IMPACT OF LIQUEFIED SOIL ON SHALLOW FOOTINGS

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ABSTRACT

This research addresses the subsurface behaviour of liquefiable sand and its influence on shallow foundations. This was achieved by performing physical experiments. A large laminar box on a shake table was used to simulate the behaviour of the footings-soil system under dynamic loads. The subsurface acceleration and excess pore-water pressure have been measured beneath the footings. Laser displacement transducers were used to record the movement of the laminar layers that constitute the box. The acceleration and settlement of the footings were also measured. Harmonic base motions with different frequencies were applied. Results of the footing in a stand-alone condition (i.e. no adjacent footing) are compared to those from a group of six-clustered footings. The footing on a stand-alone condition showed a larger acceleration for all the frequencies considered, this was also observed at 0.05 m beneath the surface. The settlement showed a strong dependency on both, the frequency content and the number of footings. The acceleration and lateral deformation of the soil beneath the footing were also influenced by the number of footings. All these observations highlight the importance of the effect of shallow footings on the soil response.

Keywords: Liquefiable soil; adjacent footings; shear soil deformation; load frequency; shallow footings

1. INTRODUCTION

Even though soil liquefaction has been widely studied, the complex geotechnical mechanisms associated are an active research field (Seed, et al. 2003; Madabhushi and Haigh, 2012; Ko, Chen, and Ueng, 2015). Methodologies to assess liquefaction potential (e.g. Seed and Harder, 1990 and Robertson and Wride, 1998) are mainly based on results from in-situ tests (e.g. SPT and CPT) or laboratory tests (e.g. triaxial and direct shear tests). These methodologies have been validated using evidence from real ground motions e.g. Ishihara and Yoshimine (1992). However, these validations considered a free-filed condition neglecting the influence of buildings. Triaxial and direct shear tests also do not consider effects such as the shear deformation and the bearing pressure induced by a building, or a partially drained soil behaviour. Therefore, other approaches, that include these variables, must be considered to achieve a better understanding of the response of structures.

The influence of a building on the response of saturated soils has been studied since the second half of the 20th century. Yoshimi and Tokimatsu (1977) studied the response of rigid blocks on saturated sand using a shake table. The authors related the settlement with the bearing pressure and the footing width. The mechanisms of liquefaction-induced settlement of buildings were discussed by Dashti, et al (2010). The influence of the shear deformation induced by the building was highlighted as one of the most important parameters. Bertalot, et al (2013), studied a large collection of site evidence of

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liquefaction-induced settlement during different earthquakes. The authors proposed a non-linear relation between the bearing pressure and the settlement. Centrifuge tests were also performed to validate these observations (Bertalot and Brennan, 2015). Recently, Bray and Luque (2017) studied the deformation of a building during the Christchurch earthquake sequence (2010-2011) their results showed that simplified procedures performed poorly in estimating liquefaction settlement.

Numerical models have also been used to study geotechnical problems. Lopez-Caballero and Modaressi (2008) showed the influence of a structure on the excess pore-pressure beneath the footing compared to the free-field case using a finite element (FE) model. They also studied the variability in the seismic response of a liquefiable soil profile (Lopez-Caballero and Modaressi, 2010). However, Regnier, et al (2016) exposed considerable differences between different numerical models for simple liquefaction cases depending on the constitutive law and other assumptions.

Field observations and numerical models have exposed the importance of considering the entire structure-foundation-soil system in evaluating the response of structures on saturated soils. However, laboratory tests are crucial for validating these observations. This paper summarises results from physical experiments conducted using a large laminar box on a shake table. Steel blocks were used to represent shallow footings. Results from stand-alone condition (only one footing), and a cluster of six footings (two rows of three adjacent footings) are presented. Results are compared in terms of the footings response (i.e. acceleration and settlement). The influence of the footings on the response of the soil in terms of acceleration, excess pore-pressure and shear deformation are also discussed.

2. METHODOLOGY

Rigid blocks were used to simulate the footings. These blocks were built using a 0.2 x 0.2 m steel plate, 0.025 m thickness (Figure 1). These dimensions were selected to have a distance larger than three times the footing width from the edge of the footings to the closest edge of the soil container. The mass of each footing was 77 N (bearing pressure of 1.93 kPa). Sandpaper was glued to the base of the footings to enlarge the friction between the footing and the sand.

![Figure 1. Footing model](image)

The acceleration and the vertical deformation of all the footings were measured. Beneath the footings the acceleration and excess pore-pressure were also measured. Lasers were used to measure the lateral displacement of the laminar layers for constituting the contents of the box at 0.05, 0.15 and 0.4 m beneath the surface. The rigid blocks were studied in a stand-alone condition and as a cluster of six footings. A cross-section of the middle of the box is presented in Figure 2(a). The location of the footings and the sensors are also presented. Schematics of the top view of the test arrangements for the stand-alone and cluster of footings are shown in Figure 2(b) and Figure 2(c), respectively.
The laminar box has dimensions of $2 \times 2$ m in plan. The box was filled with Waikato river sand reaching a height of 1.45 m. This sand is a clean, poorly-graded quartz sand with angular particles, with a small percentage of particles of volcanic origin. Properties of the soil are presented in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry density</td>
<td>1571</td>
<td>kg/m³</td>
</tr>
<tr>
<td>Void ratio</td>
<td>0.66</td>
<td></td>
</tr>
<tr>
<td>Relative density</td>
<td>0.51</td>
<td>%</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>2.64</td>
<td></td>
</tr>
<tr>
<td>Minimum void ratio</td>
<td>0.55</td>
<td></td>
</tr>
<tr>
<td>Maximum void ratio</td>
<td>0.78</td>
<td></td>
</tr>
</tbody>
</table>

The configurations of footings were subjected to harmonic loads, beginning with four cycles to gradually achieve (and decrease from) the maximum acceleration. 20 cycles of constant maximum acceleration were applied, giving a total of 28 cycles. A maximum acceleration of 0.2 g and frequencies of 1, 1.5 and 2 Hz were used. The large shake table of the test hall of the University of Auckland uses a displacement-controlled actuator, therefore the maximum displacement must be calibrated to achieve the target acceleration. The recorded displacement and acceleration at the table for the case of the stand-alone footing are presented in Figure 3.
Figure 3. Displacement and acceleration recorded at the table for the case of a stand-alone footing. Excitation of (a) 1 Hz and 50 mm, (b) 1.5 Hz and 22 mm and (c) 2 Hz with 12.5 mm.

The recorded acceleration shows an acceptable agreement with the expected value of 0.2 g for all the frequencies studied.

3. EXPERIMENTAL RESULTS

Firstly, the maximum acceleration and settlement of the footings for the two configurations are compared. Later, the displacement of layers constituting the contents of the laminar box is used to estimate the shear deformation of the soil 0.05 m beneath the surface. Finally the acceleration and excess pore-pressure beneath the footings are addressed.

3.1 Acceleration at the footings

The maximum acceleration measured on top of the footings ($a_f$) was divided by the maximum acceleration at the table ($a_t$) to eliminate the influence of small differences in the table peak acceleration between the different base motions. Results are presented in Figure 4. The stand-alone cases are shown in black circles. Results of all the footings for the clustered case are presented using a box plot. A horizontal line inside the box shows the median value, while the edges of the box correspond to the 25\textsuperscript{th} and 75\textsuperscript{th} percentiles. The whiskers of the boxes extend to the most extreme data points (MATLAB, 2014).

![Figure 4. Ratio of the maximum acceleration at the footings to the maximum acceleration at the table](image)
The stand-alone condition presented the highest acceleration for all frequencies. Additionally, the value of $a_f/a_t$ increased with increase in excitation frequency. The dispersion of the data for the six-clustered footings also increased with increasing frequency. This is related to the increasing non-linear response of the soil with increasing frequency as it will further discuss later in the text.

**3.2 Acceleration beneath the footings**

Figure 5 shows the maximum acceleration recorded at 0.05 m beneath the centre of the laminar box ($a_b$) divided by the maximum acceleration at the table ($a_t$). The $a_b/a_t$ ratio can be considered as an approximation of the acceleration amplification of the soil surface. Both cases (stand-alone and six-clustered) presented an increasing acceleration with frequency. For all frequencies, the stand-alone presented a larger acceleration amplification compared to that of the six-clustered footings. The stand-alone case presented amplification ($a_b/a_t > 1$) for all the cases. However, the six-clustered case presented values of $a_b/a_t$ larger than 1 only for the case of the 2 Hz base motion.

![Figure 5. Maximum acceleration at 0.05 m beneath the centre of the footing](image)

**3.3 Settlement of the footings**

The vertical deformation was measured at both edges of the footings. The settlement was obtained by taking the average of both measurements. For simplicity, for the six-clustered cases the result of only one footing (the footing at the centre of one of the row of three footings) is shown. Results are presented in Figure 6. Most of the settlement was observed during the shake (i.e. co-shaking settlement). This implies the soil behaves in a partially drained manner. The co-shaking settlement is associated with the shear deformation induced by the footing. Settlement was also observed after the end of the shake (i.e. post-shaking settlement). The after-shake vertical deformation is related to mechanisms such as sedimentation of the sand particles, consolidation due to the dissipation of the excess pore-pressure and sink of due to the footings weight.

![Figure 6. Settlement of the footings due to excitation with a frequency of (a) 1 Hz, (b) 1.5 Hz and (c) 2 Hz.](image)
For the lowest frequency (Figure 6(a)), the stand-alone footing presented a larger settlement compared to that from the six-clustered case. However, for the highest frequency considered (Figure 6(c)), the settlement was largest for the six-clustered case. For the 1.5 Hz the settlement was almost the same for both footing configurations. Even though, these results show an influence of the frequency content on the settlement, the low bearing pressure of the footings may also have a large influence. The relatively loose state of the sand, as well as the low effective stress state, has led to oscillatory motion with possibly dilative soil response and disturbance of the soil structure.

### 3.4 Excess pore-pressure

The excess pore-pressure at 0.05 m beneath the surface for the stand-alone footing and the six-clustered cases are presented in Figure 7(a) and Figure 7(b), respectively.

![Excess pore-pressure at 0.1 m beneath the footings](a) One footing and (b) six footings)

The dashed black line shows the effective vertical stress for the free-field case ($\sigma'_v$). The stand-alone case reaches values close to the $\sigma'_v$ reflecting the low bearing pressure induced by the footing. However, when six footings were considered the excess pore-pressure reaches values much larger. This emphasises the larger pressure due to the cluster effect.

The excess pore-pressure for the stand-alone case (Figure 7(a)) presented a similar trend for all the frequencies. However, an initial peak can be seen for the 1.5 Hz and even more clearly for the frequency of 2 Hz. On the other hand, the six-clustered footings presented a larger excess pore-pressure generation for the 1.5 Hz compared to the 1 Hz case. Unfortunately, for the 2 Hz case presented the instrumentation proved problematic. The observed results highlight the combined effect of both the number of footings and the frequency content of the loading on the excess pore-pressure generation.

### 3.5 Shear deformation of the soil beneath the footings

The shear deformation of the soil beneath the footings was estimated using the lateral deformation of two layers the box recorded at depths of 0.05 m and 0.15 m (see Figure 2). Results are presented in Figure 8.
Figure 8. Estimation of the shear deformation of the soil beneath the footings. (a) One footing and (b) six footings.

In both cases (stand-alone and six-clustered footings) the shear deformation increases with increasing excitation frequency. However, the cluster of six footings produced a considerably lower shear deformation compared to that of the stand-alone footing at same frequency. This reflects that the number of footings, and the arrangement, directly affects the response of the soil even for low bearing pressures as it is the case of this study.

3.6 Excess pore-pressure and shear strain

The progressive development with shear strain of the excess pore-pressure at a depth of 0.05 m was calculated based on the excess pore-pressure at a depth of 0.05 m, and the estimation of the shear strain, as described above. Figure 9 to Figure 11 shows the excess pore-pressure in terms of the estimated shear strain. The shear strain is highest for the stand-alone footing for all frequencies while the development of excess pore-pressure is more progressive for the six-clustered arrangement. Many factors are involved, but it may be that the more robust development of pore-pressure with strain history in the six-clustered cases is a result of less co-excitation dissipation of excess pore-pressure. These figures show the effect of the number of footings on the shear strain and excess pore-pressure developed.

Figure 9. Excess pore-pressure and shear deformation for a frequency of 1 Hz. (a) One footing and (b) six footings.
A relevant observation is that for the base motion with a frequency of 1 Hz a cyclic response was observed. This behaviour evidence similar rates of generation and dissipation of excess pore-pressure. However, for the 2 Hz frequency case, the excess pore-pressure increases monotonically. Therefore, for this higher frequency, the rate of generation is considerably larger than the rate of dissipation. The influence of the number of footings can be also observed in Figure 9. The response of the stand-alone case stays almost in the same location after each cycle, while for the cluster of six footings the cycles “migrate” generating a larger excess pore-pressure with subsequent cycles. This shows a lower drainage capacity compared to the stand-alone case due to the larger number of footings.

4. CONCLUSIONS

The response of shallow footings on saturated sandy soil was studied via physical experiments. A large laminar box on a shake table filled with sand from the Waikato rives in New Zealand was used. A rigid footing in a stand-alone condition and a cluster of six footings were studied. Harmonic loads at three different frequencies were applied. The main conclusions of this research are:

Both configurations of footings (stand-alone and six-clustered) presented an increasing acceleration with increasing frequency. However, the stand-alone case presented a larger acceleration for all frequencies compared to that of the six-clustered footings, this was observed also 0.05 m beneath the soil surface.

Regarding the vertical deformation beneath the footings, both, co- and post-shaking settlement were
observed. The vertical deformation during the shaking is has both a cyclic and monotonic component associated with the shear deformation induced by the footings. The post-shaking deformation is related to particle sedimentation, consolidation and sinking of the footings. Additionally, the settlement of the footings presented different trends depending on the frequency of the base motion. For the lowest frequency (1 Hz) the stand-alone case presented a larger settlement compare to that of the six-clustered footings. However, at the highest frequency (2 Hz) the opposite trend was observed, i.e. the six-clustered case presented a larger settlement compare to that of the stand-alone footing. For the 1.5 Hz both settlement were similar. Therefore, the settlement seems to be considerably affected not only by the frequency of the excitation but also the number of footings in a conjunction manner.

The excess pore-pressure for the stand-alone case presented similar reading at 0.05 m for all the frequencies. However, a peak at the beginning of the base motions was observed. This peak increased with frequency, possibly showing a reduction in the drainage capacity of the soil for higher frequencies. The influence of the drainage response of the soil plays a part in the nature of the response of the system, i.e. the footing-soil system with a complex interaction occurring that will differ for different footing configurations. A cyclic response, tending towards steady state, was observed for the lowest frequency excitation. However, there is a progressive migration for the six-clustered footings. This migration was not observed for the stand-alone footing. This cyclic response may relate to a similarity between the rate of generation and dissipation of the excess pore-pressure. The migration phenomenon shows certain level of excess pore-pressure remaining after each cycle. These observations highlighted the combined effects of both the number of footings and the frequency of the base motion.

The effect of the footings on the soil response was also studied in terms shear deformation of the soil and the acceleration beneath the footings compared with the excitation acceleration. The shear deformation was considerably lower for the six-clustered case for all the frequencies compared to that of the stand-alone case. The acceleration at 0.05 m beneath the footings was used to estimate the acceleration amplification (i.e. maximum acceleration inside the soil divide by the maximum acceleration at the table). Both, the stand-alone and the six-clustered cases presented an increasing amplification with increasing frequency. However, the stand-alone case presented a considerably larger amplification for all frequencies.

The results presented in this paper highlight the importance of considering the number of footings in evaluating the response of footings on saturated sand. Further research needs to be conducted to study other variables such as the soil deformation induced by the vibrations of the super-structure and higher levels of bearing pressure.

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6. REFERENCES


