*Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering*

*doi:10.3233/978-1-61499-656-9-2719*

# Liquefaction potential of horizontal layers in successive earthquakes

## Potentiel de liquéfaction des couches horizontals dans des tremblements de terre successifs

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ABSTRACT

It is believed that successive earthquakes result in densification of the soil layer decreasing the liquefaction risk. While there is some evidence on re-liquefaction potential of sandy layers in successive earthquakes, very little experimental data exists. In order to investigate this aspect further a series of centrifuge tests was conducted using fine silica sand which is susceptible to liquefaction due to its grain-size distribution. The centrifuge tests were performed at 50g in the ESB model container with accelerations and pore pressures monitored during each test when the sinusoidal ground shaking was applied. This paper presents the results of dynamic centrifuge tests on saturated horizontal sand layers to show the changes between soil layers with different relative densities and during successive earthquakes. It will be shown that with successive earthquakes the loose sand layers densify and are less susceptible to liquefaction. The strength of soil with liquefaction or partial liquefaction varies and therefore it is important to distinguish this in geotechnical design.

RÉSUMÉ

On croît que les tremblements de terre successifs ont pour résultat la densification de la couche de sol diminuant le risque de liquéfaction. Tandis qu'il y a quelque évidence sur le potentiel de reliquéfaction des couches sableuses pendant les tremblements de terre successifs, il existe très peu de données expérimentales. Afin d'étudier cet aspect de plus, une série d'essais en centrifugeuse a été conduite en utilisant le sable fin de silice qui est susceptible de la liquéfaction à cause de sa composition granulométrique. Les essais centrifugeux ont été conduits à 50g dans le conteneur de modèl ESB avec les accélérations et les pressions interstitielles surveillées pendant chaque essai quand la secousse sinusoïdale du sol a été appliquée. Cet article présente les résultats des essais dynamiques en centrifugeuse sur des les couches de sable horizontales saturées pour montrer les changements entre les couches de sol avec des densités relatives differentes et pendant des tremblements de terre succéssifs. On va montrir qu'avec des tremblements de terre successifs les lâches couches de sable deviennet dense et sont moins susceptibles à la liquefaction. La résistance du sol varie avec la liquefaction ou la liquefaction partielle et donc il est important dedistinguer ceci dans la conception géotechnique.

## 1 INTRODUCTION

Liquefaction phenomena have been intensively studied over the decades however it still remains a challenge for geotechnical engineers working in seismically active countries. It is believed that successive earthquakes result in densification of the soil layer hence decreasing the liquefaction risk. While there is some evidence on re-liquefaction potential of sandy layers in successive earthquakes, very little experimental data exists. Re-liquefaction in successive earthquakes is a function of the intensity and duration of each earthquake and is affected by changes in the loose structure of the soil. Each earthquake increases the stability of the soil layer by reorganising the grains into a denser packing. In order to investigate this further a series of centrifuge tests was conducted. Horizontal saturated sand models were constructed in an Equivalent Shear Beam (ESB) (Zeng and Schofield, 1996) model container which was built from dural and rubber layers to achieve the same dynamic response as the soil sample. Seismic loading was applied by Stored Angular Moment (SAM) actuator (Madabhushi et al., 1998) that uses energy stored in a flywheel to generate lateral shaking. The sand used for the horizontal sand layer in all the tests was fine silica sand which was susceptible to liquefaction due to its grain-size distribution. The centrifuge tests were performed at 50g in the ESB model container with accelerations and pore pressures monitored during each test when the lateral shaking was applied. Miniature Cone Penetration Tests (CPTs) were conducted after the earthquakes and CPT and Pore Pressure Transducer (PPT) readings aided in assessing the liquefaction potential.

The excess pore pressures that can develop during successive earthquakes decrease leading the soil to achieve a lower liquefaction ratio. From CPT tests performed in flight after a strong earthquake that caused the model to densify, and using Seed and Idriss liquefaction charts, it could be observed that the soil was less susceptible to liquefaction after this earthquake. Dense soils can sustain higher shear stress and hence develop less excess pore pressure.

Soil liquefaction is a problem in earthquake-prone areas with loose, saturated silty, sandy deposits as seen in Kocaeli (Turkey), the 921 Ji-Ji (Taiwan) earthquake in 1999 and Bhuj (India) in 2001. These recent earthquakes have shown damage caused by soil liquefaction such as lateral spreading, flow failure and loss of bearing capacity. In the field, the most commonly used forms of testing to evaluate soil liquefaction potential are Standard Penetration Test (SPT) and Cone Penetration test (CPT) tests. Of late, CPT testing is more popular as it provides continuous soil profiles and is simple and fast to perform.

This paper presents the results of dynamic centrifuge tests on saturated horizontal sand layers to show the changes between soil layers with different relative densities and during successive earthquakes. It will be shown that with successive earthquakes the loose sand layers densify and are less susceptible to liquefaction. Strength of soil with liquefaction or partial liquefaction varies and therefore it is important to distinguish this in geotechnical design.

## 2 EXPERIMENTAL SET-UP

The centrifuge models consisted of dry-pluviated fine silica sand at different void ratios placed in the Equivalent Shear Beam (ESB) model container for which more details can be find from Zeng and Schofield (1996), and Teymur and Madabhushi (2003). This model container was built from dural and rubber layers to achieve the same dynamic response as the soil sample. For each test, accelerations were monitored during the dynamic loading that was simulated by the Stored Angular Momentum (SAM) earthquake actuator that uses energy stored in a flywheel to generate lateral shaking, Madabhushi et al. (1998). The centrifuge tests were performed at 50g. For the analysis explained in this paper, BT-4 and BT-10, which were saturated loose sand models, were chosen. Fraction E fine slica sand was used which has a grain size distribution that is susceptible to liquefaction. This is a sand that is retained between British standard sieve numbers 100 and 170. The specific gravity of the sand is 2.65, it has a nominal grain size, $D_{50}$ of 0.14mm (Jeyatharan, 1991 and Tan, 1990).

Model BT-4 has a void ratio of 0.76 ($I_D$ = 59.8%), dry specific weight, $\gamma$=15.06kN/m$^3$ and a height of 173mm corresponding to 8.65m in prototype scale. Model BT-10 has a void ratio of 0.78 ($I_D$ = 50.2%), $\gamma$= 14.86kN/m$^3$ and a height of 165mm corresponding to 8.25m in prototype scale. The layout of instruments placed in both models is shown in Figure 1. Letters a, b and c designate accelerometers and the letter p represents the pore pressure transducers placed in the sand in different soil columns.

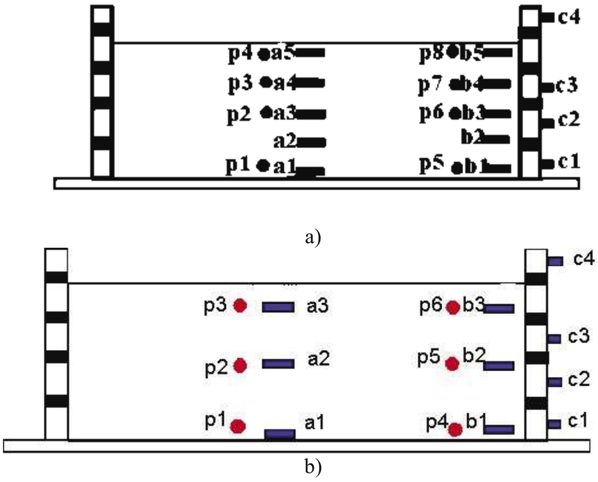

Figure 1. Instrumentation layout for a) BT-4 and b) BT-10.

## 3 CPT MEASUREMENTS AFTER SUCCESSIVE EARTHQUAKES

Seed and Idriss (1971) developed a procedure for estimating the liquefaction susceptibility of soil layers based on correlations between the normalized SPT blow count and the equivalent cyclic stress ratio to induce liquefaction in a certain number of cycles. They proposed an empirical chart, which separates site conditions which are susceptible to liquefaction from site conditions safe from liquefaction during earthquakes with magnitude 7.5. This correlation requires calculation or estimation of cyclic stress ratio or cyclic resistance ratio, which are plotted against the cone tip resistance or the normalized SPT blow count.

Empirical charts based on CPT and SPT results are available to assess the liquefaction potential. Using dynamic centrifuge modelling, liquefaction can be created in centrifuge models and change in liquefaction potential in successive earthquakes can be studied. In these experiments whether the soil has liquefied or not is assessed using miniature PPTs and accelerometers. The hydrostatic and excess pore pressures are recorded at different depths in the soil model as shown in Figure 1, from which the vertical effective stress at those locations can be calculated. From this we can infer the liquefaction ratio reliably. Further, the acceleration time histories confirm liquefaction by recording a drop in peak acceleration amplitude with the onset of liquefaction. The model soil layer liquefaction assessment can also be made based on the charts proposed. However for this study dimension effects were not considered.

The miniature CPT device used in centrifuge models has a 6mm diameter rod fitted with a 60° conical tip connected to the piston of the cylinder. A load cell is placed at the top of the rod to measure the total force. The hydraulic cylinder has 200mm penetration distance. The experimental procedure is to perform two CPTs in flight after an earthquake is simulated.

In order to compare the centrifuge test data to the empirical charts, we need to establish the equivalence of the centrifuge test conditions and the prototype events that led to the development of the empirical charts. For example, the equivalent magnitude of earthquake for the centrifuge model earthquake was converted into a Richter magnitude and the cyclic resistance ratios were calculated. The model earthquakes had 24 cycles corresponding to a magnitude of 8.25 based on the conversion factors given by Seed et al. (1985).

The NCEER (1997) workshop gave the Cyclic Stress Ratio (CSR) and Cyclic Resistance Ratio (CRR) to be:

$$CSR = \left(\frac{\tau_{av}}{\sigma'_{v0}}\right) = 0.65\left(\frac{a_{max}}{g}\right)\left(\frac{\sigma_{v0}}{\sigma'_{v0}}\right) r_d (MWF) \quad (1)$$

$$r_d = 1.0-0.00765z \quad \text{for } z \le 9.15\text{m} \quad (2)$$

$$r_d = 1/174-0.0267z \quad \text{for } 9.15\text{m} < z \le 23\text{m}$$

$$MWF = M^{2.56}/173 \quad (3)$$

where $\tau_{av}$ is the average cyclic shear stress, $a_{max}$ is the maximum horizontal acceleration at the ground surface, $\sigma_{v0}$ and $\sigma'_{v0}$ are the total and effective vertical overburden stresses respectively, $r_d$ is a stress reduction factor which depends on depth, z and MWF is the magnitude weighting factor.

In order to calculate CSR values $a_{max}$ was chosen as the input acceleration for the base. Since only total resistance $Q_T$ was logged, in order to find $q_c$, the tip resistance, the ratio of shaft and end resistance was calculated using empirical formulas following Fleming et al (1985). The skin friction $\tau_s$ was calculated by assuming $\delta$=10° where $\delta$ is the friction angle between steel and sand. Then from the measured values of $Q_T$, $q_c$ was calculated.

The clean sand curve, that divides the liquefaction and non-liquefaction zones, was estimated by the following equation (Youd and Idriss 2001)

If $q_c < 50$, then

$$CRR_{7.5} = 0.833\left[\frac{q_c}{1000}\right] + 0.05 \quad (4)$$

and if $50 \le q_c < 160$, then

$$CRR_{7.5} = 93\left[\frac{q_c}{1000}\right]^3 + 0.08 \quad (5)$$

As seen in Figure 2, in test BT-10 before and after a strong earthquake calculated CRR and normalized cone resistance can be compared. As seen in the figure, the likeliness of liquefaction occurring decreases with depth getting closer to the curve which divides the zones of liquefaction and non-liquefaction, and not changed much at the surface. For this test densification of the soil model has occurred as observed by the settlement of the soil. The soil settlement was measured after the end of the centrifuge test. 10 mm of settlement was observed due to all of the earthquakes that were fired on this model. As a result the relative density changed from 50.2% to 68%.

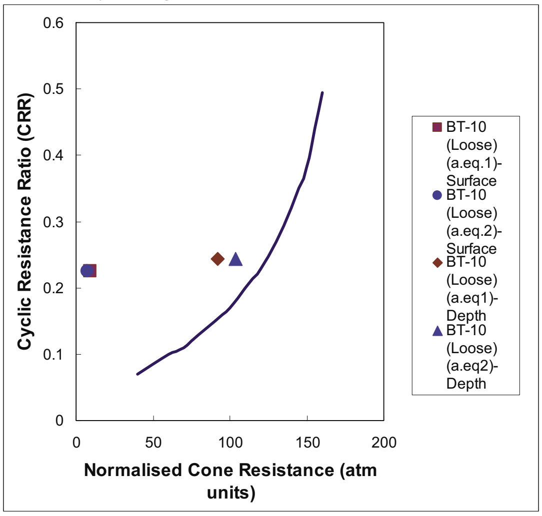


Figure 2. Liquefaction assessment of centrifuge data at the centre of the soil model after the earthquake. (Teymur, 2002)

## 4 EXCESS PORE PRESSURES AFTER SUCCESSIVE EARTHQUAKES

The input motion in tests BT-4 and BT-10 are shown in Figures 3 and 4 respectively. They were plotted for the first 50 seconds of the earthquake motion. The input acceleration for each earthquake is presented in prototype scale in Table 1. These earthquakes have different fundamental frequencies and strengths, and lasted for 25 seconds.

Table 1. Earthquake characteristics for the tests.

| Model | Earthquake no. | Frequency | Acceleration |
|---|---|---|---|
| | | Hz | (%g) m/s$^2$ |
| BT-4 | 1 | 1 | 13.3 |
| | 2 | 1 | 20.6 |
| | 3 | 0.8 | 11.7 |
| | 4 | 0.6 | 8.1 |
| BT-10 | 1 | 1 | 12.28 |

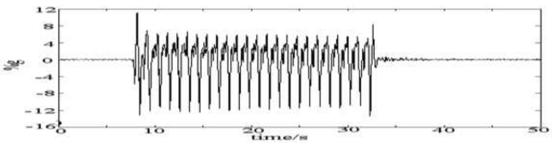

Figure 3. Input acceleration for model BT-4 earthquake-1.

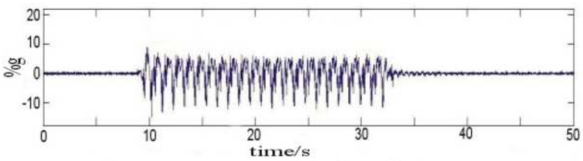


Figure 4. Input acceleration for model BT-10.

The saturated test BT-4 is considered first. There was 5mm of settlement after the earthquakes in model scale. This is equivalent to a volumetric strain of 2.9% in the saturated model. The excess pore pressure results of the saturated model BT-4 are seen in Figure 5. In this figure it can be seen that as successive earthquakes were fired, the magnitude of excess pore pressures that developed drops with each earthquake owing to densification. The liquefaction ratio is defined as the ratio of the excess pore pressures developed to the initial effective vertical stress. These have decreased from 0.91 for the first earthquake to 0.81, 0.61 and finally to 0.30. It should also be noted that the earthquake strengths differed in each earthquake. The fact that excess pore pressures are reduced in successive earthquakes is also confirmed by the acceleration data. Less excess pore pressure was produced in the second earthquake even though it was stronger than the first one. Subsequent earthquakes also had enough cyclic shear strain to trigger liquefaction, but did not produce enough pore pressures to fully liquefy the soil. Figure 6 shows the acceleration time history results at a slightly higher position than where the excess pore pressures were measured. As seen in Figure 6, earthquakes 3 and 4 have enough number of cycles to continue this process of liquefaction as well, but not to fully liquefy the soil.

Densification of the soil at depth is observed by the settlement of the ground surface. This settlement in dry sands takes place quickly and in saturated sand layers usually takes more time and occurs as the excess pore pressures caused by the earthquake dissipate. Settlement of saturated sands depends on the density of the sand, the shear strain imposed in the sand and the excess pore pressures generated by the earthquake.

## 5 DISCUSSION

In the above two sections, the likelihood of liquefaction occurring after successive earthquakes is shown on two dynamic centrifuge tests. The first test has four successive earthquakes applied to the same soil model and liquefaction ratios decrease proving the re-liquefaction to depend on the intensity of each earthquake and the change in the loose structure of the soil as it densifies with each earthquake. The second example has shown the use of CPT testing to assess changes in density of the soil structure and hence to assess the liquefaction susceptibility after successive earthquakes. It is seen that with successive earthquakes the possibility of liquefaction reduces and the values approach the boundary between liquefaction and non-liquefaction zones.

## 6 CONCLUSIONS

It is important to establish the re-liquefaction potential of loose, saturated soil deposits so that their vulnerability in future earthquakes can be established. While there is some evidence that liquefaction potential decreases in successive earthquakes, very little experimental data exists. In this paper results from a centrifuge study are presented that investigate re-liquefaction potential of saturated sand beds. The strength of soil with liquefaction or partial liquefaction varies and therefore it is important to distinguish this in geotechnical design. With each earthquake, the soil undergoes densification thus decreasing the liquefaction susceptibility of the soil.

In this paper we report the results of simplified CPT tests that were carried out on liquefiable soils before and after model earthquakes were fired. This information in addition to the excess pore pressures recorded during centrifuge tests gives a complete picture of the liquefaction vulnerability of level soil deposits. The results show that there is a decrease in liquefaction potential of saturated soils but this decrease is a function of the intensity of the earthquake and the thickness of the liquefiable soil stratum.

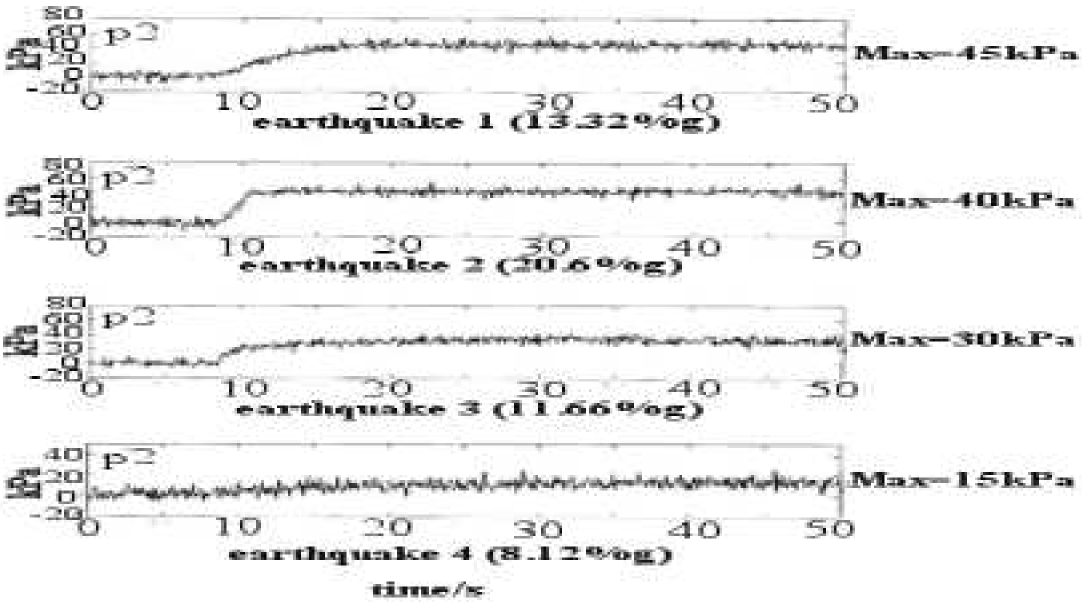


Figure 5. Excess pore pressure results for test BT-4 (after Teymur and Madabhushi, 2003).

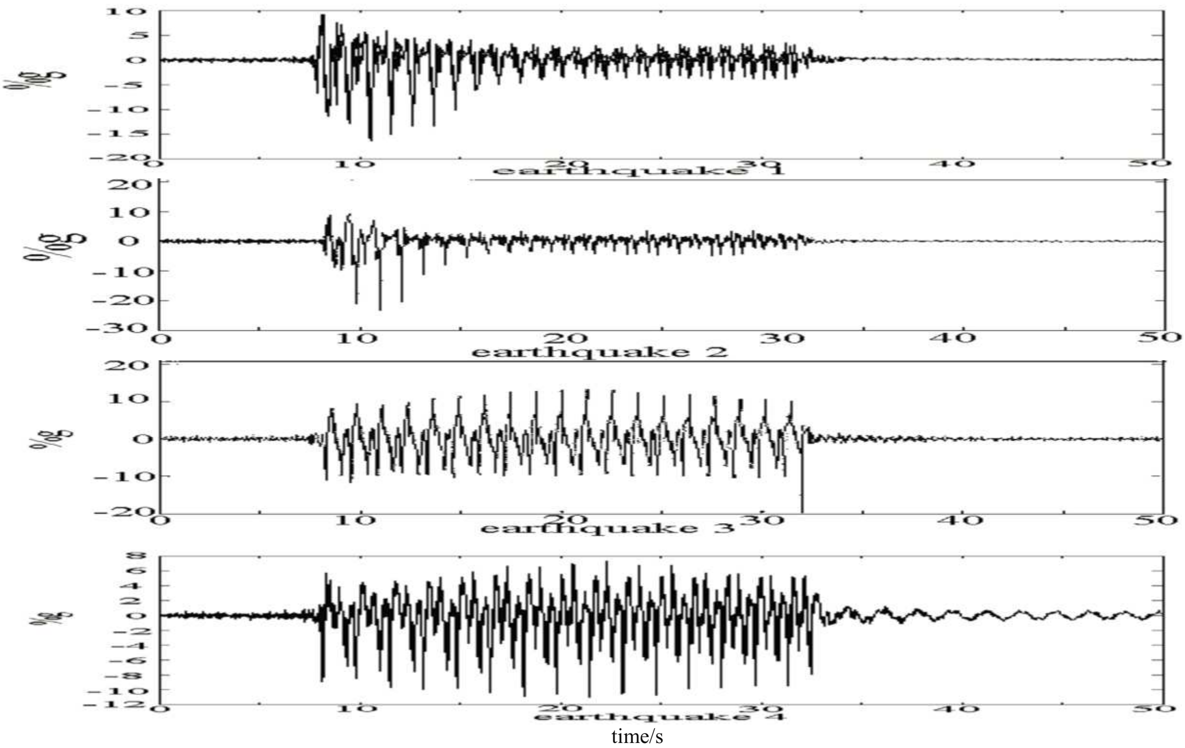


Figure 6. Acceleration histories for test BT-4

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