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Centrifuge Modelling of the Behaviour of Shallow Foundations in Liquefiable Ground

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ABSTRACT

Liquefaction can cause extremely severe damage to shallow foundations built on liquefiable ground in seismically active regions. Because detailed observations of the effects of earthquake-induced liquefaction are rare and because these are often difficult to perceive based on post-event analysis of case histories, centrifuge modelling is regarded as an extremely useful tool to evaluate the performance of structures affected by this catastrophic phenomenon. This paper describes the preparation and testing of a centrifuge model, tested at Cambridge University's Schofield Centre, representing shallow foundations built on liquefiable ground including different liquefaction mitigation techniques. Firstly, the complex technology and experimental techniques used to create suitable models, which govern the significance of the experimental results, are described. Secondly, the characteristics of the test carried out are presented in detail. Finally, the behaviour of the structure built on top of a narrow densified zone is presented. The excess-pore-pressure developed and the major attenuation of the horizontal ground accelerations under the structure proves liquefaction occurs, leading to large displacements of the footing.

Introduction

Ground liquefaction is associated with large permanent ground displacements, which can lead to major damages of structures during a seismic event. Although earthquake-induced liquefaction can cause large destruction, it was only after 1964 earthquakes that struck Japan and USA that this phenomenon was brought to the attention of the scientific community (Seed and Lee, 1966). Even so, it remains a phenomenon quite difficult to define; proof is that even today a few different definitions can be used (Boulanger, 2005). Earthquake-induced liquefaction is a major concern for structures built on saturated deposits of cohesionless soils in seismically active regions. The effects of this phenomenon continue to cause large direct economic losses as a result of earthquakes. Moreover, the consequences of their collapse can cause serious impediment to post-earthquake emergency operations and impose a long-lasting disruption of social and economic life. Damage to shallow foundations can be particularly severe, mitigation measures being poorly understood (Mitchell, 2003; Bardet et al, 1997).

As structures built with shallow foundations are often used in saturated sand deposits, their vulnerability is particularly critical, as they are prone to the risk of liquefaction-induced

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foundation failure. On the other hand, liquefaction has been observed in many recent major earthquakes, as in Kobe earthquake of 1995 in Japan, the Kocaeli earthquake in Turkey and the 921 Ji-Ji earthquake in Taiwan in 1999, the Bhuj earthquake of 2001 in India and even in the 2010-11 New Zealand earthquakes, which highlight the need for further research into the complex behaviour of shallow foundations built on liquefiable soils. For instance, in Turkey, the Adapazari district suffered extensive liquefaction induced damage during the Kocaeli earthquake of 1999. Figures 1 and 2 show some examples of buildings resting on shallow foundations that suffered liquefaction-induced damage (Madabhushi and Stuart, 2009). In view of the objective uncertainties regarding the interpretation of field case studies, the liquefaction performance of shallow foundations has been modelled in centrifuge and large-scale shaking table experiments over the years (Liu and Dobry, 1997; Kawasaki et al., 1998; Adalier et al., 2003; Dashti et al., 2010; Marques et al., 2012). Due to the extensive liquefaction-induced settlements suffered by shallow foundations it is important to ensure foundation safety through ground improvement.

Figure 1. Liquefaction induced damage during the Kocaeli earthquake of 1999 in Turkey (adapted from Madabhushi and Haigh, 2009)

Characteristics of the dynamic centrifuge testing program

Material and equipment used

This centrifuge test was performed to gain insight into the seismic performance of shallow foundations built on liquefiable ground, using different liquefaction mitigation techniques. Drawing of the model experiment, with 18 m deep prototype scale, and a summary of the centrifuge testing program are presented in Figure 2. As the figure shows, two equal shallow foundations were placed resting on narrow densified zones having the same depth as the layer of loose sand. In one of the cases, it was intended to combine densification with high-capacity vertical drains, so the narrow densified zone was embedded with a particular geotextile extending to the bottom of the deposit.

The test was conducted using the 10-m diameter Turner Beam Centrifuge available at the Schofield Centre which is described in detail by Schofield (1980). The centrifuge model was prepared inside an ESB container (Schofield and Zeng, 1992), in order to minimise undesirable boundary effects. The actuator used in the centrifuge test to generate seismic simulations was the so-called Stored Angular Momentum (SAM) actuator (Madabhushi et al., 1998), which is a simple and reliable mechanical actuator that uses the energy stored in a pair of flywheels to generate the input motion. Despite not being able to reproduce real seismic actions, it generates nearly sinusoidal horizontal acceleration motions of chosen duration and amplitude, which is considered valuable for fundamental research on earthquake effects, as it avoids the difficulties introduced by more complex dynamic loading.

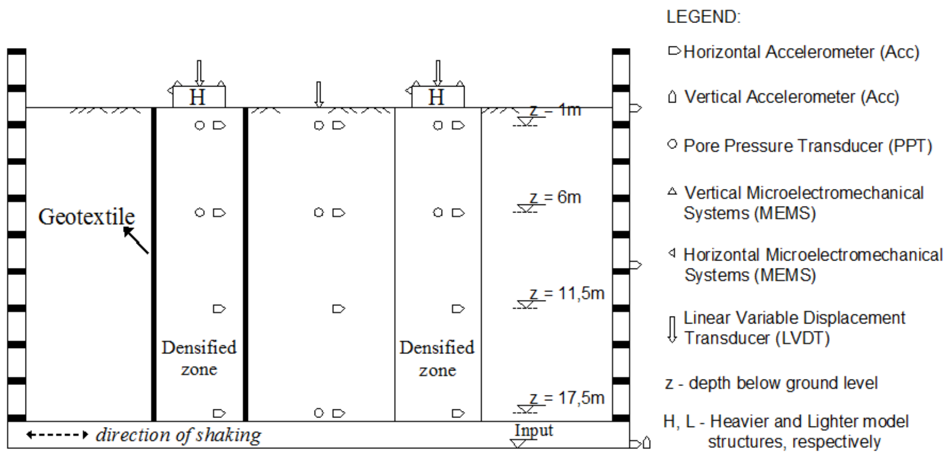

Figure 2. Centrifuge model layout in experiment CT-B (cross section view).

The sand employed in this study is the Hostun RF fine-grained, clean and uniform silica sand, which is a type of sand very susceptible to liquefaction . It is a reference sand for many French geotechnical laboratories and it is also widely studied by the international geotechnical community (Doanh et al., 2010). The properties of Hostun sand are summarized in Table 1 and described in detail by Flavigny et al. (1990).

Table 1. Properties of Hostun sand (Stringer, 2008).

Angle of repose (^{o})	D_{10} (mm)	D_{50} (mm)	$C_u=D_{60}/D_{10}$	e_{max}	e_{min}	G_s
33	0.286	0.424	1.59	1.067	0.555	2.65

Considering the aim of the test, structural models had a simple design, consisting of solid steel blocks with prototype dimensions 3×3×1.225 m for length, width and height, respectively. The pressure transmitted through the foundations basis equals 95kPa. Figure 3.a shows the model structure used to perform the centrifuge experiment. A high-capacity vertical drain was simulated through a specific geotextile, rigid enough to avoid squeezing of the vertical drainage paths once the final horizontal stresses are installed in the model (Figure 3.b).

Model preparation

The preparation of the model tested in this centrifuge experiment involved the creation of two dense narrow blocks created within liquefiable ground, one of which was embedded by the geotextile. In order to create uniform loose and dense zones, an air dry pluviation technique was used by means of the automatic sand pourer available at the Schofield Centre facilities (more details on the automatic sand pourer can be found in Madabhushi et al., 2006). This equipment allows different sized nozzles to be placed at the bottom of a hopper to control the flow rate, the drop height being controlled through a computational program used to control the equipment.

a)  b) 

Figure 3. Model structures (a) and geotextile (b) used to simulate high-capacity vertical drains.

However, despite uniform throughout the model, the eventual relative density achieved using this technique can be up to ±5% of the desired value. Sand is poured in pairs of steps, passing in each one of them along the model and along one axis in a single step. With up to 4mm/step being poured, often instrumentation cannot be located at precisely the desired depth. However, this is a small compromise for the benefits that the automation process brings to model preparation.

The geometry of the densified zone was delimited by a box made of thin metallic sheet that was employed to temporarily support that zone while the model was being built. This temporary formwork, which was removed during the pouring process, was not required when the densified zone was encased within a geotextile, in which case the dense sand could be placed directly inside the geotextile. Taking into account the disturbance that could be caused by the formwork removal, as well as the larger difficulty in creating a narrower denser zone with the automatic sand pourer, the geotextile and the formwork were 20 mm wider (at model scale), in each direction, than the width of the model structures.

The method that was used to create the desired denser and looser sand zones has some complexity. First of all, a small amount of loose sand was poured in the model so the deepest instruments could be placed in the desired locations. Then, another layer of loose sand was poured until the next level of instruments. Once this height was achieved, the instrument corresponding to the free-field positions was placed, and the sand placed inside the formwork and geotextile was carefully aspirated. After this process, dense sand was poured, this time until it achieved the second deepest layer of instruments inside the dense blocks. Subsequently, the dense sand filled outside the dense blocks was remove with a vacuum-cleaner and the instruments required in the dense blocks were carefully placed. The formwork was cautiously removed so that the instruments in that dense zone could be positioned. This process was repeated until the model preparation was completed. With this process, some sand (loose or dense) may have been poured in the wrong part on the model, despite all effort to make this problem as insignificant as possible.

After creating the loose (D_r = 50%) and dense (D_r = 80%) zones and removing the formwork, the model was saturated with a solution of hydroxypropyl methylcellulose in water as the pore fluid. This fluid had a viscosity 50 times that of water, in order to achieve the so-called viscosity scaling at 50-g (centrifuge acceleration used in the test) and overcome the conflict between time scaling in flow and dynamic phenomena that occur simultaneously during earthquake-induced liquefaction. The saturation system was controlled by a computational program known as CAM-Sat (Stringer et al, 2009).

At prototype scale, the 1-D earthquake simulation lasts about 25 s, imposes maximum peak horizontal accelerations close to 0.3g and has a predominant frequency of 1 Hz. The time histories and FFTs of the horizontal input motion (Figure 54) show that the seismic simulation is not single-frequency but matches the desired characteristics of the seismic loading. The long earthquake duration aims at intensifying liquefaction effects and facilitating model behaviour analysis.

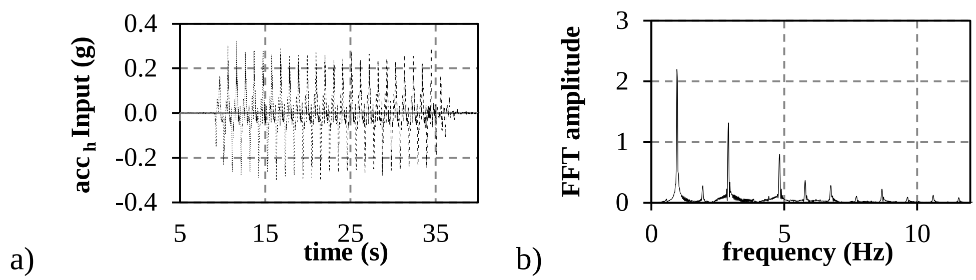

Figure 4. Time history (a) and FFTs (b) of the horizontal seismic motion applied to the model.

Experimental results and analysis

This paper focus on the performance of the structure built over the narrow densified zone without geotextile, located on the right side of the model (Figure 2). It is possible to discuss the behaviour of the models separately as no interaction effects were observed between the structures analysed.

Excess pore pressure

Figure 5 shows the excess pore pressure (epp) measured in the centrifuge model under the footing without geotextile (right footing in Fig. 2). Results show that when the soil under the footing is densified, it increases the co-seismic dilation effect also affecting deeper levels. During the earthquake, the epp measured under the footing never exceeds the initial value of the free-field vertical effective stress. Near the surface important negative epp can even be induced once the first couple of cycles take place. This clearly suggests that temporary stress variations occur at this stage, under the footings, in this zone, whose effects are visible during the entire earthquake duration.

Immediately after the earthquake ends, considerable epp migration from the free-field affects those locations where co-seismic dilation is visible, particularly at the shallower depths. This causes a continuous and significant decrease of the vertical effective stress through time, reaching its minimum value approximately 4 minutes after the earthquake. After this, the epp remains fairly constant for some time. The epp migration ceases once hydraulic equilibrium is achieved at each level. Finally, subsequent epp dissipation progresses at every depth, starting firstly at deeper levels, where vertical effective stress increase first occurs.

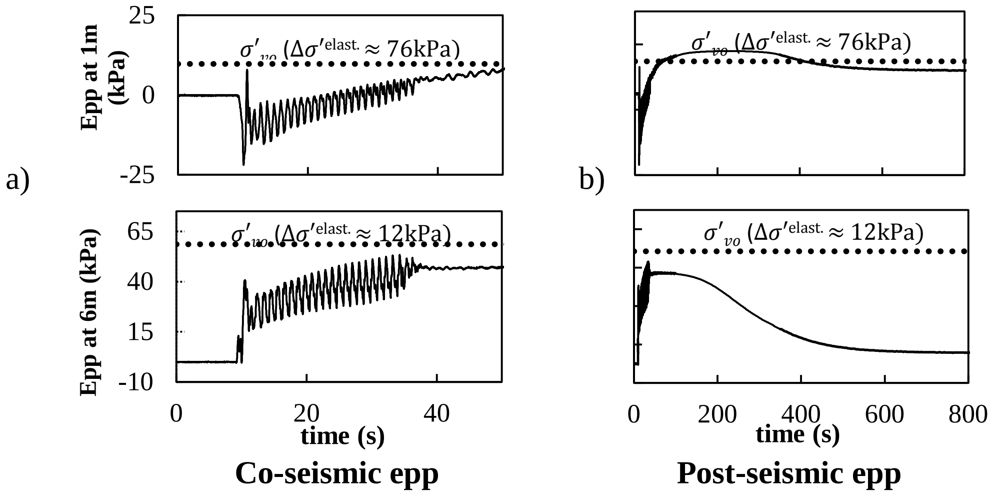

Figure 5. Co- (a) and post- seismic (b) epp at different depths under the footing.

Footings displacements

Figure 6 shows the settlements of the structure, on top of the narrow densified zone without geotextile, and of the ground surface in the middle of the model. The first observation is that it takes about 10 minutes for the settlements to end. The data also shows that the settlements measured in the structure are significantly larger than those experienced by the loose soil. In fact, if the ground surface settles about 50 cm, the footing settles almost 50 % more, which suggests that the densification technique used does not reduce the settlements of the shallow foundation to an acceptable level.

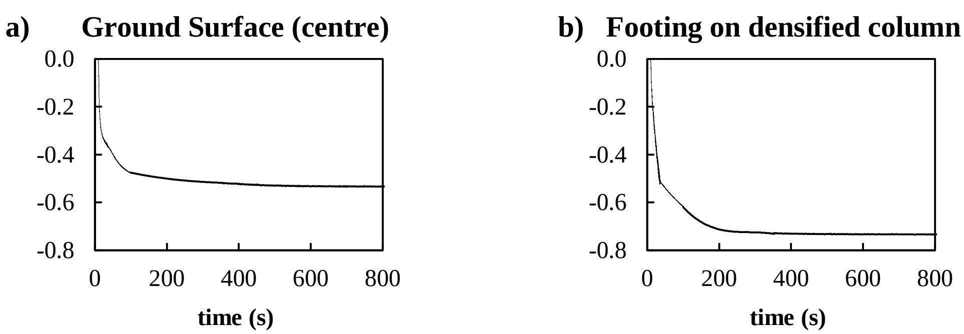

Figure 6. Ground surface (a) and footing (b) settlements (in m)

Moreover, the percentage of the co- and post-earthquake settlements measured in the loose soil and in the footing are almost the same, approximately 70 and 30% respectively. This means that most of the settlements suffered by the structure built on a densified block of sand take place mostly during the shaking. However, the settlements occurring after the earthquake ends are still important, and they must be taken into consideration. After that, the settlements observed may result mostly from the dissipation of the excess pore pressure developed close to the surface during the seismic loading and subsequent soil settlement.

Motion propagation

The horizontal accelerations measured in the shallow foundation placed on top of the narrow densified zone, as well as at different locations in the model under the centre of that structure, are presented in Figure 7. As a result of the motion propagation through the soil, the horizontal accelerations exhibit progressive attenuation from the bottom to the surface. The attenuation is more significant after the first couple of cycles and near the surface. However, as the horizontal motions reach the structure, the time histories of the accelerations measured are qualitatively similar to those measured in the soil at 1m depth, even if some amplification can be observed.

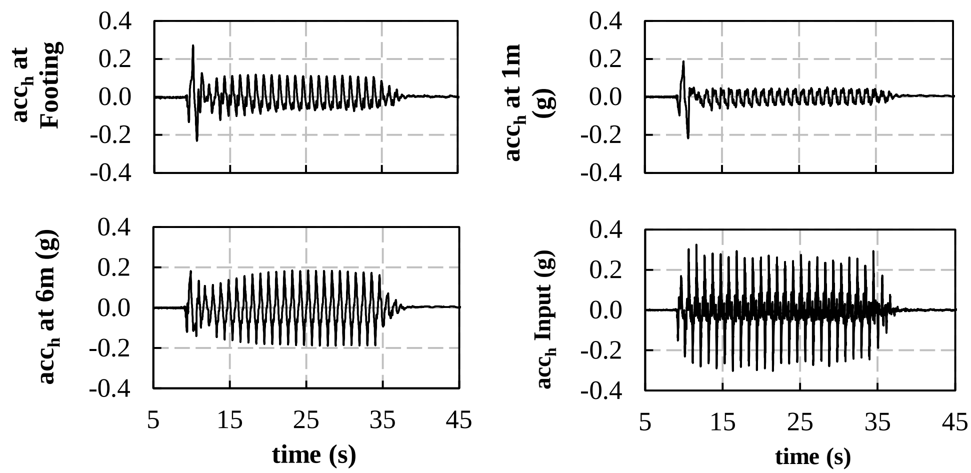

Figure 7. Horizontal accelerations measured at the footing located on top of the narrow densified zone and in the ground under the centre of the same footing at different depths

Conclusions

A centrifuge model experiment was performed to evaluate the performance of earthquake-induced liquefaction mitigation techniques. Narrow densified zones combined or not with vertical drainage were tested to assess the behaviour of shallow foundations built with this methodology. This paper describes the design of the centrifuge test, the test setup and the experimental techniques used to prepare the complex model, as well as the materials used. It is shown that it is possible to create different models representing different prototype conditions, irrespective of the complexity of the model required. The behaviour of the structure built on a narrow densified block of sand to mitigate liquefaction effects is also presented and discussed. The observed epp developed and the major attenuation of the horizontal ground accelerations under the structure prove that liquefaction occurs under the footing, which results in large settlements of the footing exceeding those observed at the ground surface. The capabilities and importance of centrifuge modelling in research on the effects of earthquake-induced liquefaction are clearly demonstrated.

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References

Adalier, K., Elgamal, A., Menese, J., & Baez, J.I. (2003). Stone columns as liquefaction countermeasure in non-plastic silty soils *Journal of Soil Dynamics and Earthquake Engineering*, **23**(7), pp. 571-584.

Bardet, J. P., I. M. Idriss, T. D. O'Rourke, N. Adachi, M. Hamada, & K. Ishihara (1997). *Report on North America. Japan Workshop on the Geotechnical Aspects of the Kobe, Loma Prieta, and Northridge Earthquakes*, Civil Engineering Department, University of Southern California, Los Angeles.

Boulanger, R.W. (2005). General report- earthquake related problems (TS-4b). *Int. Conf. on Soil Mechanics and Geotechnical Engineering*, September 2005, Osaka, Japan: 3117-3124.

Coelho, P.A.L.F. (2007). *In situ densification as a liquefaction resistance measure for bridge foundations*. PhD thesis, University of Cambridge, UK.

Dashti, S., Bray, J.D., Pestana, J.M., Riemer, M.R. and Wilson, D. (2010). Mechanisms of Seismically-Induced Settlement of Buildings with Shallow Foundations on Liquefiable Soil. *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, **136**(1), 151-164.

Doanh, T., Dubujet, P., and Touron, G. (2010). Exploring the undrained induced anisotropy of Hostun RF loose sand. *Acta Geotechnic*. 10.1007/s11440-010-0128-x, 239-256.

Flavigny, E, Desrues, J & Palayer, B (1990).Le sable d'Hostun «RF».*Revue Française de Géotechnique*, **53**, 67–69.

Kawasaki, K. Sakai, T., Yasuda, S. & Satoh, M. (1998). Earthquake-induced settlement of an isolated footing for power transmission tower. *Proc. Centrifuge 98*, Tokyo, Balkema, pp271-2.

Liu, L. & Dobry, R. (1997). Seismic response of shallow foundation on liquefiable sand. *J. Geotech. Geoenviron. Eng.*, **123**(6), 557-566.

Madabhushi, S.P.G., Schofield, A.N. & Lesley, S. (1998). A new Stored Angular Momentum Earthquake Actuator. *Proc. Int. Conf. Centrifuge '98*, Tokyo, Japan: 111-116.

Madabhushi, S.P.G., Houghton , N.E. & Haigh S.K. (2006). A new automatic sand pourer for model preparation at university of Cambridge. *6th International Conference on Physical Modelling in Geotechnics*, Hong Kong.

Madabhushi, S.P.G. & Haigh, S.K., (2009). Effect of Superstructure Stiffness on Liquefaction-induced Failure Mechanisms. *Journal of Geotechnical Earthquake Engineering* **1**(1) 70-87 DOI: 10.4018/jgee.201009080.

Marques, A.S., Coelho, P.A.L.F., Cilingir, U., Haigh, S.K. & Madabhushi, S.P.G. (2012). Centrifuge modeling of liquefaction-induced effects on shallow foundations with different bearing pressures. *2nd Eurofuge conference on Physical Modelling in Geotechnics*. Delf.

Mitchell, J.K. (2003.) Performance of Improved Ground in Earthquakes (Do the results justify the expense?). Seminar in Geotechnical Engineering at Cambridge University Engineering Department, February 2003, Cambridge University, UK.

Schofield, A.N (1980). Cambridge geotechnical centrifuge operations. *Geotechnique*, **30**(3): 227–268.

Schofield, A.N. & Zeng, X. (1992). *Design and performance of an equivalent-shear-beam (ESB) container for earthquake centrifuge modelling*. Technical Report, CUED/D-SOILS/TR245, University of Cambridge, UK.

Seed, B. & Lee, K.L. (1966). Liquefaction of saturated sands during cyclic loading. *Journal of Soil Mechanics and Foundation Division* **92**, SM6: 105-134.

Stringer, M.E. (2008.) *Pile Shaft Friction in Liquefaction*. First Year Report, University of Cambridge.

Stringer, M.E., McMahon, B.T.& Madabhushi, S.P.G. (2009) *CAM-Sat: Computer Controlled Saturation for Geotechnical Modelling*, Technical Report, CUED/D-SOILS/TR348, University of Cambridge, UK.