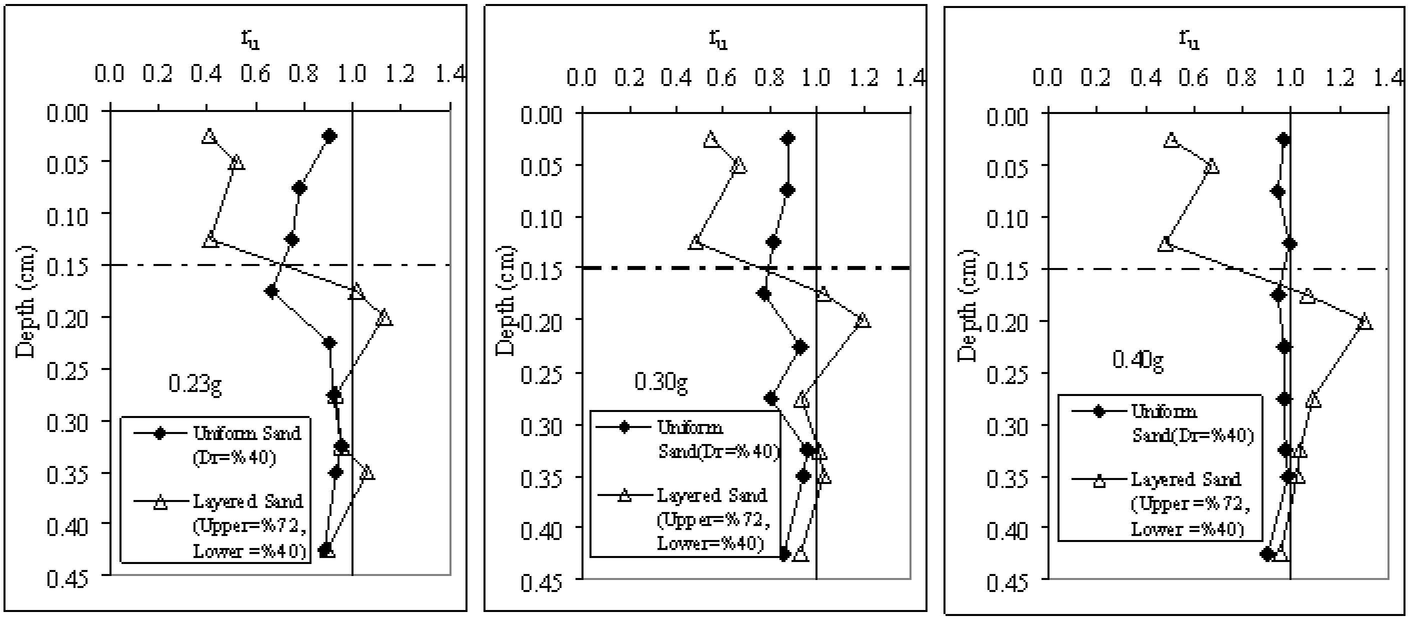


Fig.. 11. Comparison of variation of maximum r_u values in a loose sand deposit overlaid by a dense sand layer (Model L1) and a uniform loose sand (Model U1)

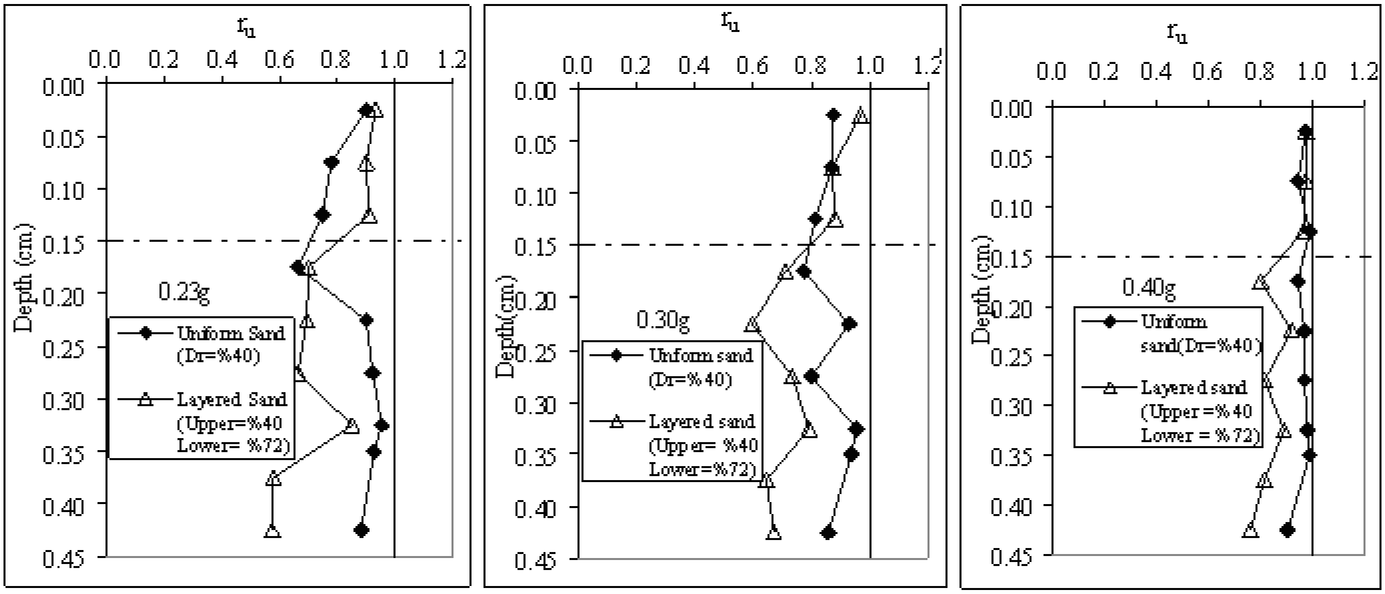


Fig.12. Comparison of variation of maximum r_u values in a dense sand deposit overlaid by a loose sand layer (Model L2) and a uniform loose sand (Model U1)

this purpose, the excess pore water pressure ratios computed in the layered models are compared with the ones computed in the uniform sand model at 40%. In Figure 11, it is observed that the presence of overlying dense sand layer has an increasing effect on the excess pore water pressures developed in the lower loose sand layer, but on the contrary of the results drawn from the experimental results, the development of high excess pore water pressures in the upper dense sand layer due to the migration of excess pore water pressures from the bottom loose sand layer is not predicted by the numerical analysis. In Figure 12 where the computed r_u values of layered sand model comprising of dense sand layers overlaid by loose sand layers are compared with the uniform sand model, it is seen that the excess pore water pressures generated in the upper sand layer are not influenced from the presence of underlying dense sand layers, consistent with the experimental observations.

It is believed that the numerical analysis, employed in this study can quite successfully predict the effect of a silt seam on the generation of pore water pressures and formation of a water film observed in the model tests. However, the development of excess pore water pressures in layered sand columns are not satisfactorily simulated in the numerical analysis. This is due to the fact that the constitutive model employed in the analysis can not capture the migration of upward water flow during the generation of excess pore water pressures. Therefore, it is believed that a constitutive model coupled with a ground water flow analysis must be used to simulate the generation of excess pore water pressures especially in layered sand deposits.

CONCLUSIONS

In this paper, the results of numerical analysis which were carried out to investigate the liquefaction mechanism in layered and silt inter layered sands are presented. As a result of the study, the following conclusions are drawn.

Based on the observations in the shaking table tests on uniform sand models, silt inter layered sand models and two layered sand models, the generation of excess pore water pressures are highly influenced by the pore water pressure transmission. From the experimental observations in silt inter layered sand models, it is concluded that the presence of a thin silt layer which prevents drainage and dissipation of excess pore water pressure can cause formation of water film at the interface between two sand layers. The experimental results from two layered sand columns comprising of loose sand layers overlaid by a dense sand layer and loose sand layers overlying dense sand layers also demonstrated the significant role of pore water transmission in the development of excess pore water pressures during earthquakes. The transmission of excess pore water pressures from bottom loose sand layers is observed to liquefy the dense overlying sand layers.

The numerical modelling of silt inter layered sand model tests showed that there is a small amount of increase in the r_u values below the silt seam demonstrating the accumulation of pore water pressures at that depth due to the presence of silt seam. However, there are some discrepancies between the computed and recorded results for layered soils. These discrepancies are believed to be related to the inability of the constitutive model to model the upward migration of excess pore water pressures developed during cyclic loading. Therefore, further research work is needed primarily for more accurate modeling of upward flow during liquefaction and it is believed that a constitutive model coupled with a ground water flow analysis must be used to simulate the generation of excess pore water pressures especially in layered sand deposits. In spite of a number of shortcomings, the results are believed to show that numerical analysis can quite successfully predict the behavior observed in cyclically loaded uniform and silt inter layered sands.

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