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Seismic Liquefaction Hazards on Shallow Foundations

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ABSTRACT: Liquefaction can cause extremely severe damage to shallow foundations built on liquefiable ground in seismically active regions. As precise observations of the effects of earthquake-induced liquefaction are rare and frequently based only 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. A centrifuge experiment has been undertaken at the Schofield Centre, University of Cambridge, UK, using a squared shallow foundation resting on a narrow densified column of dense Hostun sand surrounded by liquefiable soil. This model is very complex to construct as it has loose and dense zones that must be created separately. The data shows that centrifuge modelling is capable of simulating complex situations that are difficult to observe in detail in the field, highlighting the importance of centrifuge modelling, particularly when modelling the effects of natural hazards. The influence of the stress state imposed on the ground by the shallow foundation, particularly in terms of the excess-pore-pressure generation, is discussed.

1 INTRODUCTION

Earthquakes have been historically perceived as one of the most destructive natural hazards. In general, these seismic events can cause a number of dangerous ground conditions that can lead to structural damage and failure resulting in large social and economic losses. Although natural disasters are always distressful, earthquakes can be separated from other disasters by their complete uncontrollability. Unlike most other natural hazards, earthquakes occur without any warning, leaving people with no opportunity to minimize losses, damage or injury by, for example, evacuating from risk areas and vulnerable buildings. In addition, earthquakes have no exact defined endpoint. Aftershocks can continue over a period of months, or even years – in the recent Christchurch earthquakes of 2010/2011 more than 12,500 aftershocks were recorded (CPAG, 2014). This extends the possibility of further injury and damage, and causes people to relive the sensations of the initial traumatic experience, delaying their recovery. Consequently, besides the visible economic and structural damage that earthquakes can bring to the community (Fig. 1), social life can be adversely affected by these massive natural disasters.

Earthquake-induced soil liquefaction is a major cause of damage that can happen during earthquake shaking. This phenomenon is a process which liquefies the soil while shaking, largely reducing bearing capacity and thus leading to massive destruction due to lateral movement of buildings, destruction of infrastructure and disruption of the natural environment. Shallow foundations are often used in structures built on saturated deposits of cohesionless soils in seismically active regions. These structures are therefore very susceptible to seismic liquefaction.

Figure 1. Effects of earthquake-induced liquefaction during 1964's Niigata Earthquake (Penzien, 1964).

Foundation failures due to earthquakes have been observed during several past and recent earthquakes, for instance in Mexico City during Michoacan earthquake of 1985 (Mendoza and Avunit, 1988), in the city of Adapazari due to 1999 Kocaeli earthquake (Karaca, 2001; Bakir et al., 2002; Yılmaz, et al., 2004) 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, including studying efficient techniques to ensure foundation safety through ground improvement. Typical examples of liquefaction induced failure of buildings resting on shallow foundations are shown in Figure 2 (Madabhushi and Haigh, 2009).

Figure 2. Liquefaction induced damage during the Kocaeli earthquake of 1999 in Turkey (adapted from Madabhushi and Haigh, 2009).

Despite extensive implementation of ground improvement to mitigate liquefaction-induced ground deformation over the past four decades, until recently the effectiveness of improvement methods to limit ground strain remained largely unevaluated due to a lack of field performance data under strong shaking (Dobry, 1996). Consequently, the data available for ground improvement under shallow foundations is not yet sufficient to be able to predict the ground deformations for a given set of site conditions and earthquake motion (Hausler and Sitar, 2001). As a result, liquefaction analyses of shallow foundations have been studied in centrifuge and large-scale shaking table tests over the last few years (Liu and Dobry, 1997; Kawasaki et al., 1998; Adalier et al., 2003; Dashti et al., 2010a, b; Marques et al., 2012; Marques et al., 2013; Bertalot 2013; Marques et al., 2015). This paper aims at proving that complex models can be prepared for testing in the centrifuge and describing in detail the behaviour of the ground under a shallow foundation during seismic loading.

2 CHARACTERISTICS OF THE DYNAMIC CENTRIFUGE TEST

2.1 *Modelling techniques and facilities*

Centrifuge experiment was conducted at Cambridge University’s Schofield Centrifuge Centre, which has a long tradition of using dynamic centrifuge modelling to assess geotechnical earthquake problems. The 10-m diameter Turner Beam Centrifuge (Schofield, 1980) was used to perform the test. This machine has a 150g-tonne capacity, achieving a maximum centrifugal acceleration of approximately 130g at 4.125m radius.

The scaling factors (presented in Table 1) for dynamic events imply that the model earthquakes with high acceleration amplitudes need to be applied in a fraction of a second. Consequently, high amounts of kinetic energy need to be transmitted to the model for a very short time. This is achieved by the Stored Angular Momentum (SAM) actuator (Madabhushi et al., 1998) available at the Schofield Centre, which is a simple and reliable mechanical actuator that works by spinning two flywheels up to the required speed. This earthquake actuator, despite not being able to reproduce real seismic actions, is capable of generating nearly sinusoidal motions at different durations and frequencies for successive tests, which has great value for fundamental research on earthquake effects.

The centrifuge modelling was prepared inside an Equivalent Shear Beam (ESB) container, which consists of a series of alternating aluminium and rubber rings, the overall stiffness of the composite column being identical to that of the soil column contained within it. This allows the box to deform to the same mode-shape as the soil contained within it in the unliquefied condition, minimising the reflection of stress waves, though this breaks down slightly once the soil has liquefied. More details on this model container can be found in Schofield and Zeng (1992). The ESB container has internal dimensions of 673×253×427 mm^3 (L×B×H).

Table 1. Scaling laws in centrifuge modelling for a centrifugal acceleration of N×g (Schofield, 1981; Madabhushi, 1994).

Parameter	Scaling factor (Model/Prototype)	Dimensions
Length	1/N	L
Mass	$1/N^3$	M
Time (seepage)	$1/N^2$	T
Time (dynamic)	1/N	T
Velocity	1	LT^{-1}
Seepage velocity	N	LT^{-1}
Acceleration	N	LT^{-2}
Frequency	N	1/T
Force	$1/N^2$	MLT^{-2}
Stress	1	$ML^{-1}T^{-2}$
Strain	1	1

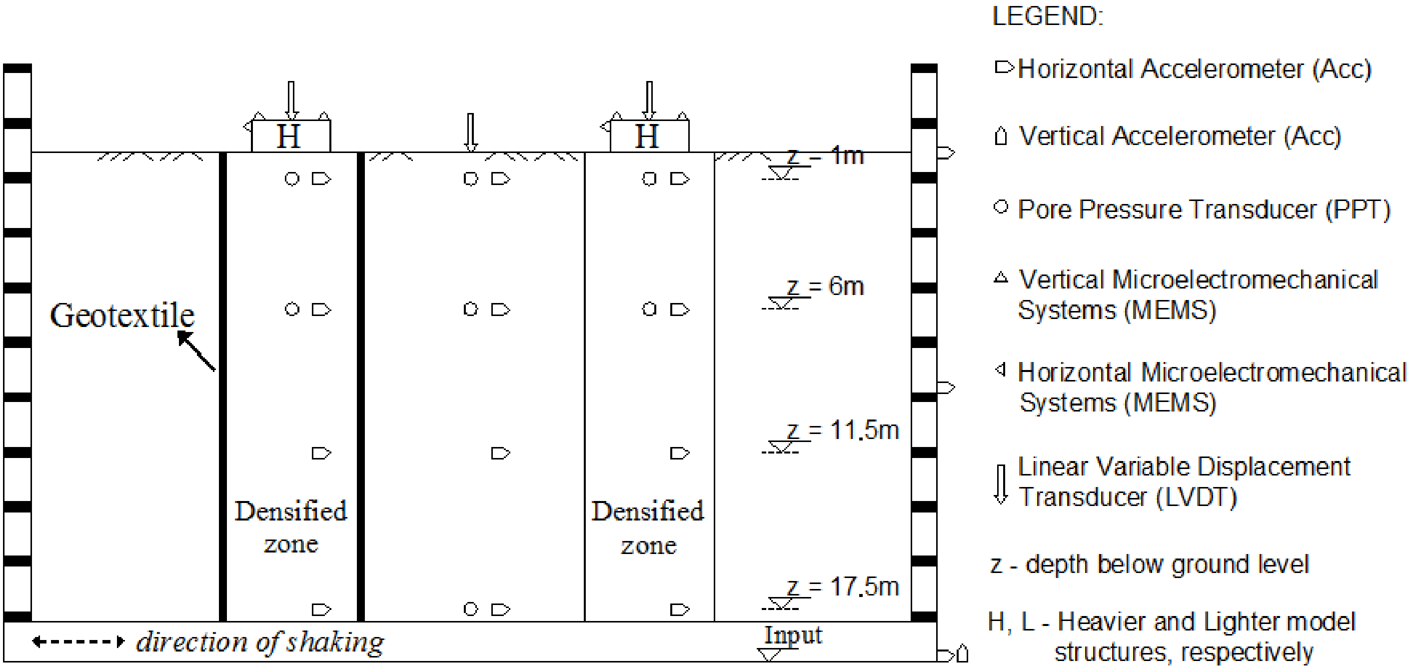

Figure 3. Centrifuge model layout (cross section view).

2.2 *Experimental configurations and materials*

This paper presents data concerning to the seismic performance of a shallow foundation built on top of a narrow densified zone surrounded by liquefiable soil. Table 2 lists the main features of the squared shallow foundation placed on top of the soil.

Figure 3 presents a cross sectional drawing of the prototype generic model experiment performed. 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. This model is very complex to build as different densities are necessary in different locations in the same model, and, above all, the dense zones are narrow, making this harder to achieve.

Table 2. Characteristics of the footing model (prototype dimensions).

Material	Steel
$\rho\ (g/cm^3)$	7.74
$q\ (kPa)$	95
B×L (m^2)	3×3
H (m)	1.225

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, which operates on similar principles to the overhead manual hopper. 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. Sand is poured in pairs of steps, passing along the model and along one axis in a single step. However, although uniform throughout the model, the eventual relative density achieved using this technique can be up to ±5% of the desired value. More details on the automatic sand pourer can be found in Madabhushi et al. (2006).

To create the desired dense and loose sand zones several steps were performed. First, small amounts of loose soil were poured in the model, until the depth required for the deepest instruments was achieved. Then, the loose sand placed in the undesired zones was carefully taken out. The same process was repeated with dense sand, this time removing the dense sand out of the undesired places. This was repeated until the model preparation was completed.

A series of pore-pressure transducers (PPTs), accelerometers (acc) and linear variable displacement transducers (LVDTs) were installed to assess the soil behaviour during the centrifuge test. A series of microelectromechanical system accelerometers (MEMS) were carefully attached to the footing to measure the vertical and horizontal accelerations. Several acc were installed to the bottom and walls of the container to measure the vertical and horizontal input motions and to evaluate the horizontal motion propagation through the ESB walls.

The sand used to perform the centrifuge test was an Hostun RF fine-grained, clean and uniform silica sand, which is a type of sand very susceptible to liquefaction, as the particle size distribution (PSD) curve lies well within the bounds of soils most susceptible to liquefaction (Fig. 4). This type of sand is used by 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 3 and described in detail by Flavigny et al. (1990).

After the creation of the model, the saturation process is an essential part of the model preparation in centrifuge-based liquefaction research, requiring time and strict control for superior results. So, a solution of hydroxypropyl methylcellulose in water was used as the pore fluid (Madabhushi, 1994). This fluid had a viscosity 50 times that of water, in order to achieve the so-called viscosity scaling (Lambe and Whitman 1982) 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 liquefaction. This saturation procedure was processed with a novel automatic saturation system, available at Cambridge, called the Cam-Sat. The design and application of this system are described fully in Stringer & Madabhushi (2009) and subsequent improvements to the system are discussed in Stringer & Madabhushi (2010). With this system the saturation procedure is automated, not requiring a constant human presence through the entire process.

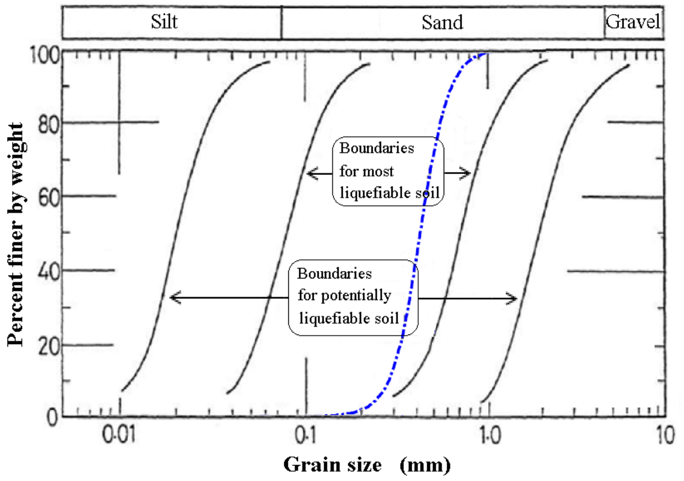

Figure 4. Particle size distribution curve for Hostun sand, superimposed on liquefaction susceptibility curves, after Tsuchida (1970) – adapted from Stringer (2008).

Table 3. Properties of Hostun sand (Stringer, 2008).

Property	Value
Angle of repose (°)	33
D_{10} (mm)	0.286
D_{50} (mm)	0.424
Uniformity coefficient ($C_u = D_{60}/D_{10}$)	1.59
e_{min}	1.067
e_{max}	0.555
G_S	2.65

2.3 *Input motions*

The centrifuge model was subjected to an input seismic motion at the base, applied parallel to the long side of the model and designed to replicate a relatively strong real earthquake motion, planned to last about 25 seconds, have a predominant frequency of 1 Hz and impose maximum peak horizontal accelerations close to 0.3-g.

The time history and FFT of the earthquake simulation applied to the centrifuge model are depicted in Figure 5. It should be noted that the seismic simulation is not purely single-frequency, although the predominant frequency matches the desired value of 1Hz.

The long earthquake duration aims at intensifying liquefaction effects and facilitating model behaviour analysis.

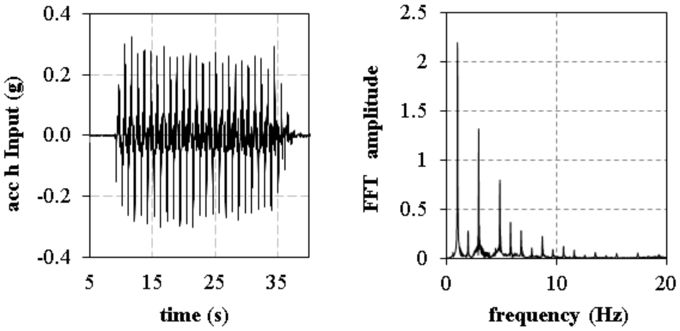

Figure 5. Time histories and FFT of the seismic loading applied to the model.

3 ABILITY OF THE MODEL TO ASSESS THE PROBLEM

The data presented focus on the structure placed on top of a narrow densified zone with no geotextile surrounding it (Fig. 3).

Figure 6 shows the excess pore pressure (epp) measured at different positions in the centrifuge model under the centre of the footing during (left) and after (right) the earthquake simulation. The first major finding is that negative epp is measured at shallow depths under the footing during the seismic simulation. Even if this fact is more obvious during the first cycles, the epp remains negative for a significant period of the earthquake. At a deeper level, however, the epp remains positive practically from the beginning and keeps increasing during the seismic event. This phenomenon shows that the presence of the foundation clearly has effects on the behaviour of the underlying soil during the cyclic loading. The co-seismic epp measured indicates that the structure influences more the behaviour of the soil at shallower depths, where the initial shear stresses imposed by the shallow foundation is more significant.

On the other hand, post-seismic epp shows that the epp starts to dissipate much sooner at a deeper level than near the ground surface. This is critical to shallow foundations, as these rest on soil with extremely low effective stresses for a longer period time, which increases the chances of large deformations or even failure. The epp dissipation progresses through time within the deposit similarly to a situation with no foundation (free-field) (Ishihara, 1994; Coelho, 2007), which suggests that the shallow foundation has minor effect on the post-earthquake epp dissipation.

Table 4 compares the average relative co- and post-seismic settlements of the footing, as a % of total. According to the data, the footing keeps settling after the earthquake. Despite the co-seismic displacements observed being significantly higher, post seismic settlements still represent an important part of the total settlements and must not be ignored.

Figure 7 shows the horizontal motions that reach the structure and that are measured on the soil immediately under its center. As Figure 7 shows, the horizontal accelerations imposed by the earthquake are significantly reduced on top of the soil. However, that attenuation is only visible after the first couple of cycles, remaining relatively constant after those initial peaks. The horizontal accelerations measured in the structures are also a lot smaller that the input motion, their propagation being similar to the measurements of the underlying soil, except with a slight increase.

Table 4. Average relative settlements of the footing during and after the earthquake.

Footing position	Average relative settlement (%)	
	During the earthquake	Post-earthquake
CT-B – on top of narrow densified column	~78%	~22%

4 CONCLUSIONS

Centrifuge modelling of the seismic effects of shallow foundations resting on narrow densified sand was undertaken at the Schofield Centre, University of Cambridge, UK.

The data collected evidence that the presence of a structure clearly has a strong influence on the epp measured on the soil under the footing, especially at shallow depths and mostly during the seismic event. The different shear stresses imposed on the ground by the shallow foundation, which vary significantly with depth, are certainly responsible for the behavior observed. Post-seismic epp dissipation is identical to a soil with no improvement or structure on top, which suggests that this dissipation process is mostly governed by the characteristics of the deposit. The settlements of the shallow foundation measured as a result of ground liquefaction clearly shows that the co-seismic displacements of the footings are the most important part of the total settlement, even if it keeps increasing after the earthquake.

The capabilities and importance of centrifuge modelling in research on the effects of earthquake-induced liquefaction are clearly demonstrated, as the ability to observe the soil behavior in detail at different locations supports clarification of the mechanisms involved and provides valuable data for calibrating advanced numerical modelling.

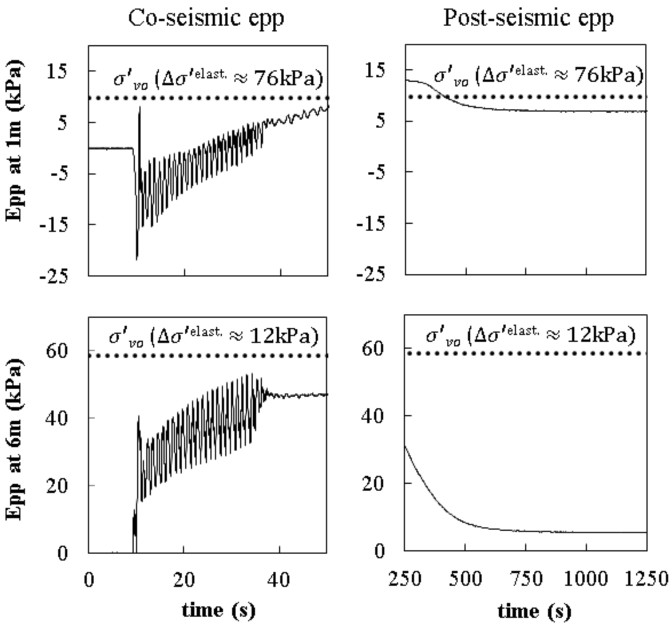

Figure 6. Co- and post-seismic epp at different depths under the footing.

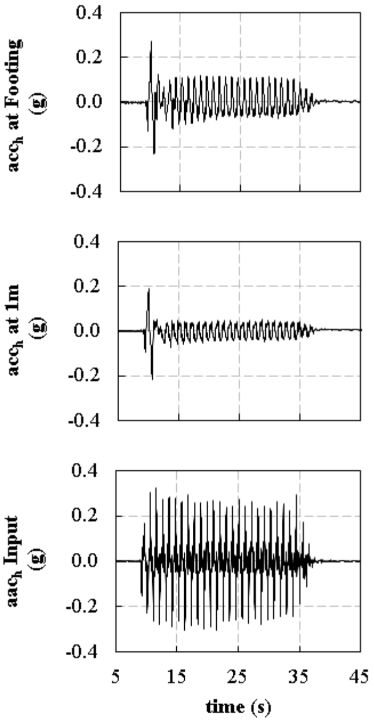

Figure 7. Horizontal accelerations measured at the footing located on top of the narrow densified zone and in the ground under the center of the same footing.

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