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BOUNDARY EFFECTS IN DYNAMIC CENTRIFUGE MODELLING OF LIQUEFACTION IN SAND DEPOSITS

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ABSTRACT

Centrifuge modelling is commonly accepted as a valuable tool for research on earthquake-induced phenomena, its significance depending on proper simulation of boundary conditions. This is a controversial aspect of centrifuge modelling of soil's dynamic behaviour, especially if involving liquefaction, as the issue of significant soil stiffness and shear strength degradation with increasing strain, which should ideally be reproduced by the physical boundaries of the centrifuge model, becomes much more pertinent.

Centrifuge tests performed on uniform deposits of saturated sand at Cambridge University highlight the boundary effects caused by a deep Equivalent Shear Beam (ESB) container. Excess pore pressure and accelerations in the centre and edges of models of dense and loose sand are compared, illustrating the adverse effects of the boundaries, which increase with progressive soil softening during shaking due to rising excess pore pressures. The results show that, during the earthquake, boundaries significantly affect the soil's dynamic response and the transient excess pore pressure close to the box walls, but also suggest that the soil behaviour observed in the model's centre is authentic. As a result, provided that model edges are disregarded, ESB containers are suitable for centrifuge modelling of earthquake-induced liquefaction.

Keywords: Liquefaction, centrifuge modelling, boundary effects, ESB container.

INTRODUCTION

Centrifuge modelling is commonly accepted as a valuable research tool in geotechnical engineering, due to its acknowledged ability to combine the potential of conventional physical modelling with a fundamental replication of field stresses. In fact, centrifuge models featuring essential soil properties can be tested under the relevant state of stress in appropriately chosen boundaries. Moreover, appropriate instrumentation provides accurate measurements of stresses and deformations in the models during and after the loading. Since the temporal and geographical unpredictability of earthquake events reduces the chances of obtaining detailed full-scale observations, centrifuge modelling employing controlled dynamic loading is an incomparable technique for investigating earthquake-induced phenomena such as liquefaction.

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In order to enhance the value of the experimental results resulting from centrifuge tests, proper simulation of boundary conditions is required. This issue remains one of the most controversial aspects of centrifuge modelling of soil's dynamic behaviour, especially if the seismic event leads to liquefaction, since the dramatic reduction of soil stiffness and shear strength caused by liquefaction should ideally be reproduced by the model boundaries.

This paper highlights the boundary effects caused by a deep Equivalent Shear Beam (ESB) container, designed and built at Cambridge University's Schofield Centre, based on the results of dynamic centrifuge tests performed on level deposits of uniform saturated sands intended to clarify the behaviour of sands under earthquake loading leading to liquefaction.

CONTAINERS USED IN DYNAMIC CENTRIFUGE MODELLING

Centrifuge models are enclosed within finite boundaries provided by containers, which produce more or less significant boundary effects. In order to minimize these effects, which can seriously affect the accuracy of results, and simulate the semi-infinite lateral extent usually found in real situations, early rigid-wall containers were successively replaced by flexible-boundary containers, aiming to reduce distortion of stress and strain fields at model edges. Some examples are:

- Rigid containers with absorbing boundaries;
- MIT stack ring apparatus;
- Laminar model container;
- Equivalent Shear Beam (ESB) container.

Teymur (2002) provides a detailed description of the most significant features of the containers mentioned, including their major advantages and drawbacks when used in centrifuge modelling.

ESB containers have been used in dynamic centrifuge modelling at Cambridge University for more than 10 years. Zeng (1991) presented the first design of an ESB container, built with alternating layers of aluminium and rubber intended to deform with the soil while maintaining an appropriate state of stress. The dynamic behaviour of this original ESB container was depicted by Madabhushi (1994) and Zeng and Schofield (1996). Recently, a deep ESB container, having internal dimensions of 674mm × 253mm × 429mm (L×B×H), was built at Cambridge University in order to perform dynamic centrifuge tests on deeper models. The main features of this enhanced ESB container, which introduces the use of hollow sections of aluminium alloy, to reduce the container's weight, and rubber layers of increasing thickness towards the top, to model the reduction of soil stiffness near the surface, are presented by Brennan and Madabhushi (2002). Table 1 shows the values used for the parameters required for the container design, from which the small strain shear modulus, G_{max}, was estimated using the expression established by Hardin and Drnevich (1972), based on experimental results obtained from sands amongst other soils.

TABLE 1. Parameters used in container design (Brennan and Madabhushi, 2002)

Soil parameters			Earthquake parameters		
void ratio-	e:	0.77	peak horizontal acceleration coef.:		
unit weight-	γ (kN/m^3):	15		k_h:	0.3
coef. of earth pressure at rest-K_0:		0.55	centrifuge g-level:		
angle of internal friction-	ϕ' (^{o}):	33		N (g):	50 and 100

TABLE 2. Characteristics of centrifuge models of level sand deposits

Model & test ID		Model geometry		Sand properties			
Model	*Test*	*Depth*[(a)] *(mm)*	*Area*[(a)] *(mm²)*	*Rel. density*[(b)] *(%)*	*e*	γ_d *(kN/m³)*	γ_{sat} *(kN/m³)*
Loose sand	PC02	344	673 ×253	50	0.812	14.4	18.8
Dense sand	PC03	360	673 ×253	80	0.695	15.4	19.4

[(a)] Model scale (1:50 of prototype scale) [(b)] Considering e_{min}= 0.613 and e_{max}= 1.014

CENTRIFUGE MODELLING OF EARTHQUAKE-INDUCED LIQUEFACTION

In order to clarify the performance of the new deep ESB container in dynamic centrifuge modelling of saturated deposits of sand undergoing liquefaction, centrifuge tests were carried out on level ground deposits. The tests aimed to evaluate the boundary effects produced by the box in the model edges, especially after the soil was significantly softened due to excess pore pressures generated during cyclic loading.

Characteristics of tests performed

Some of the characteristics of the centrifuge models tested are shown in Table 2, which includes the geometry of the models and the properties of the sand used. The major difference between the two models, prepared by dry pluviation of Fraction E silica sand, is the relative density of the sand. In order to accomplish viscosity scaling and to eradicate the time-scaling conflict between dynamic and diffusion phenomena, the models were saturated with a solution of hydroxypropyl-methylcellulose (HPMC) having viscosity (50 cSt) corresponding to the centrifuge g-level (50 g) used in the test. The accelerations and pore pressures in the model were measured during the simulation of the seismic loading using the instrumentation layout shown in Figure 1. The instrument positions shown, corresponding to projected prototype depths of 4 and 13 m, vary slightly in each test. Additional testing details are provided in Coelho (2003).

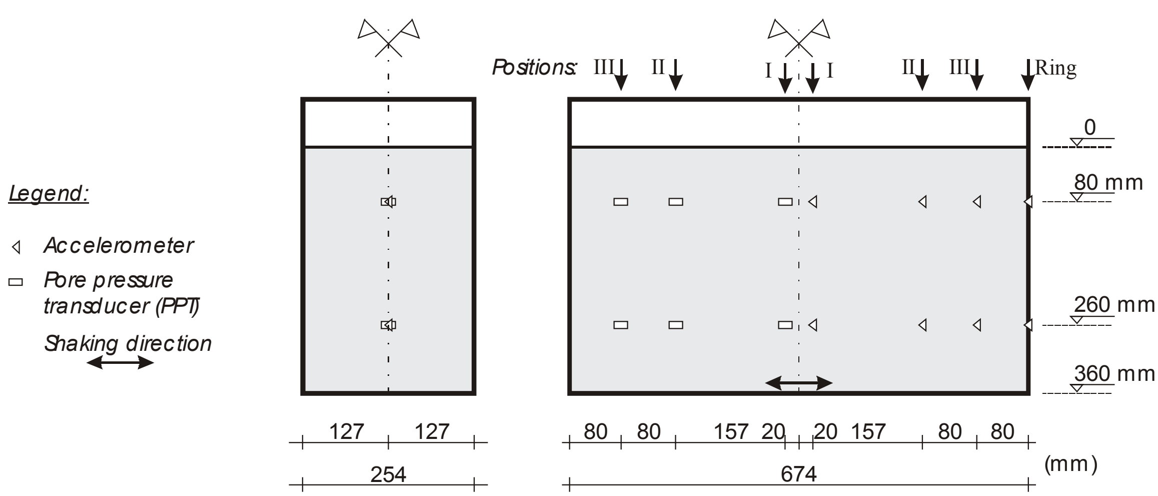


Figure 1- Schematic of the sand model and instruments layout (model scale)

Characteristics of earthquake simulations

Earthquakes were simulated with the SAM actuator, described in detail by Madabhushi et al (1998), which is able to generate a sinusoidal input of accelerations of predetermined frequency and amplitude at the base of the model. In order to replicate prototype events that last 25 s and have a main frequency of 1 Hz, 50 Hz model earthquakes were fired during 0.5 s. The time histories and FFT analysis of the earthquakes applied to the models of loose (R_D= 50%) and dense (R_D= 80%) sands are presented, in prototype scale, in Figure 2, showing that the loose model was subjected to a slightly longer seismic event, probably because of a poorer performance of SAM's fast-acting hydraulic clutch in test PC02. Peak horizontal accelerations imparted on the loose model also exceed by 10 to 20 % those imparted on the dense model, resulting in somewhat higher FFT amplitudes, particularly at 1 Hz. Apart from that, in both events the Fourier amplitude spectra is fairly similar and the fundamental frequency closely matched the desired prototype frequency of 1 Hz.

Boundary effects observed

During the centrifuge tests, the accelerations and excess pore pressures were measured at different positions inside the model (Figure 1), in order to compare the influence of the container on the behaviour of the soil. The instruments were located in the centre of the model (position I) as well as 160 mm (position II) and 80 mm (position III) away from the walls of the container. Accelerations were also measured at the bottom and relevant rings of the container. Two different depths, corresponding to prototype depths of around 4 and 13 m, were selected for the analysis.

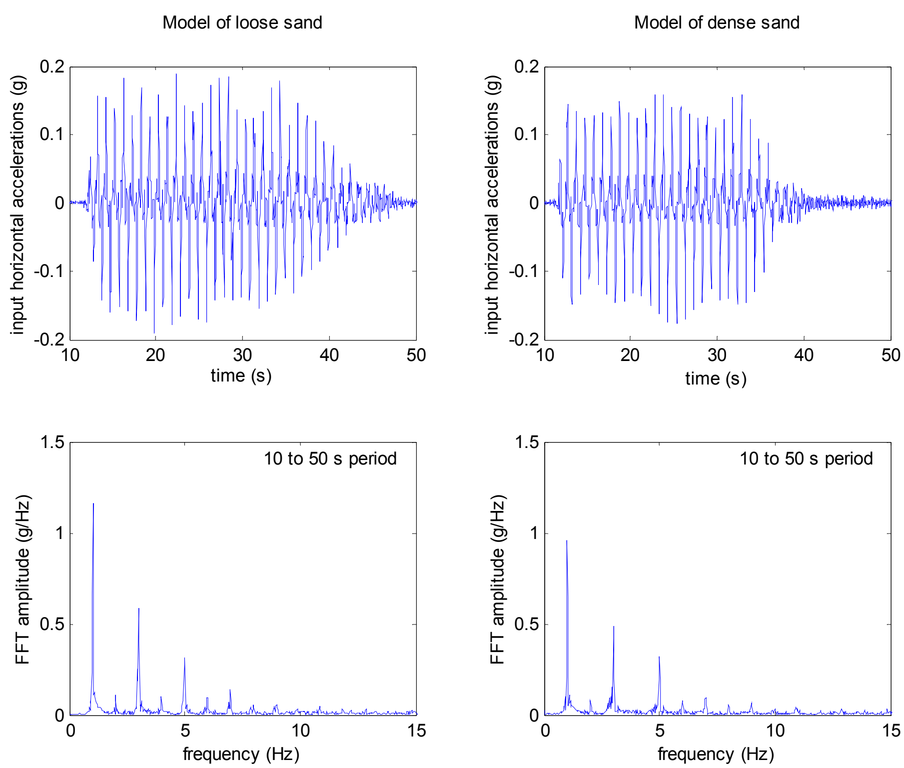


Figure 2- Time histories and FFT analysis of earthquake events (prototype scale)

a) 4.3 m depth

b) 12.5 m depth

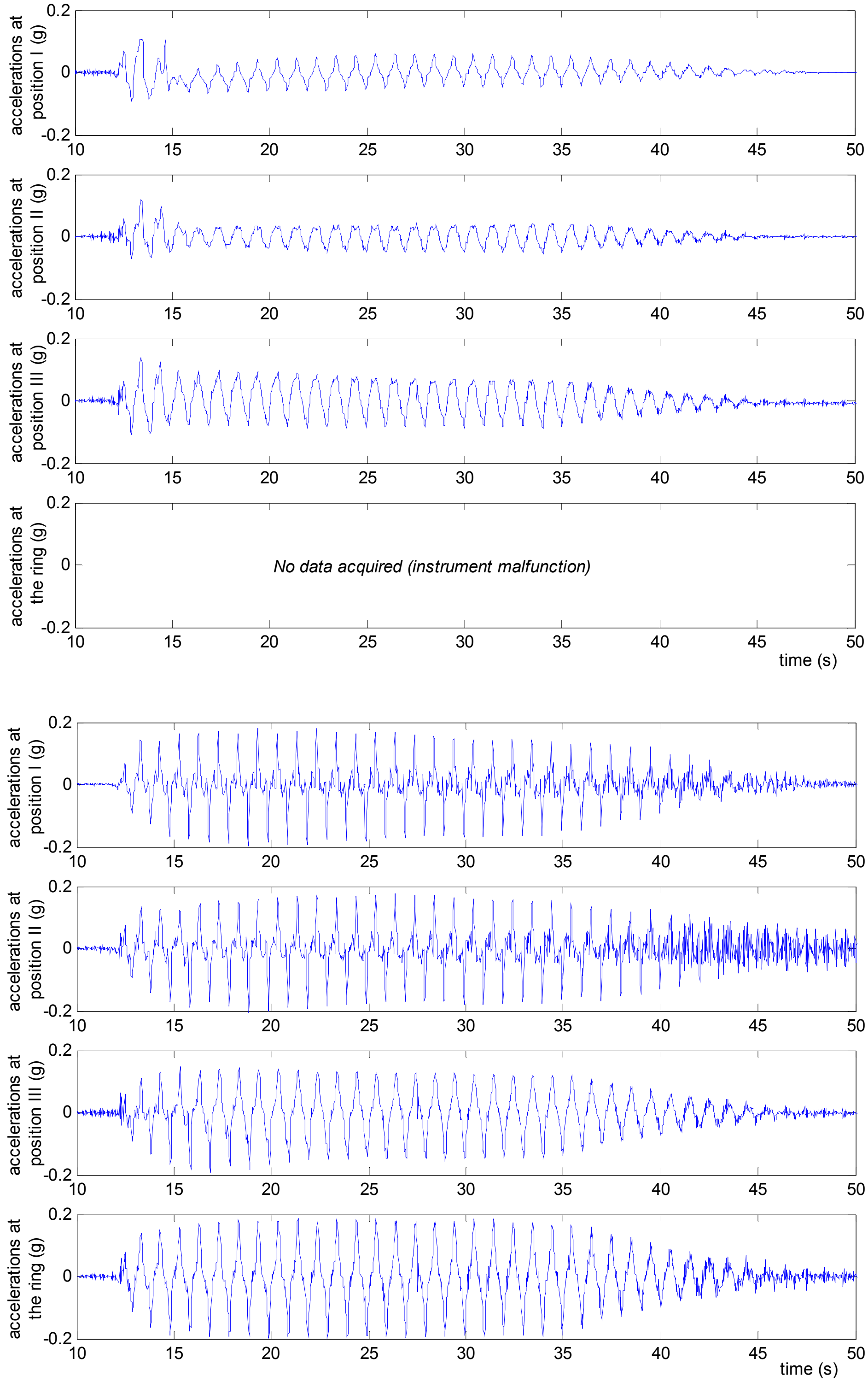


Figure 3- Horizontal accelerations measured at different depths and at different distances from model container in loose sand (prototype scale)

Boundary effects on accelerations

The time history of the horizontal accelerations measured during the seismic event is shown in Figure 3, for the two depths considered, at positions I, II and III, as well as at the ring located at the same level. Data relative to the ring corresponding to the shallower depth (4.3 m) is not available due to malfunction of the accelerometer. Figure 4 presents data FFT analysis performed on the accelerations measured between 25 and 35 s.

At shallower depths, where acceleration changes with time are more pronounced as a result of more significant soil softening, accelerations at positions I and II are quite similar (Figure 3-a). At position III, however, accelerations are larger as a result of higher box stiffness, the difference being more marked after the first couple of cycles, due to the dramatic degradation of soil stiffness that leads to the large attenuation of soil accelerations in the centre of the model. The FFT analysis of accelerations at the described positions, from 25 to 35 s, shown in Figure 4, definitely confirm the effects of container on the soil accelerations at position III during this stage.

At 12.5m depth, where soil softening is not so marked and peak accelerations are steadier with time, time histories of horizontal accelerations at different positions look similar, although in the centre of the model acceleration peaks corresponding to the main frequency have shorter duration and higher frequency components are more important (Figure 3-b). These discrepancies are clearly expressed by the FFT analysis of accelerations at the different positions, from 25 to 35 s, presented in Figure 4, which clearly shows the similarity of Fourier amplitude spectra observed at positions I and II, the significant amplification of main frequency and attenuation of higher frequencies observed in the container ring, as well as the boundary effects at position III.

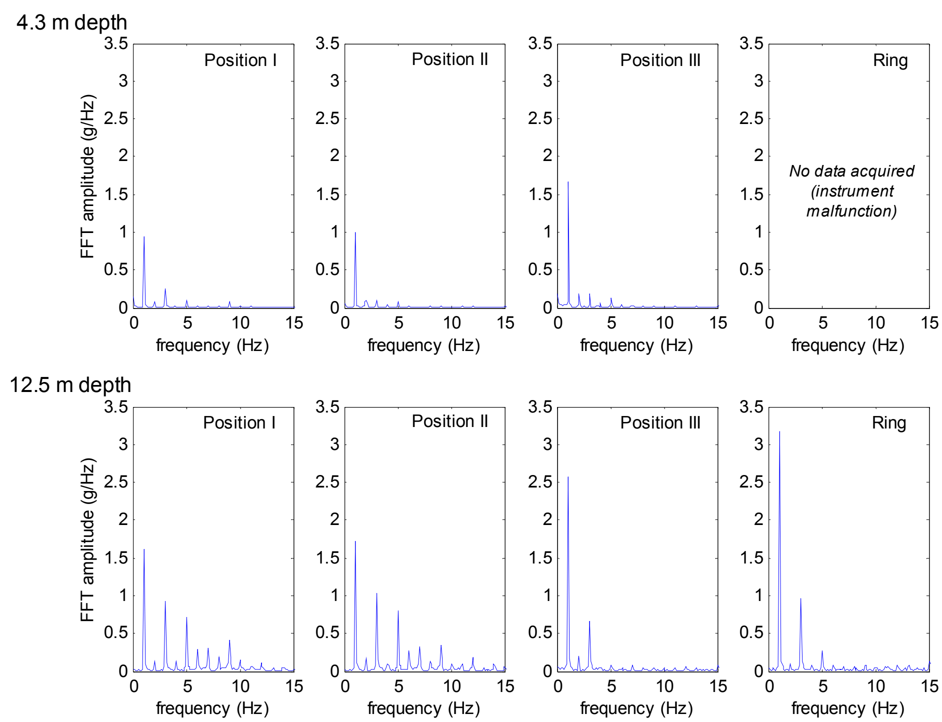
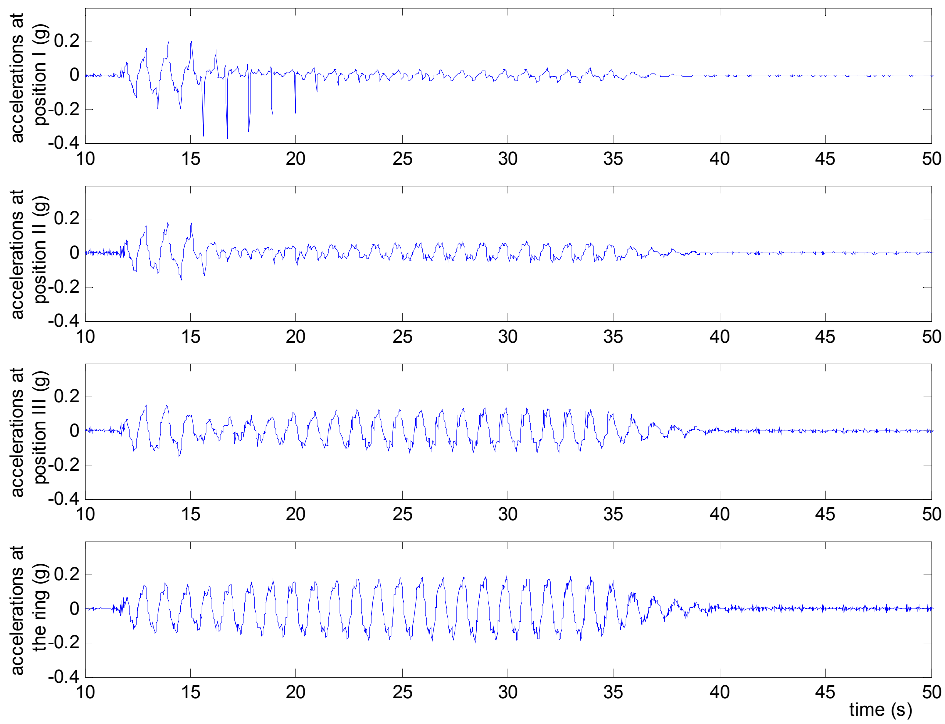


Figure 4- FFT analysis of accelerations measured in the model of loose sand between 25 and 35 seconds (prototype scale)

a) 4.2 m depth



b) 13.1 m depth

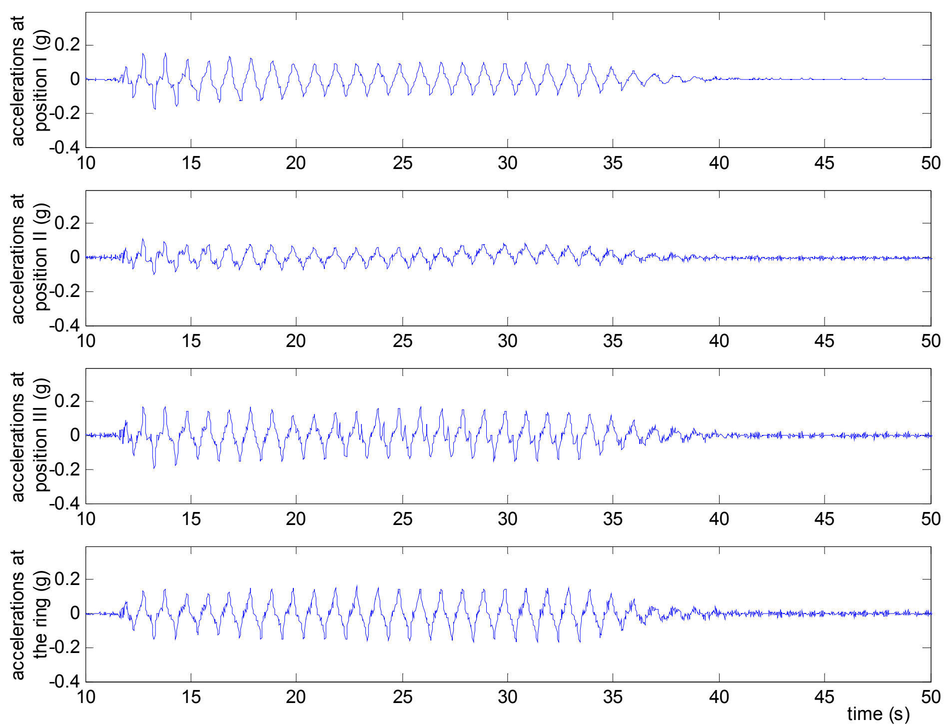


Figure 5- Horizontal accelerations measured at different depths and at different distances from model container in dense sand (prototype scale)

In the case of the dense model, the time history of the horizontal accelerations measured during the seismic event is shown in Figure 5, for the two depths and different positions considered. Figure 6 presents the FFT analysis of the accelerations measured from 25 to 35 s.

At 4.2 m depth (Figure 5-a), where, despite of the fact that the sand is in a dense state, considerable soil softening and attenuation of accelerations are observed, the similarity of acceleration time histories varies during the event. During the first couple of cycles, accelerations are fairly similar at the various positions instrumented, probably because soil stiffness degradation is insignificant and the container reasonably matches soil's initial stiffness. Between 15 and 20 s, large-magnitude short-duration acceleration spikes are observed at position I, while the container accelerations show no major changes from previous stage. At other positions, large attenuation of accelerations is visible at this stage, especially at position II. After about 22 s, the soil has been softened to a point that peak accelerations inside the model remain fairly constant with time, having a magnitude much lower than accelerations measured at the container ring. Fourier amplitude spectra of accelerations at instrumented positions (Figure 6) clearly show that the effect of the container on soil accelerations near the box, between 25 and 35 s, is substantial, even influencing the soil behaviour at position II. The ability of dense soil to preserve higher shear stiffness, even after cyclic loading caused excess pore pressures, may be responsible for the fact that the container affects soil behaviour at larger distances, compared to the test on the loose model.

Boundary effects are less significant at 13.1 m (Figure 5-b), probably due to the fact that the soil stiffness in the centre of the model is not so affected by cyclic strain softening and is better matched by the walls of container. The Acceleration measured at position II does not seem realistic, when its Fourier spectra is compared to those corresponding to positions I and III (Figure 6).

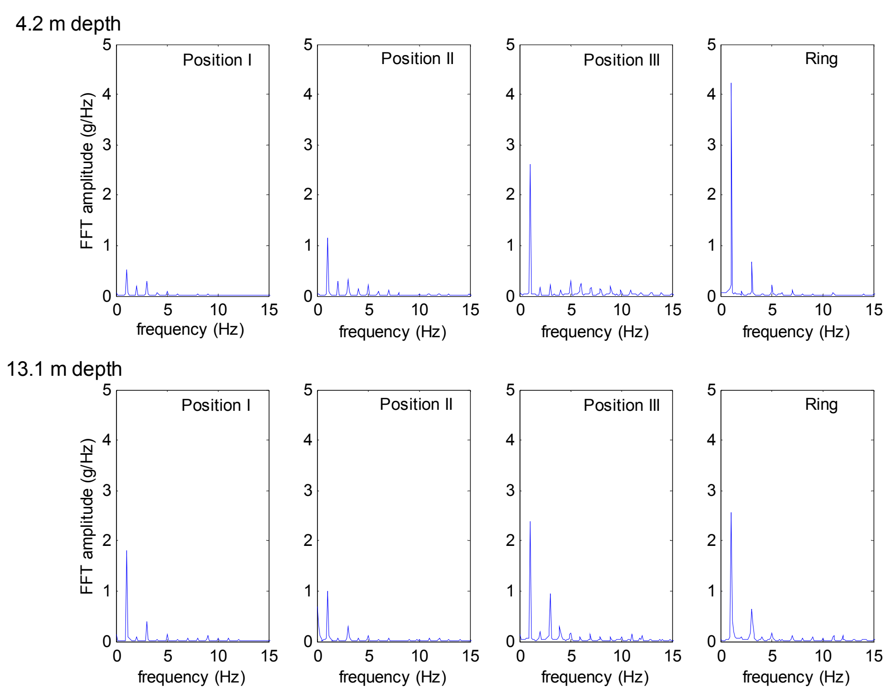


Figure 6- FFT analysis of accelerations measured in the model of dense sand between 25 and 35 seconds (prototype scale)

It is apparent that the fact that, as soon as significant stiffness degradation occurs, boundary effects can be observed at larger distances from the walls in the case of dense sand should be mainly a consequence of the characteristics of softened soil, as the box is expected to behave in a similar way in both tests and, during the period considered as relevant (25 to 35 s), FFT spectra analysis of the input seismic events simulated in each test are very similar (Figure 7).

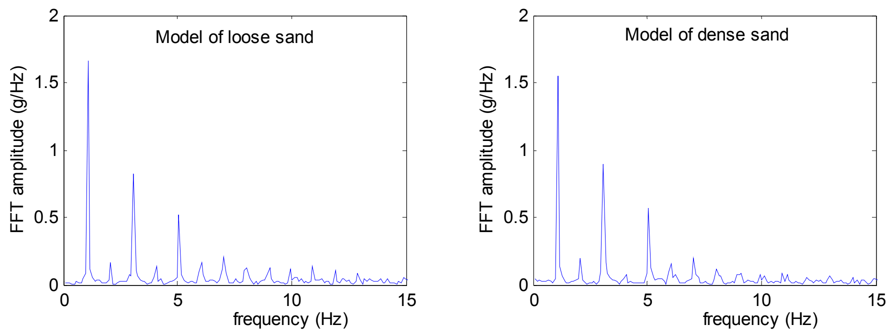


Figure 7- FFT analysis of horizontal input accelerations measured in both models between 25 and 35 seconds (prototype scale)

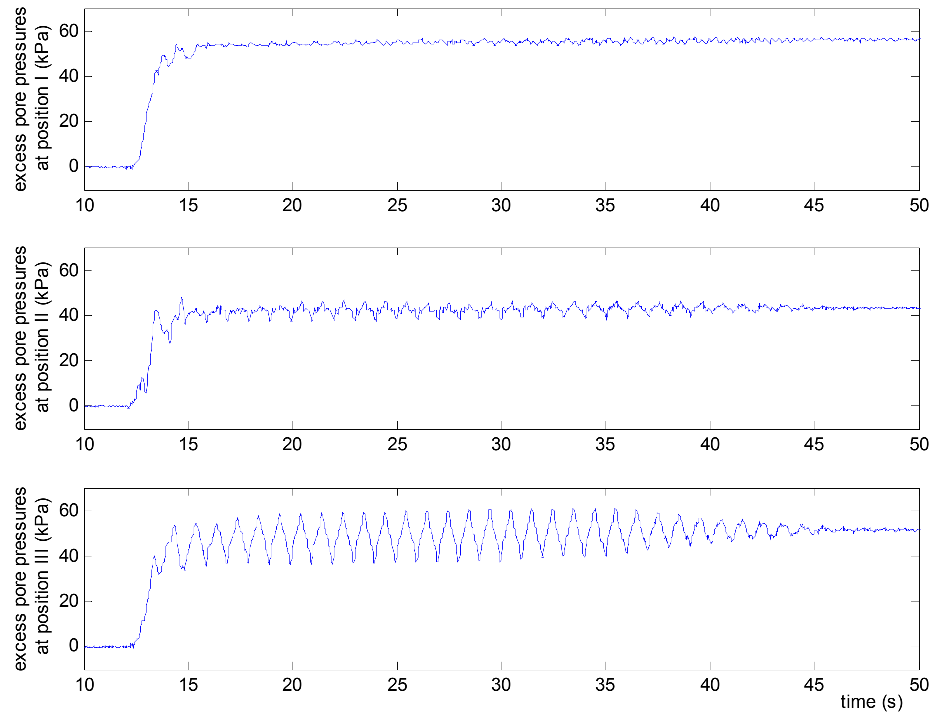
Boundary effects on excess pore pressure generation

Figures 8 and 9 present, in prototype scale, the excess pore pressure generation with time observed, respectively, in the models of loose and dense sand. In order to perceive the effects of the deep ESB container on the cyclic pore pressure generation in the centrifuge model, time histories of pore pressure at different depths are compared at different distances from walls.

In the loose model (Figure 8), the excess pore pressure generated at each level by the end of the seismic event is fairly similar at positions I, II and III, there being only minor differences probably due to small variations in actual depth of the instruments. In contrast, during the seismic event, the transient excess pore pressure generated during each cycle is noticeably different, assuming much higher values closer to the walls of the container. At both instrumented levels, cyclic peak-to- peak excess pore pressure variations are close to 50 % of average excess pore pressure, at position III, being much less significant at position II and practically irrelevant at model's centre (position I). These observations suggest that the container is not deforming in the same manner as the softened soil and thus induces additional transient excess pore pressure generation in the soil.

The situation observed in the dense model and shown in Figure 9 is similar to that observed in the loose model. During shaking, the values of transient excess pore pressure generated during each shear cycle are much higher near the walls of the container, especially at position III, where they can mount up to 60 % of average excess pore pressure. Similarly, suction spikes during the first cycles, near the surface of the model, are observed both in the centre and at the borders of the model but are more significant near the walls of the container. This suggests that the dilative behaviour of the dense sand is preserved near the container, which may explain why boundary effects in terms of accelerations affect a larger area in the case of the dense model. The rate of excess pore pressure generation at each level is similar at different positions and the value at the end of the seismic event seems to increase slightly due to the presence of the box, though it is difficult to consider it a mere effect of the container. As in the loose model, the observations clearly suggest that the container is not deforming in consonance with the softened soil, which leads to increased transient excess pore pressure generation, especially in the model edges.

a) 4.3 m depth



b) 12.5 m depth

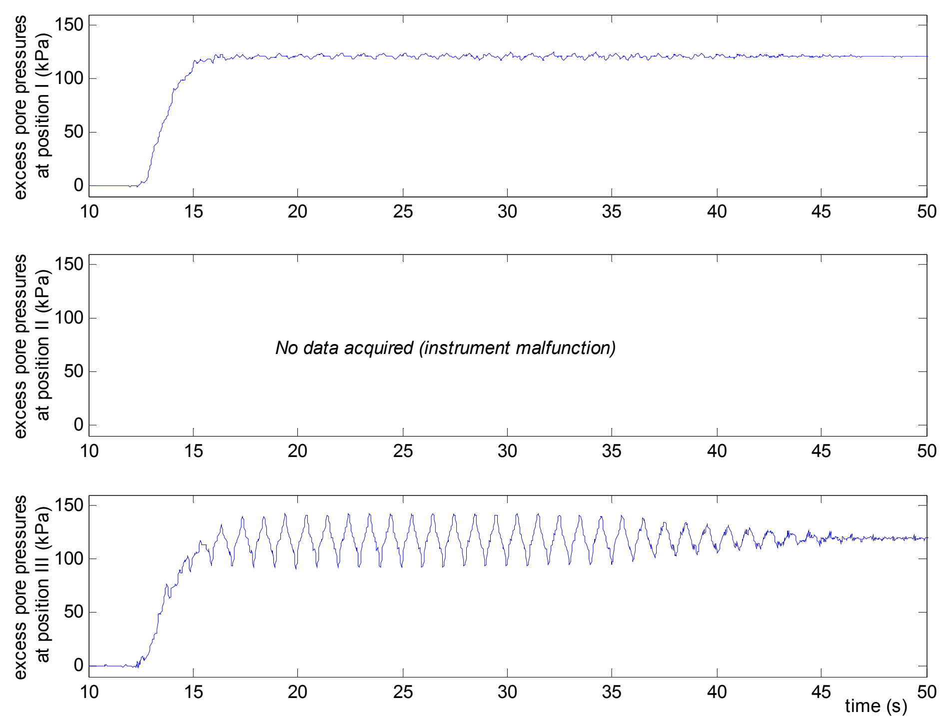
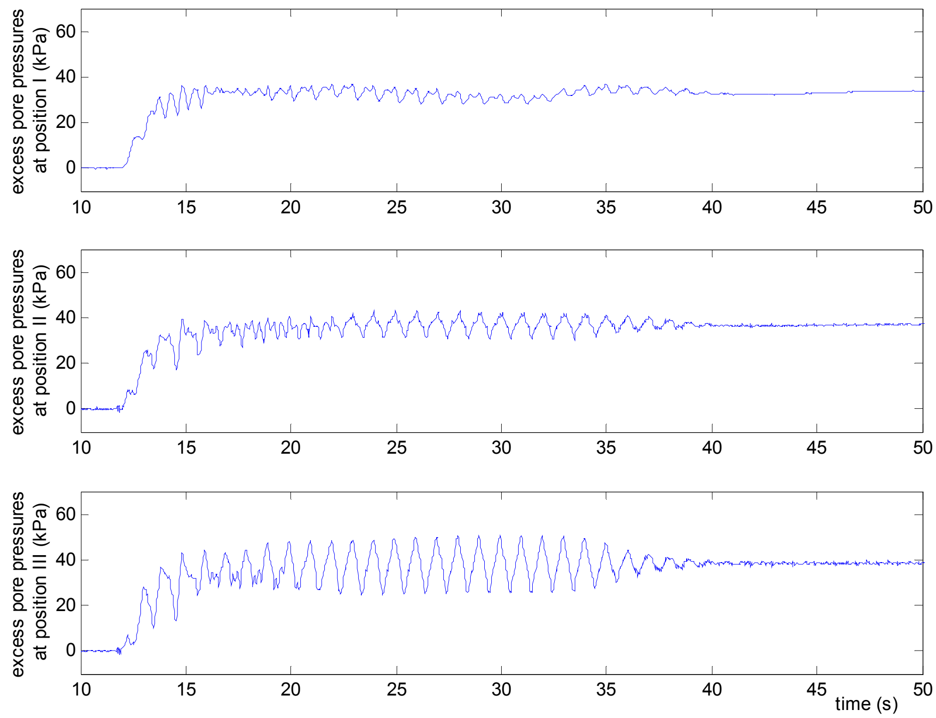


Figure 8- Excess pore pressures measured at different depths and at different distances from model container in loose sand (prototype scale)

a) 4.2 m
depth



b) 13.1 m
depth

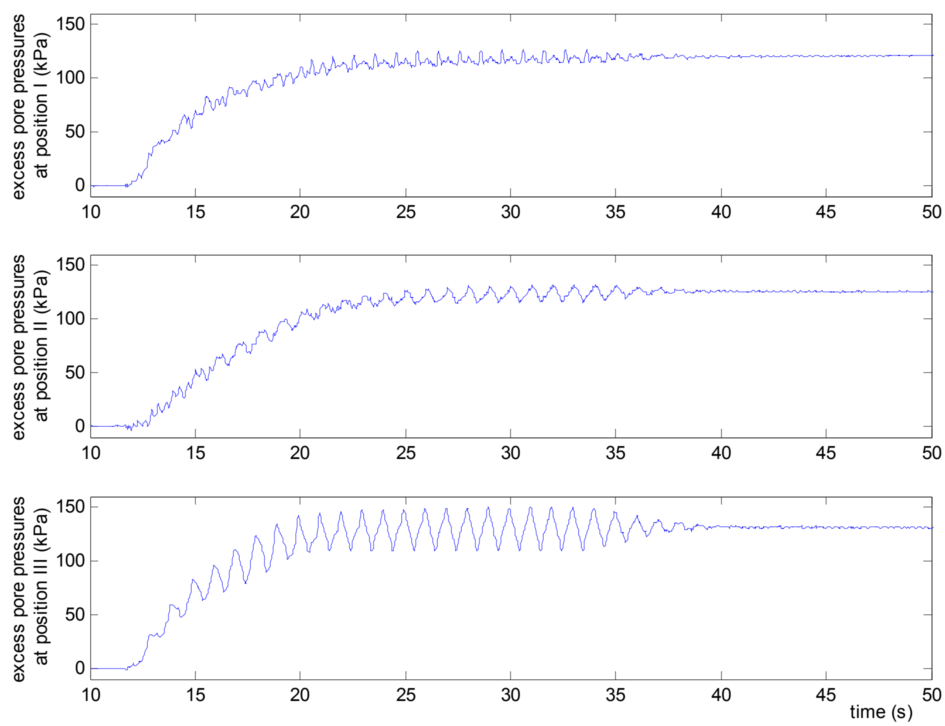


Figure 9- Excess pore pressures measured at different depths and at different distances from model container in dense sand (prototype scale)

CONCLUSIONS

This paper presented the results of centrifuge tests performed on uniform deposits of saturated sand at Cambridge University in order to clarify the boundary effects caused by a recently developed deep Equivalent Shear Beam (ESB) container. The boundary effects were observed when investigating earthquake-induced liquefaction, which causes large soil stiffness and shear strength degradation that cannot be reproduced by the physical boundaries of the centrifuge model. Accelerations and excess pore pressures in the centre and edges of models of loose and dense sand clearly illustrated the adverse effects of the boundaries, which progressively increase with soil softening due to the generation of excess pore pressure.

The results have shown that boundary effects are most significant in regions where the soils behaviour is most changed due to excess pore-pressures, whether this is attenuation of accelerations due to the loss of strength of loose soils, or acceleration spikes transmitted by the dilation of dense soils. These effects tend to be most significant towards the surface of models, with the behaviour observed at depth being substantially unaffected.

The results show that, during the earthquake, boundaries significantly affect the soil dynamic response and the transient pore pressure generation close to the box walls, but also suggest that the soil behaviour observed in the central 300mm of the model is authentic and is reasonably unaffected by the container. Therefore, provided that the behaviour of the soil close to the model edges is disregarded, ESB containers are suitable for centrifuge modelling of earthquake-induced liquefaction. Centrifuge-based investigation of the effects of liquefaction on structures should use models of structures preferentially founded on the central part of model.

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REFERENCES

Brennan, A.J. and Madabhushi, S.P.G. (2002), “Design and Performance of a New Deep Model Container for Dynamic Centrifuge Modelling”, Proc. of the Int. Conference on Physical Modelling in Geotechnics, St John's, Newfoundland, Balkema, Rotterdam, pp 183-188.

Coelho, P.A.L.F. (2003), “Densification as a Liquefaction Resistance Measure for Bridge Foundations”, 1st Year Report, Cambridge University, UK.

Hardin, B.O. and Drnevich, V.P. (1972), “Shear modulus and damping in soils: design equations and curves”. J. Soil Mechanics and Foundations Division, ASCE, vol. 98, No. SM7, 667-692.

Madabhushi, S.P.G. (1994), “Dynamic response of the equivalent shear beam (ESB) container”, Technical Report, CUED/D-Soils/TR270, Cambridge University, UK.

Madabhushi, S.P.G., Schofield, A.N. and Lesley, S. (1998) “A new Stored Angular Momentum (SAM) earthquake actuator”, Centrifuge’98, I. Conf. on Centrifuge Modelling, Tokyo, Japan.

Teymur, B. (2002), “The significance of boundary conditions in dynamic centrifuge modelling”, PhD Dissertation, Cambridge University, UK.

Zeng, X. (1991), “Design of the Cambridge dynamic shear box”, Technical Report, CUED/D-Soils/TR241, Cambridge University, UK.

Zeng, X. and Schofield, A.N. (1996), “Design and performance of an equivalent-shear-beam container for earthquake centrifuge modelling”, Geotechnique, vol. 46, No. 1, pp 83-102.