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WATER PRESSURE TRANSMISSION AND SOIL LIQUEFACTION

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ABSTRACT

This paper attempts to interpret and assess the behavior of saturated sandy soils during an earthquake based on the experiment results in 1 g shaking table tests on clean sand in a large biaxial shear box at the National Research Center for Earthquake Engineering, Taiwan. Observations of the soil responses in the experiments by others and those of in situ soils in the field during large earthquakes were also considered. According to a postulate of water pressure transmission in a transient and nearly undrained condition, the pore water pressure generations at various locations can quickly affect the soil behavior, and possibly induce liquefaction, at different depths and locations. Numerical computations were conducted to illustrate this phenomenon. Therefore, it is necessary to consider the seismic responses of soils globally within all pertinent soil strata at different locations and depths in order to have a better understanding of the behavior of soil under earthquake loading. Some important implications and their significances in the assessment of soil liquefaction are discussed.

Keywords: Saturated sand, Water pressure, Liquefaction, Shaking table tests, Earthquake.

INTRODUCTION

In the recent years, there are many experiments using large soil specimens on shaking tables that can reproduce the actual seismic ground shaking in either centrifuge tests or large scale 1 g shaking table tests, e.g., Hushmand et al. (1988), Taylor et al. (1995). Under well-controlled boundary conditions, these tests can reasonably simulate the field stress conditions and the anticipated earthquake loading.

Large scale 1 g shaking table tests were performed using the biaxial laminar shear box (1.880 m × 1.880 m in plan and 1.520 m in height) developed at the National Center for Research on Earthquake Engineering (NCREE), Taiwan. This biaxial laminar shear box at NCREE can be used to simulate a soil stratum of about 1.5 m under a multidirectional shaking on a horizontal plane. Figure 1 shows the large biaxial laminar shear box on the shaking table. The performance and instrumentation in the shear box were tested and verified, and they were found satisfactory (Ueng, et al., 2006). Densely placed instrumentation in the large size specimen provides well distributed measurements, spatial and temporal, for a better understanding of the behavior, especially liquefaction, of a clean sand stratum.

Based on the phenomena observed in the shaking table tests at NCREE, field data available to the authors, and the pertinent data by other researchers, this paper presents the studies and postulate on the responses, especially pore water pressures and liquefaction, of saturated sandy soils to earthquake loading.

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Figure 1. Large biaxial laminar shear box on shaking table at NCREE

SHAKING TABLE TESTS AT NCREE

Nine series of shaking table tests on clean sand in the shear box have been conducted at NCREE since August 2002. A fine silica sand from Vietnam was used to prepare the sand specimen for the shaking table tests at NCREE. The representative gradation curve of this sand is shown in Fig. 2. The maximum void ratio, e_{max}, and minimum void ratio, e_{min}, range from 0.887 to 0.912 and 0.569 to 0.610, respectively, for different batches of sand used in the tests. The permeability of the sand ranges from 0.04 cm/s to 0.1 cm/s for relative densities between 35% and 90%. One- and multi-directional shaking motions including sinusoidal waves (with frequencies from 1 to 8 Hz and amplitudes, A_{max}, from 0.03 to 0.15 g) and acceleration time histories, full and reduced amplitudes, recorded in various earthquakes were applied. Miniature piezometers and accelerometers were installed within the sand specimen for pore water pressure and acceleration measurements at different locations and depths in the soil during shaking. Transducers for displacements and accelerations were also placed on different layers of the frames to record the movements of the specimen.

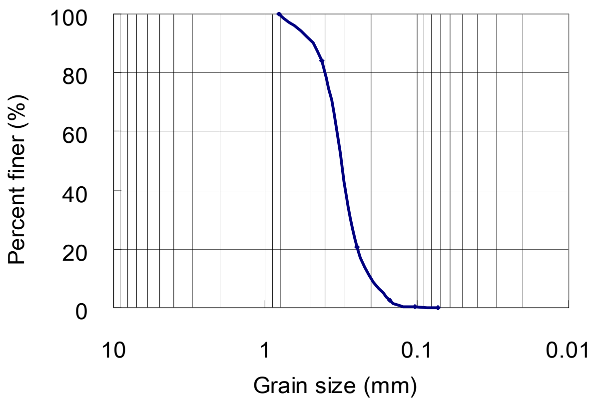

Figure 2. Typical grain size distribution of clean Vietnam sand

Large amount of data were obtained from the rather densely placed sensors inside and outside the sand specimen. The observations and analyses of the soil behavior during the shaking table tests using the biaxial laminar shear box provide the primary bases for the following discussions on the behavior of saturated sandy soil under earthquake loadings. It should be noted that in these shaking table tests and most field conditions, water drainage only occurred through the upper surface of the soil stratum.

In reality, the long drainage path through the bottom of the soil stratum should render very limited bottom drainage under the transient seismic loading.

WATER PRESSURE CHANGES AND LIQUEFACTION DEPTH

The effective stress in the soil is regarded as the controlling factor on the behavior of saturated sand. As the external total overburden stress generally remains unchanged, the change in pore water pressure is the main parameter affecting the responses of saturated sand under earthquake loading. Therefore, the discussions in this paper will emphasize on the generation, changes, and transmission of pore water pressure and their effects on the behavior of saturated sand. Along this line, the liquefaction of soil in this paper is defined as the state of soil with its pore water pressure, u, equal to the total overburden pressure, σ_v, i.e., the effective stress, $\sigma_v' = 0$. In other words, the soil is at a state of liquefaction when the excess pore pressure ratio, $r_u = u_e/\sigma_v'$, reaches 1.0.

For a homogeneous sand stratum subjected to earthquake loading, the shallower part is always found more susceptible to liquefaction than the deeper soil. With an impervious bottom of the shear box, there is an upward hydraulic gradient during and after shaking. Figure 3 is the pore water changes at different depths during a shaking test at NCREE. In Fig. 3, and hereafter in this paper, the pore water pressure is presented in terms of water height (mm). This plot indicates that the sand above a depth of 92 mm liquefied first, followed subsequently by the deeper soil, but does not liquefy below the depth of about 898 mm. It also shows that the excess pore water pressure at the shallower depth generally does not exceed and at most equal the pressure at the deeper depth. The same observations were reported by others in their shaking table tests both under 1 g or centrifuge condition (e.g., Van Laak, et al., 1994). Field observations during earthquakes also showed that liquefaction occurred in the sandy soil at a shallower depth rather than in the deeper soils, although it might be owing to a possibly higher density of the deeper soils.

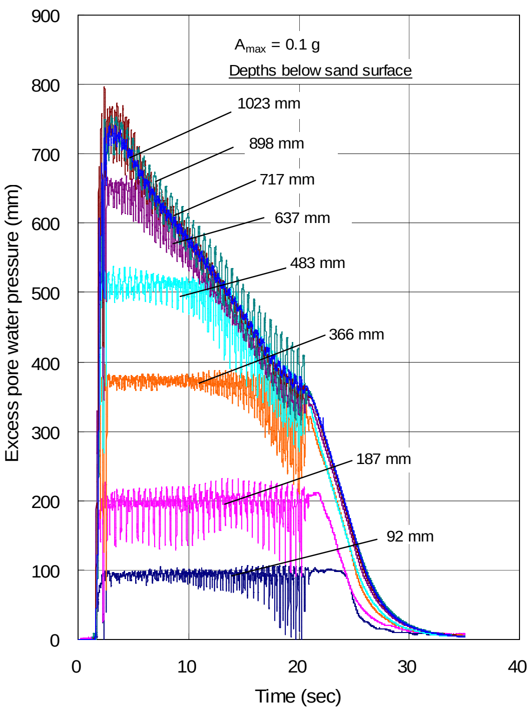

Figure 3. Pore water changes at various depths during a shaking test, October 2004

For a homogeneous stratum of sandy soil tested on the shaking table, the above-mentioned observed phenomena seem to contradict the common understanding of the liquefaction mechanism. According to Seed (1979), the equivalent cyclic shear stress ratio (CSR) acting on a soil element in a level ground is:

$$CSR = 0.65 \frac{A_{max}}{g} \frac{\sigma_v}{\sigma_v'} r_d \qquad (1)$$

where A_{max} = peak ground acceleration of an earthquake, m/s^2,
g = acceleration of gravity = 9.81 m/s^2,
σ_v = total vertical overburden stress, Pa,
σ_v' = effective vertical overburden stress, Pa, and
r_d = reduction factor considering the flexibility of soil stratum.

Within the soil depth (≈1.5 m) of a shaking table test (or within the field liquefiable strata near the ground surface), r_d should be near 1.0, and the value of σ_v/σ_v' is the same throughout the whole uniform stratum of saturated soil. Therefore, the soil should undertake the same CSR within the whole depth according to Eq. (1). As a result, the excess pore pressure ratio, r_u, induced by the cyclic loading at a given time should be the same at every depth of the specimen. That is, the whole soil stratum should liquefy at the same time if the earthquake loading exceeds the cyclic resistance stress ratio (CRR). Additionally, the deeper soil with a larger effective overburden pressure should exhibit a lower liquefaction resistance (Seed and Harder, 1990), and liquefaction would occur first at the deeper depth rather than at the shallower depth. This contradictory behavior of easier liquefaction of the shallower soil was explained by Ueng (2006) based on the postulate of transmission of excess pore water pressure generated during earthquake shakings.

PORE WATER PRESSURE TRANSMISSION

Considering a level homogeneous soil stratum, either on the very top of the ground or beneath some layers of other soils, undergoing an earthquake shaking as shown in Fig. 4(a), the induced excess pore water pressure is $u_e = r_u \sigma_v'$ at all depth in the stratum. If the generation of the water pressure is very rapid under a dynamic loading, it is usually considered that the soil is under an undrained condition, namely, the pore water is in an enclosed container. That is, according to Pascal's principle, the pressure change will be transmitted to all parts of the water within the enclosed container or the soil stratum. Furthermore, the transmitting of the pressure change should be immediate if the water and soil particles are assumed incompressible. Therefore, as shown in Fig. 4(a), there will be an increase of pore water pressure of a value of about $(r_u z \gamma')/2$ in the whole stratum of soil, where z is the depth of the soil stratum and γ' is the submerged unit weight. The effective stress will be less than 0, or liquefaction occurs in the soil above the depth z_L where the effective overburden pressure, $z_L \gamma'$, is less than the induced excess pore water pressure, $(r_u z \gamma')/2$. As the water pressure in the soil above z_L is greater than the total overburden stress, there should be an uplift of the soil layer above z_L. The pore water pressure thus reduces to a maximum of the total overburden pressure with a tiny amount of expansion of the soil due to the very high bulk modulus of water. Once this happens, the mechanism of water pressure transmission becomes more complex, and the amount of transmitted water pressure and the pressure distribution at various depths change accordingly. The above argument leads to the distribution of excess pore water pressure as shown in Fig. 4(b) that we often see in the shaking table tests. For example, Figure 5 is the excess water pressure distribution along the depth of the sand specimen in a shaking table test at NCREE. The one-directional shaking caused a liquefaction depth of around 220 mm, while the multidirectional shaking induced liquefaction at a deeper depth of about 760 mm with a higher pore water pressure generation.

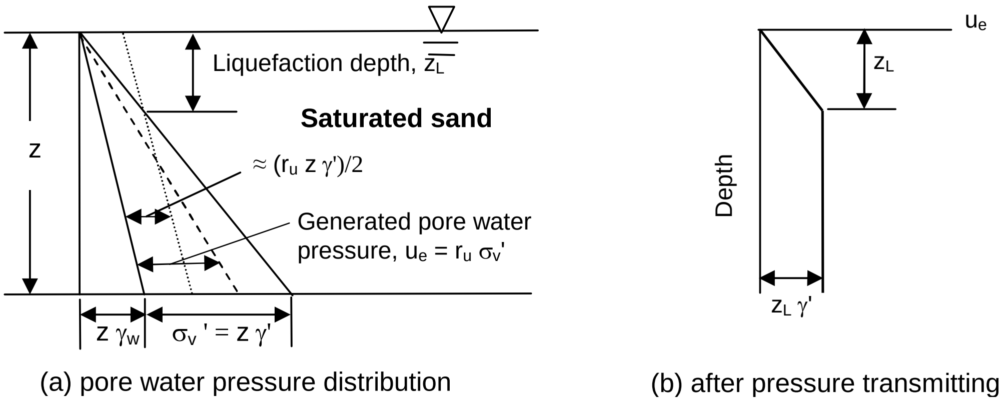

Figure 4. Schematic pore water pressure distribution and its changes in a soil stratum

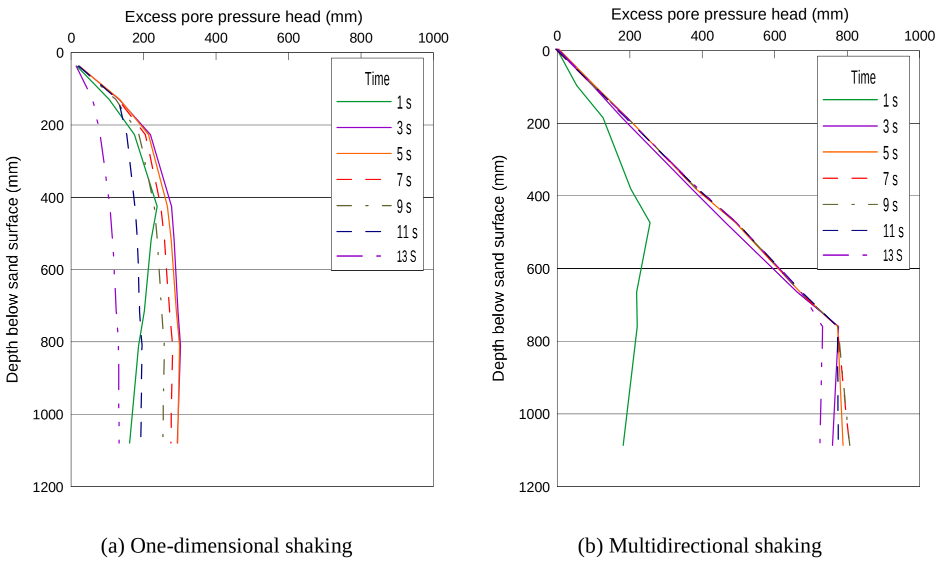

Figure 5. Pore water pressure distribution in the sand specimen in a shaking table test (A_{max} = 0.075 g) at NCREE

It should be noted that the above-mentioned water pressure transmission and liquefaction can occur without any water flow or upward hydraulic gradient; it is independent of the type of soil; and it can occur during and/or after earthquake shakings. That is, no water seepage is necessary to induce liquefaction or flow failure. This differs from the proposed flow failure due to seepage by Sento et al. (2004). In realty, the water and soil grains are not truly incompressible, and there is always drainage at the surface of an in situ sandy soil layer unless it is covered by an impervious, non-liquefiable soil layer. Consequently, there would be some diminished amount and time delay of the pore water pressure transmission depending on the easiness of the boundary drainage, the permeability of the soil, and the compressibility of water and soil particles. Theoretically, there should be water pressure wave propagation but the pressure should reach an equilibrium value in a very short time due to the high damping effect of water movement inside the small pore sizes of the soil. Detailed analyses of the phenomena of water pressure generation and transmission are outside the scope of this paper.

The above postulate of pore water pressure change and pressure transmission lead to that the pore water pressure change at a given location within a soil stratum does not only depend on the characteristics of the pore pressure generation of the soil at that location but is also affected by the pore water pressure changes of soils at other locations. Thus, the behavior of the soil at one point in the ground would be affected globally by the soils at all locations within the strata of the pertinent area and depth. For example, the results of shaking tests in the VELACS (Hushmand, et al., 1994) showed that the water pressure changes in the loose and dense sand columns side by side are essentially the same during shaking, even though the denser sand should have had a lower pore water pressure generation under the same shaking.

SIMPLIFIED NUMERICAL COMPUTATIONS

Numerical computations with simplified assumptions were performed to illustrate the postulated mechanism of water pressure transmission within a soil stratum under seismic shakings. The commercial code, FLAC, was used with special input conditions to simulate the situations of water pressure changes in the shaking table tests. One-dimensional water pressure transmission and water drainage in the vertical direction were considered in a homogeneous soil stratum of 1.5 m in thickness. Excess pore water pressure was induced by shocks of shakings and followed by transmission and redistribution of water pressure within the soil stratum. At any depth of the soil stratum, the water pressure can no longer increase when the soil reaches liquefaction, i.e., a maximum water pressure equal to the total overburden pressure, i.e., $r_u \leq 1.0$, is imposed. Two modes of pore water pressure generations are examined in this study.

Single shock shaking

The excess pore water pressure with $r_u \approx 0.4$ in all depths of the specimen (i.e., a triangular distribution with depth) is induced by a single shock and no drainage is allowed during and after shaking. Water as the sole material (water-only model) was adopted in FLAC to simulate the water pressure wave propagation with high damping within the soil stratum. The computation results in Fig. 6 give a similar excess water pressure distribution versus depth as that shown in Fig. 4(b) suggested by the postulate of water pressure transmission. It can be seen that the water pressure transmission occurs in a very short time ($\leq$ 0.006 s). The values of density and bulk modulus of water used in the computations are 1000 kg/m^3 and 2×10^9 N/m^2, respectively.

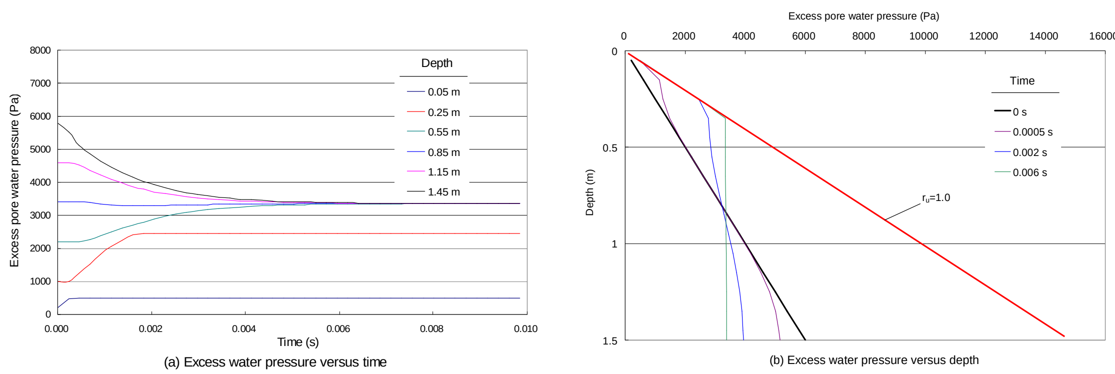

Figure 6. Computed excess pore water pressure changes induced by a single shock shaking

Successive shakings

The excess pore water pressure is generated and cumulated without drainage by successive small shocks at an interval of 0.25 s for a total duration of 10 s. In each shock of shaking, the excess water pressure is induced only in the non-liquefied zone with an increment of $\Delta u_e = 0.136\ \gamma'\ h$, where h is the depth from the top of the non-liquefied layer. After the end of shaking, the water is allowed to drain through the upper surface of sand specimen. As in the single shock shaking, the water-only model was used in FLAC for the water pressure transmission during shaking, while soil and water were both included in FLAC to consider the drainage (consolidation) condition after shaking. The values of 1500 kg/m^3, 3.76×10^7 N/m^2, and 1.44×10^7 N/m^2 were assumed respectively for the density, bulk modulus, and shear modulus of the soil. Two hydraulic conductivities (k) of the soil, 0.06 cm/s and 0.001 cm/s, were considered in the computations. Figures 7 and 8 show the results of the numerical computations for k = 0.06 cm/s and 0.001 cm/s, respectively. A prolonged higher water pressure at the shallower depth is observed. The dissipation rate of water pressure due to drainage indicates that the water pressure transmission during shaking could be affected by water drainage for a soil of a very high k value. That is, the assumption of an undrained condition during earthquake shaking may not be valid in such case.

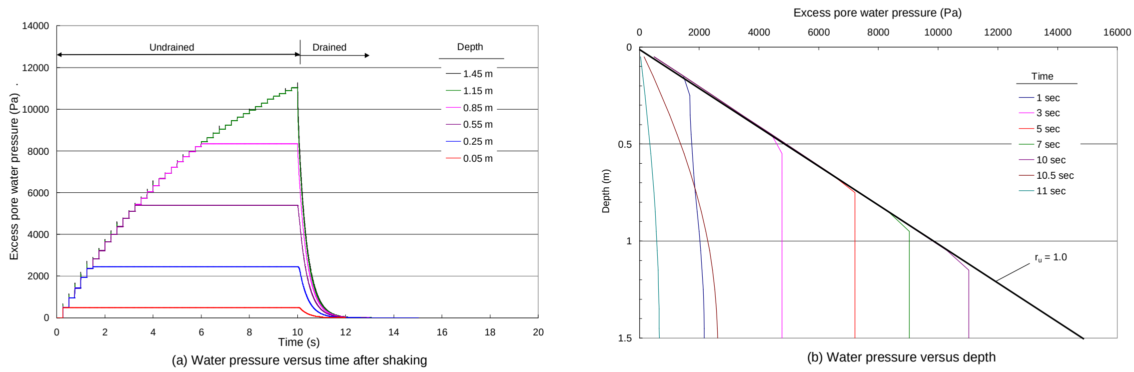

Figure 7. Computed excess pore water pressure changes induced by successive shakings, k = 0.06 cm/s

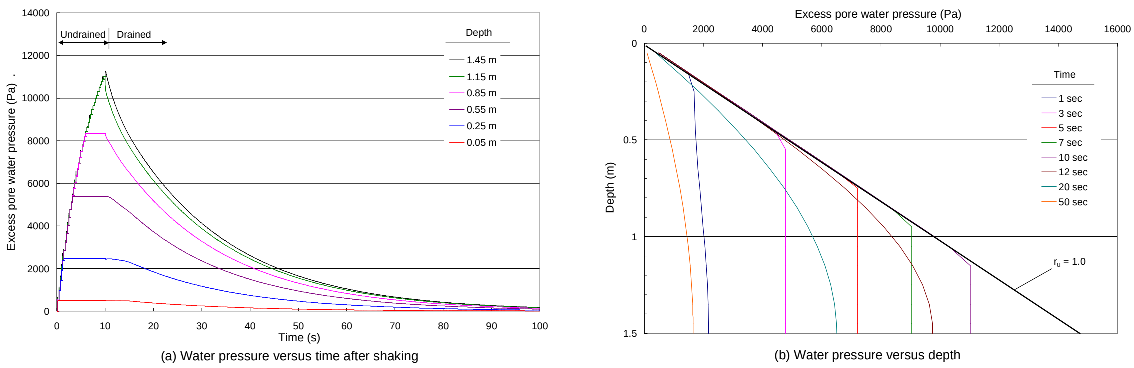

Figure 8. Computed excess pore water pressure changes induced by successive shakings, k = 0.001 cm/s

SIGNIFICANT IMPLICATIONS

Even though further studies are needed for a better understanding of some of the phenomena observed in the shaking table tests and in the field during earthquakes, the following significant implications from the postulate of water pressure transmission can be drawn:

1) The common methods of liquefaction potential assessment by simply comparing the CRR of a soil element with the CRS induced by an earthquake at that location may not be sufficient without considering the water pressure transmission phenomenon as discussed in this paper. The analysis, analytical or numerical, should be able to take into account the effect of pressure transmission and drainage of pore water during and after earthquake shaking.
2) For soil of a high liquefaction-resistance, such as gravelly soil, even though the earthquake shaking is not sufficiently strong to cause liquefaction of this soil element, the soil can liquefy

because its pore water pressure can exceed the total overburden pressure when water pressure is transmitted from another location, where a high pore water pressure is generated by the earthquake loading. Many field cases of liquefaction of gravelly soils could have occurred due to this mechanism. This phenomenon was confirmed in the centrifuge tests by Steedman and Sharp (2001) who found that rapid transmission of excess pore water pressure from loose layer below can cause liquefaction of the dense overlying layers.

3) The rates of pore water pressure generation and drainage play the essential roles in the water pressure transmission in the soil stratum. A faster water pressure increase but slower water drainage causes the more rapid and less diminished pressure transmission. The higher the frequency, the faster the pore water pressure is generated, resulting in a faster water pressure transmitting to the shallower depth. This explains why soil liquefies easier under vibrations of a higher frequency in the shaking table tests.
4) A liquefiable sandy soil overlain by an impervious crust, which prevents the drainage and dissipation of the induced water pressure, should have a good chance of liquefaction and possibly a water film beneath the impervious layer if sand boiling does not occur and the liquefied sand particles starts to sediment (Kokusho, 1999, Brennan and Madabhushi, 2005). The quickly transmitted pore pressures and prolonged high water pressures reported by Youd (1999) indicated a poor field drainage condition at the Wildlife site.
5) At the upper part of a sand stratum, if the effective overburden pressure is low (zero when the stratum is on the surface), it can liquefy readily at a shallow depth. On the other hand, if this liquefiable soil is overlain by a thick non-liquefiable soil such that the induced pore water pressure at the top of this stratum after aforementioned pressure transmission is still less than the effective overburden pressure, then no liquefaction will occur. This may be one of the reasons why a thicker overlying non-liquefiable causes less liquefaction damage (Ishihara, 1985).
6) For a sloping ground surface, the mechanism of water pressure transmission can cause flow failure and lateral spreading due to reduction of effective stress and softening of soil under a sustained shear stress. This shear stress could be substantially less than the residual strength obtained from the laboratory tests without considering the water pressure transmission (Finn, 2000). As mentioned before, this phenomenon does not necessarily require water flow or hydraulic gradient in the soil.
7) The remediation measures against liquefaction and flow failure could also take advantage of water pressure transmission within the soil strata. Short gravel drainage piles in the shallower depths of the liquefiable soil could be as effective as deep stone columns. Further studies on this matter are needed, even though Brennan and Madabhushi (2006) suggested installation of drains through the full liquefiable depth for liquefaction mitigation according to their centrifuge test results.

CONCLUSIONS

Based on the observations in the 1 g shaking table tests on large soil specimens, it is concluded that because of the phenomenon of water pressure generation and transmission during and after an earthquake shaking, the pore water pressure changes in the soil under earthquake loading not only change the soil behavior at that location, but also affect the responses of soil within the whole relevant stratum globally. The easier occurrence of liquefaction of soil at a shallower depth in a uniform soil stratum is an example. The numerical computations and results by others also confirm this phenomenon. The effect of the water pressure transmission depends on the rate of pore water pressure generation, boundary drainage, permeability of the soil, etc. A soil with a high liquefaction resistance can thus liquefy even without a sufficiently strong shaking, but due to a high water pressure transmitted from other soil strata. Therefore, the assessment, analysis, and remediation measures of a liquefiable soil stratum should take this phenomenon into account.

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