International Conference on Case Histories in Geotechnical Engineering
(2004) - Fifth International Conference on Case Histories in Geotechnical Engineering

17 Apr 2004, 10:30am - 12:30pm

Centrifuge Modelling of Earthquake Effects in Uniform Deposits of Saturated Sand

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Proceedings: Fifth International Conference on Case Histories in Geotechnical Engineering
New York, NY, April 13-17, 2004

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ABSTRACT

Centrifuge models representing level uniform saturated deposits of relatively loose and dense sand were tested at Cambridge University's Schofield Centre to clarify the behaviour of these deposits under earthquake loading. The excess pore pressure, vertical propagation of the accelerations and ground surface settlements resulting from a model earthquake are presented and discussed. The results show that, for similar dynamic loading, the models undergo large shear stiffness degradation resulting from significant pore pressure build up, this taking place at a slower rate in the dense sand. As a result of the cyclic loading, the models suffer settlements, occurring mostly during the event, that are noticeably smaller in the dense model. The upwards propagation of the accelerations through the model depends on the relative density of the sand and changes during the seismic event, following degradation of sand mechanical properties. Large short-duration acceleration spikes are observed near the surface of the dense model, corresponding to large amplification of input acceleration. The results presented and discussed contribute to the understanding of the basic mechanisms of earthquake-induced liquefaction and the use of densification as a measure to mitigate its effects.

INTRODUCTION

The behaviour of saturated deposits of sand under dynamic loading stands as one of the most complex problems faced by geotechnical engineers, the effects of earthquake-induced liquefaction remaining a significant hazard for structures built on areas of seismic risk. Mitchell et al (1995) and Hausler and Sitar (2001) provide detailed information on the performance of improved and non-improved liquefiable deposits during earthquakes. Even though there is a satisfactory qualitative consensus regarding the issues of pore pressure generation in loose uniform sand under cyclic shear and the dramatic effects of liquefaction of granular deposits following earthquake loading, complete understanding of the phenomena is not achieved. This would explain why at present the design of liquefaction-resistance measures is mainly based on empirical criteria and numerical modelling of liquefaction-related problems still presents an intricate geotechnical challenge.

This paper presents the results of dynamic centrifuge tests performed at Cambridge University on models of saturated sandy deposits of varying relative density to clarify their behaviour under earthquake loading. Valuable observations regarding pore pressure generation and shear stiffness degradation in loose and dense sandy deposits induced by cyclic loading, as well as the propagation of shear waves and surface settlements resulting from the shaking, are discussed. The experimental evidence provided herein further improves the fundamental understanding of the phenomena and the use of densification as a liquefaction resistance measure.

MODEL PREPARATION AND TESTING FEATURES

Centrifuge models of level saturated deposits of uniform sand were prepared by air pluviation of Leighton Buzzard Fraction E silica sand, with distinct relative densities. After saturation and loading, the sand in the models for tests PC02 and PC03 had relative densities of 50 and 80 %, respectively. These values of relative density are close, respectively, to the loosest state usually found in nature and the state commonly resulting from densification. In order to accomplish viscosity scaling at 50 g and to eradicate the time-scaling conflict between dynamic and diffusion phenomena, models were saturated with 50 cSt methylcellulose, as described in detail by Coelho et al (2003a).

In order to observe the deposits behaviour during the earthquake simulation, pore pressure transducers (PPT), accelerometers (Acc) and linear variable differential transformers (LVDT) were placed in the centre of the model. Table 1 shows the depths, at prototype scale, at which PPT and Acc were installed in the model. The depths corrected for the instruments' movements during saturation and loading procedures, which were used for the interpretation of the experimental results, are also shown.

Table 1. Position of PPT and Acc in the centrifuge models

Reference level	Original depth* (m)		Estimated depth** (m)	
	PC02	PC03	PC02	PC03
A	1.7	1.6	1.5	1.8
B	4.2	4.2	6.8	4.5
C	7.2	7.1	9.9	7.4
D	10.6	10.4	12.4	10.5
E	12.7	13.3	13.7	13.3
F	16.2	15.9	15.7	15.9
Bottom	18.0	18.0	17.2	18

**After model building (dry state)* ***After saturation and loading procedures*

Models were tested under a centrifuge acceleration of 50 g and submitted to dynamic loading produced by the SAM actuator (Madabhushi et al, 1998). The model earthquake, planned to have a fundamental frequency of 50 Hz and a duration of 0.5 s, corresponds to a prototype event with a fundamental frequency of 1 Hz lasting 25 s, according to the relevant dynamic centrifuge scaling laws (Coelho et al, 2003a). During the centrifuge test, models were enclosed within the finite boundaries provided by a deep Equivalent Shear Beam (ESB) container, with flexible end walls designed to minimise stress wave reflections, whose construction and performance is discussed by Coelho et al (2003b).

BEHAVIOUR OF THE LOOSE SATURATED DEPOSIT

The behaviour of the loose saturated sand deposit (relative density 50 %) during seismic loading can be inferred from the observations of the model employed in test PC02.

Figure 1 presents the prototype input earthquake time history and its associated FFT for the seismic event generated in test PC02. Apart from the fact that the earthquake lasted slightly longer than desired, the characteristics of the cyclic loading closely matched those desired, namely a fundamental frequency that is close to 1 Hz.

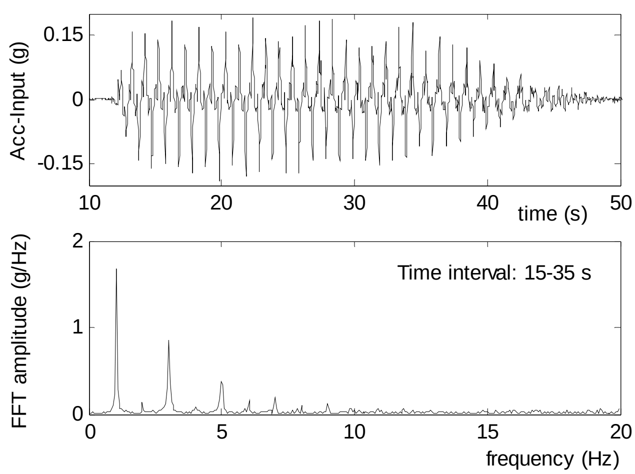

Fig. 1. Time history and FFT analysis of the seismic event applied to model in test PC02 (prototype scale).

The excess pore pressure generated at each level during the cyclic loading imposed to the model is presented in Fig. 2, which also shows predictions of the initial effective vertical stress, represented by dashed lines. The value of the excess pore pressure measured at level A, which does not exceed 10 kPa, is relatively small, rendering the difference between the maximum value recorded and the predicted effective vertical stress at that level of little significance. The fact that, at that same level, the excess pore pressure stabilizes around two different values during the shaking can be explained by sinking of the instrument during the period for which the soil is liquefied , which was proved to affect shallow instruments.

The major overall conclusion that can be drawn from Fig. 2 is that the earthquake causes pore pressures in the model to rise, at each level, to a value that is very close to the initial effective vertical stress, a state that will be referred to as liquefaction. The profile of pore pressure build-up with depth shows that the number of cycles required to reach that state, which varies between 5 and 13, increases with depth, due to the higher initial effective stresses. Although full liquefaction of the saturated deposit of loose sand requires 13 cycles of shaking, 2 cycles are enough to cause a massive drop of effective stress throughout the depth.

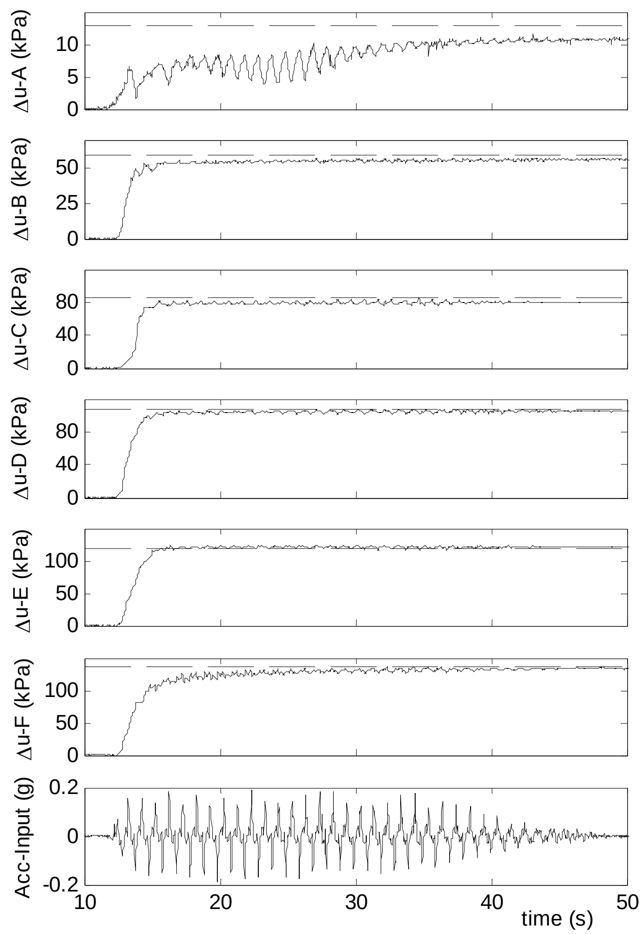

Fig. 2. Excess pore pressure generation observed in test PC02 (prototype scale).

Figure 3 represents the upward propagation of the horizontal accelerations measured, in the direction of shaking, in the loose sand model. The results clearly show that, from the first cycle of loading, peak accelerations reaching the ground surface (Level A) suffer attenuation relative to the input accelerations. After the first 2 to 3 cycles, during which the values of excess pore pressure generated during the cyclic loading progressively approach, throughout the deposit, the initial effective vertical stress at each level, ground surface peak accelerations are tremendously degraded to residual values that represent less than 15 % of the peak input accelerations. Similar patterns of behaviour are observed at deeper instrumented levels, although some differences result from the facts that the initial effective stress is higher and the number of cycles required to reach a state of quasi zero effective stress is larger. Thus, at these deeper levels, the change of behaviour from the first few cycles to the following ones is not so clear and the attenuation is not as severe as near the surface, providing evidence of the progressive attenuation of accelerations as shear waves travel towards the top of the deposit. This behaviour is a consequence of the degradation of shear stiffness undergone by the deposit as a result of the progressive reduction of effective stress that occurs during the cyclic loading.

The characteristics of the attenuation of horizontal accelerations after the deposit has substantially softened is further elucidated by Fig. 4, where the FFT analysis of accelerations measured, at each level, between 25 and 35 s are presented. The figure shows that, as the deposit liquefies, every frequency found in the input acceleration record is progressively attenuated towards the surface, frequencies other than the fundamental frequency being almost entirely removed from the acceleration time history recorded near the surface. However, it should be noted that, despite the massive reduction of effective stress observed at level E, it seems that local accelerations show a slight amplification of the input, which affects all the frequencies of the event.

As expected, the seismic loading applied to the model also caused a quite significant ground settlement, which was measured, once deformations ceased, as 430 mm at prototype scale. Taking into consideration that the initial depth of the prototype was 17.2 m, the observed value of the total settlement corresponds to a post-liquefaction volumetric strain, ε_v, of 2.5 %. As a consequence of the seismic event and the subsequent rearrangement of the grains, the relative density of the sand increased from an initial value of 50 % to a final value of 62 %.

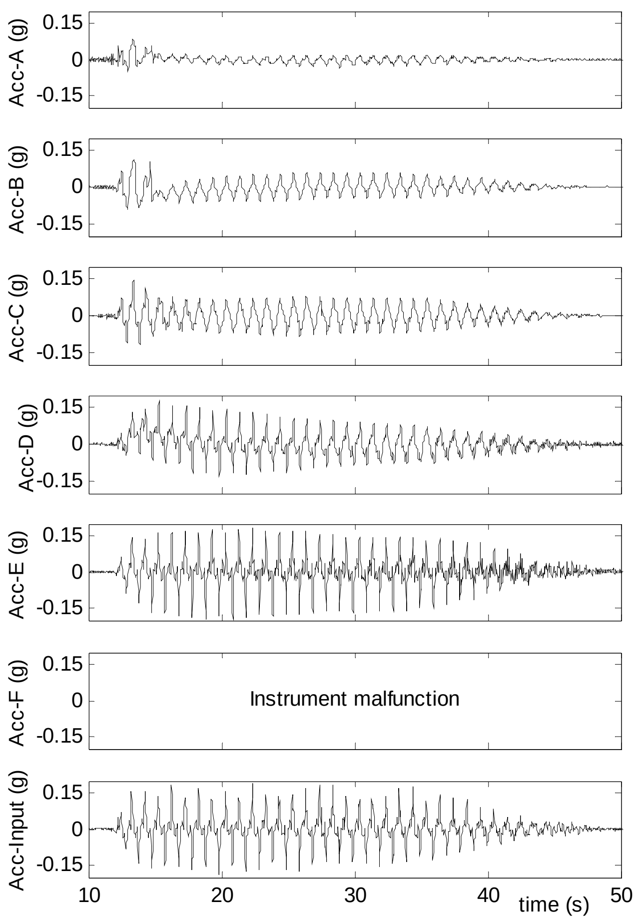

Fig. 3. Propagation of horizontal accelerations observed in test PC02 (prototype scale).

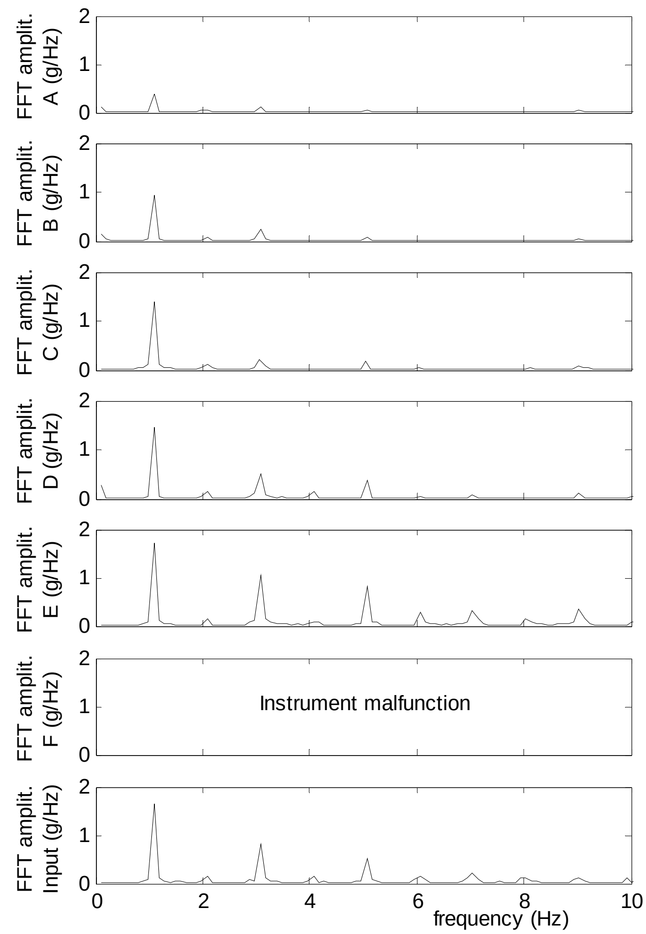

Fig. 4. FFT analysis of the horizontal accelerations measured between 25 and 35 s in test PC02 (prototype scale).

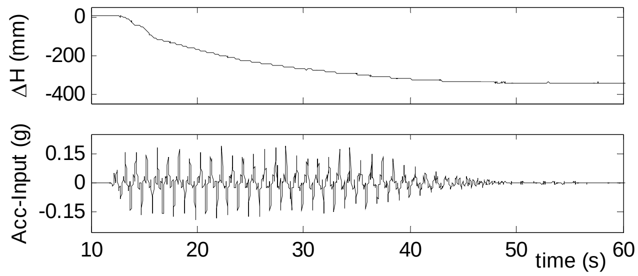

Fig. 5. Short-term ground surface settlement versus input accelerations in test PC02 (prototype scale).

Figure 5, representing the evolution of the ground settlement during the earthquake, shows that the most significant part of the total settlement (430 mm), occurs simultaneously with the shaking, reaching 342 mm, or 80 % of the total when shaking ceases. Examination of the long-term ground surface settlement, plotted in Fig. 6, confirms that the deformations of the ground surface tend to stabilize as soon as the seismic event comes to an end, even though the excess pore pressure in the deposit has not yet been dissipated. In fact, as Figure 6 clearly shows, the excess pore pressure remains near its maximum value after the end of shaking, especially near the surface, where dissipation only begins more than 15 minutes after the end of the seismic event. This behaviour suggests that the permeability of the sand during the shaking may increase significantly, allowing the water to be expelled from the voids and the particles to rearrange quickly during that period, allowing significant volumetric strains to occur during what would normally be considered an undrained event.

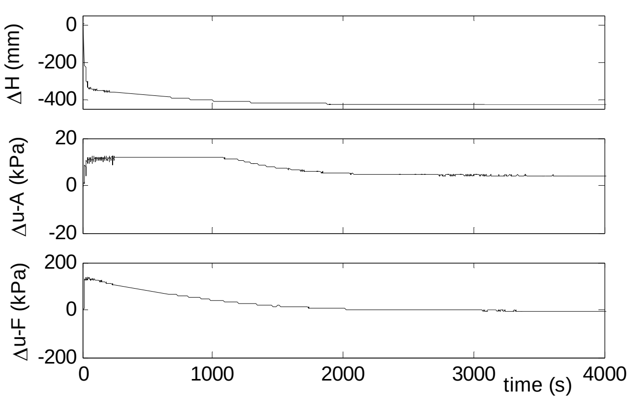

Fig. 6. Long-term ground surface settlement and pore pressure dissipation in test PC02 (prototype scale).

BEHAVIOUR OF THE DENSE SATURATED DEPOSIT

Test PC03 typifies the behaviour of a dense saturated deposit of sand with a relative density of 80 % during an earthquake.

The prototype input acceleration time history and associated FFT of the seismic event generated in test PC03 are shown in Fig. 7. The figure shows that both the predominant frequency and the duration of the seismic event applied to the model of dense sand are extremely close to those that were desired.

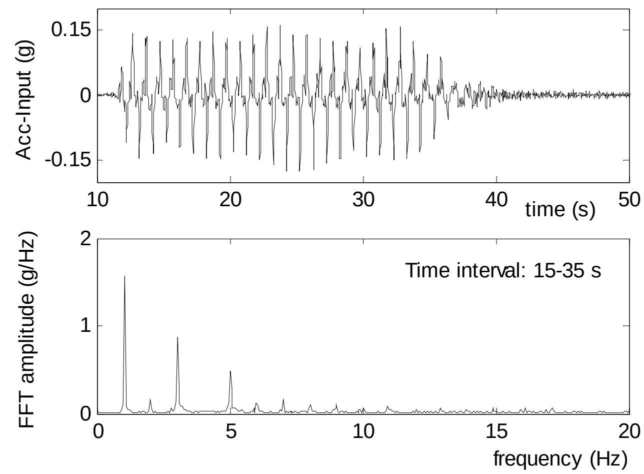

Fig. 7. Time history and FFT analysis of the seismic event applied to model in test PC03 (prototype scale).

Figure 8 compares the predicted initial effective vertical stress (dashed line) with the excess pore pressure generated at each level during the earthquake. The pore pressure generation at level B seems inconsistent with that of other adjacent levels.

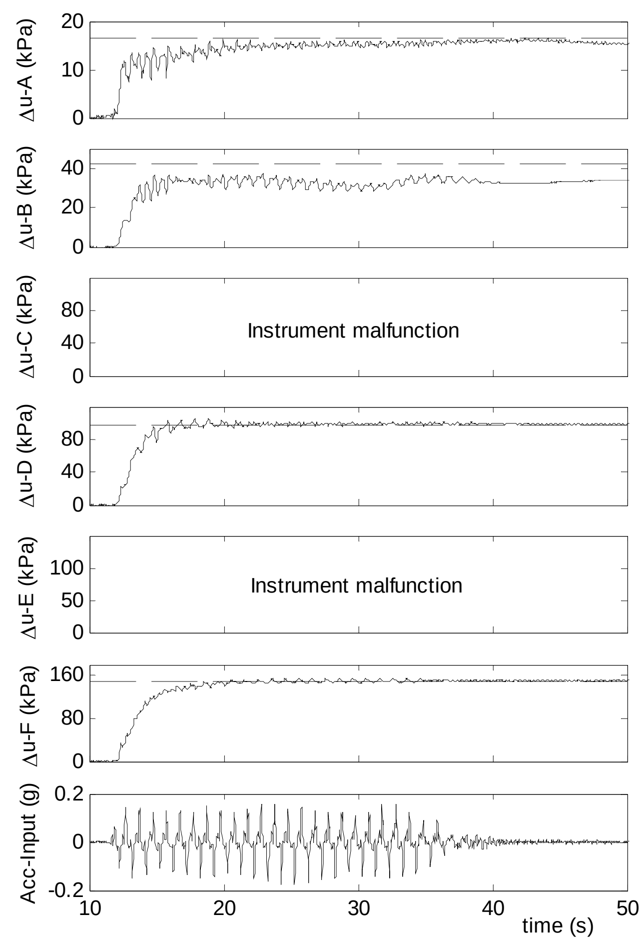

Fig. 8. Excess pore pressure generation observed in test PC03 (prototype scale).

From the analysis of the figure, it can be stated that the cyclic loading leads to a broad and consistent build up of excess pore pressure in the dense model that reaches values that are very near to the initial effective vertical stresses predicted at each level. The number of cycles at which the generation of excess pore pressure stabilizes is estimated at between 8 and 14, increasing with depth, due to the corresponding increase of initial effective stress. However, after just 3 to 4 cycles of loading the drop of effective stress is already considerable and affects the entire depth of the deposit.

The characteristics of the propagation of the horizontal accelerations, in the direction of shaking, from the bottom to the top of the model of saturated deposit of dense sand during test PC03 are illustrated in Fig. 9. The major general finding that can be deduced from the figure is that the behaviour of the sand under the cyclic loading is significantly different at shallow depths and at deeper levels, probably as a consequence of the different value of effective stress present at each level. In fact, while below a depth of around 10 m, coinciding with instrumented level D, the recorded time histories of acceleration are smooth, near the surface there are large and abrupt changes.

Considering the records obtained at level B as a reference for the behaviour of dense sand at shallow depths (as the instrument placed at level A didn’t work accurately during the test), the characteristics of the horizontal accelerations near the surface can be separated into three distinct stages. During the first three cycles, as shear waves travel through the deposit the main frequency of the event is amplified while higher frequencies are reasonably preserved. At this stage, the peak ground surface accelerations slightly exceed the peak input accelerations. During the following period, which roughly occurs between 15 and 20 s, the time history of accelerations varies significantly with time, the most significant feature of behaviour being the occurrence of large magnitude short duration acceleration spikes corresponding, sometimes, to more than 100 % amplification of peak input accelerations. The trend of the propagation of accelerations suggests that this amplification can be even higher closer to the surface, as level B is estimated to be at a depth as high as 4.5 m. A third and final stage can be observed after 20 s, when the attenuation of accelerations is massive and reasonably constant with time. In this final stage, the peak accelerations measured at level B represent only about 25 % of the peak accelerations transmitted the bottom of the model.

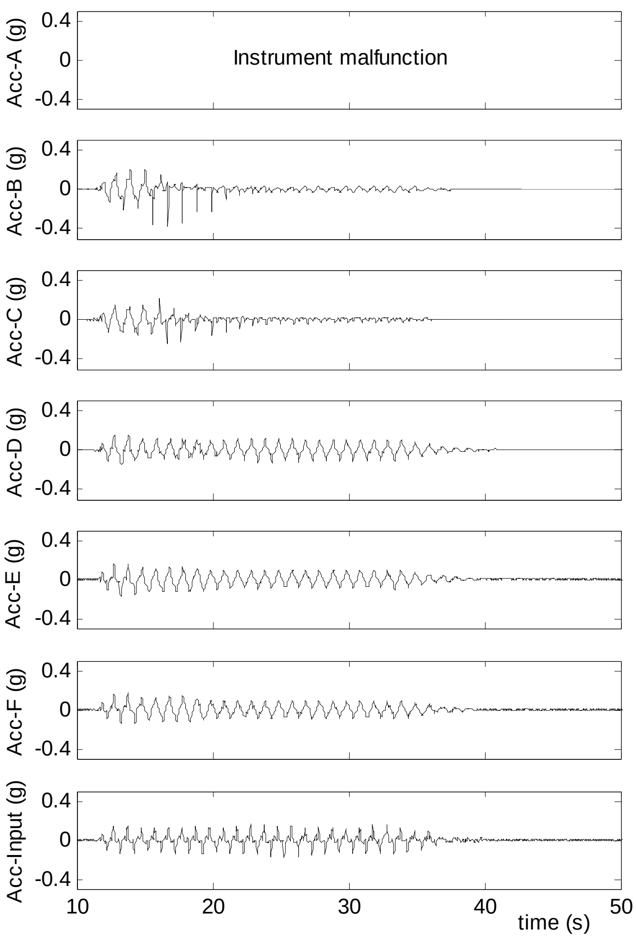

Fig. 9. Propagation of horizontal accelerations observed in test PC03 (prototype scale).

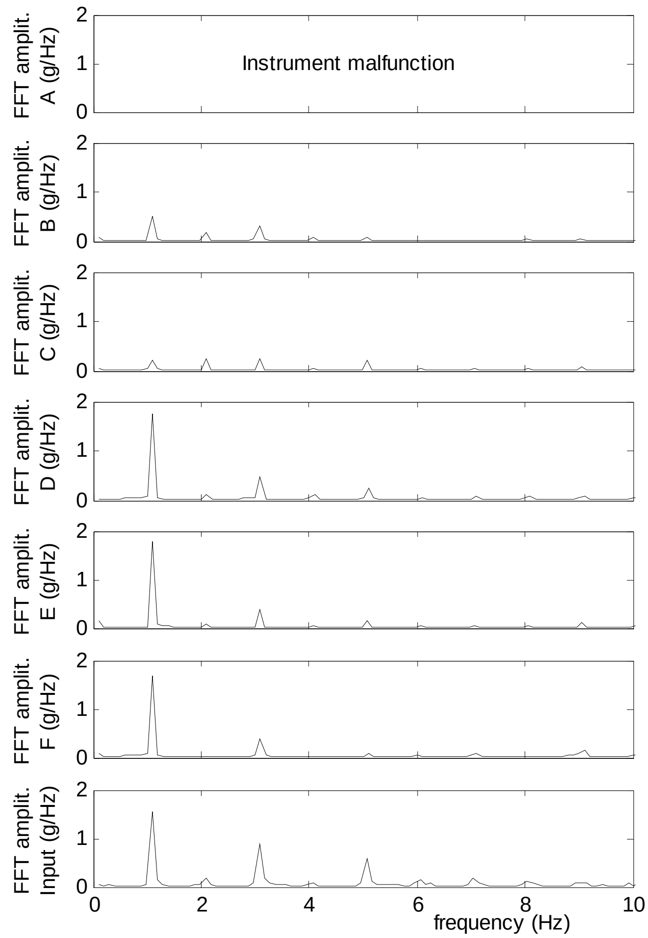

Fig. 10. FFT analysis of the horizontal accelerations measured between 25 and 35 s in test PC03 (prototype scale).

The behaviour observed at deeper instrumented levels is qualitatively different from that observed near the surface, as the intermediate period coinciding with the occurrence of large acceleration spikes is not detectable. Thus, as can be seen at levels D, E and F, there is a smooth transition from the first few cycles, where the peak accelerations measured at each level are quite similar or show very slight amplification of the input, to the subsequent cycles, during which peak accelerations are moderately attenuated as a consequence of the degradation of shear stiffness, which is determined by the reduction of effective stress that occurs during the cyclic loading.

Figure 10 provides more detailed information on the characteristics of the accelerations measured at each level during a period, ranging from 25 to 35 s, where significant softening of the soil caused by the excess pore pressure has already taken place. The FFT analyses shown reinforce the idea that the behaviour of the soil is highly dependent on the depth considered. Below level D, there is a slight and progressive amplification of the main frequency, corresponding to 1 Hz, and some attenuation of higher frequency components. At shallow depths, there is a remarkable decrease of the FFT amplitude for every single frequency found in the event, which is more significant, in relative terms, for the main frequency.

The earthquake simulation applied to the model of dense sand also resulted in a non-negligible settlement of the ground surface that, once deformations stabilized, mounted up to a value of 155 mm at prototype scale. This absolute value of settlement corresponds, in a deposit with an initial total depth of 18 m, to an average post-liquefaction volumetric strain, ε_v, of 0.86 %. Due to the rearrangement of the grains induced by the cyclic loading, which is expressed by the observed settlement of the ground surface, the sand has, at the final condition of equilibrium, a relative density of 83 % compared to the initial relative density of 80 %.

Figure 11 compares the development of the ground surface settlements of the model of dense sand during the period of shaking with the input accelerations. According to the experimental results plotted, the amount of settlement measured as soon as the model earthquake comes to an end can be estimated as 148 mm, which means that 95 % of the total settlement occurs during the shaking.

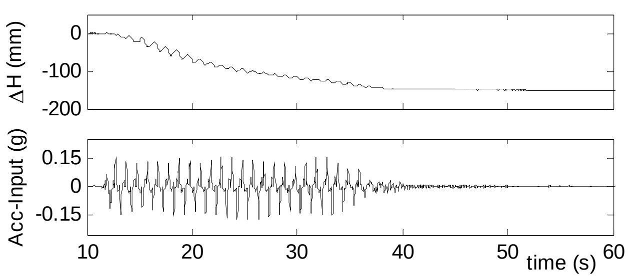

Fig. 11. Short-term ground surface settlement versus input accelerations in test PC03 (prototype scale).

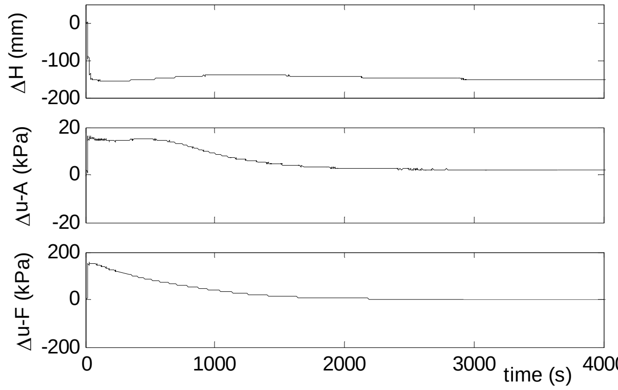

Fig. 12. Long-term ground surface settlement and pore pressure dissipation in test PC03 (prototype scale).

The analysis of the long-term ground surface settlement and pore pressure dissipation in the deposit observed in test PC03, shown in Fig. 12, suggests, in conjunction with Fig. 11, that the permeability of the sand increases significantly during the period of cyclic loading. In fact, the outward flow of water during the seismic event must be significant, in order to allow the observed amount of settlement to occur during that period. On the other hand, as soon as the shaking is over, the settlements carry on at a very slow rate and the excess pore pressure retained in the sand voids takes quite a long time to dissipate fully. In effect, if at level F the dissipation of excess pore pressure starts about 30 s after the end of the earthquake, near the surface (level A) the same is not observed before about 8 minutes. It should also be noted that not even half an hour is enough for the deposit to achieve a new state of equilibrium, as the settlement is still continuing and residual excess pore pressures persist through the depth of the deposit. Finally, a particular feature of the ground surface settlement and the excess pore pressure generation at level A should be considered. At about 3 minutes after the earthquake ceases, the ground surface starts to heave and the excess pore pressure at level A begins to increase again after an initial period where some perceptible dissipation had already taken place. Although no obvious reasons were found to justify such peculiar behaviour, this may be related to the changes of the characteristics of the one-dimensional flux towards the surface determined by the alleged variation of permeability of the soil.

COMPARISON OF THE BEHAVIOUR OF SATURATED DEPOSITS OF LOOSE AND DENSE SAND

The comparison of the behaviour of the centrifuge models used in tests PC02 and PC03 can clarify the differences of behaviour of natural saturated deposits of loose and dense sand under earthquake loading. The results of the two tests can be compared, as the cyclic loading applied to the models is similar, as can be seen from figures 1 and 7. The only significant difference, which results from the fact that the model earthquake generated in test PC02 was slightly longer than planned, should not compromise the quality of the assessment.

In terms of the generation of excess pore pressure due to the earthquakes, it was observed that, in both cases, there was a massive build up of excess pore pressure from the first cycle of loading (Fig. 2 and 8). Similarly, in both cases, the maximum measured values of excess pore pressure are very close to the initial vertical effective stress predicted at each level. The main difference between the features of the behaviour of pore pressure generation is the rate at which it develops: in the loose sand model the pore pressure grows at a slightly higher rate. In fact, a state of near-zero effective vertical stress is achieved after 5 to 13 cycles in the loose model, which compares with equivalent numbers of 8 and 14 in the dense model. In both cases, as expected, the number of cycles to reach such a state increases with depth and hence with initial vertical effective stress. Apparently, the influence of the sand density on the rate of pore pressure generation is significant at lower effective stresses, as observed near the surface. It should also be noted that a very small number of cycles, between 2 and 4, is enough to cause a dramatic loss of effective stress throughout the deposit. As no major qualitative differences of behaviour were observed in the pore pressure generation in the models of loose and dense sand, where maximum excess pore pressures roughly equalized the initial effective vertical stresses at each level, it seems suitable to consider that both models liquefied under the model earthquake employed in the tests.

If the build up of excess pore pressures in the models develops with only minor differences in the models of loose and dense sand, some more important discrepancies can be found when considering the upwards propagation of the accelerations, as can be concluded from Fig. 3 and 9. The most remarkable difference is the existence, only in the case of the model of dense sand, of an intermediate period where large magnitude short duration acceleration spikes corresponding to 100 % or more amplification of the peak input accelerations can be observed near the surface. In addition to this significant feature, the peak accelerations observed at shallow depths during the first couple of cycles in the loose sand model show reasonable attenuation, whereas in the dense sand model a slight amplification of peak acceleration occurs. As the shear stiffness of the deposit degrades massively due to the existence of a state of very low effective stress, the propagation of accelerations through the deposit has comparable characteristics in the two cases: peak accelerations reaching the ground surface of the deposit correspond to just a very small fraction of the input, indicating a substantial attenuation of accelerations. The only difference that could be observed during this final stage of shaking is that the attenuation of accelerations seems to be more uniform through the deposit, in the case of loose sand, while in the case of dense sand it seems to be concentrated at a level between 7.4 and 10.5 m depth (Fig. 4 and 10).

Although it can be considered that, during the centrifuge tests performed, both deposits of loose and dense sand fully liquefied under the model earthquake applied, the resulting final settlement was considerably different in the two tests. In absolute terms, the deposit of loose sand underwent a settlement of 430 mm, which is much larger than the corresponding deformation of the dense model, measured as 155 mm. If the settlement of the models is compared in terms of the average post-liquefaction volumetric strain, in order to take into account the fact that the models had slightly different total depths, it becomes apparent that the settlement of the dense model (ε_v= 0.86 %) is just about one third of that of the loose model (ε_v= 2.5 %).

Finally, both centrifuge tests proved that the most significant component of the settlement occurs during the shaking: after the end of the seismic event, the settlement was already 80 % to 95 % of its final value (Fig. 5 and 11). Considering, in addition, that the excess pore pressures take a very long time to fully dissipate after the earthquake comes to an end (Fig. 6 and 12), it seems that the permeability of the sand increases significantly during the shaking. This interpretation coincides with the one suggested by Ishihara (1994) in order to explain a similar phenomenon observed in test 1 performed as part of the VELACS program.

MAIN CONCLUSIONS AND IMPLICATIONS

Two centrifuge models representing uniform saturated deposits of sand, with relative densities of 50 % (PC02) and 80 % (PC03), were submitted to earthquake loading in order to establish the dynamic behaviour of these deposits. The tests were performed at Cambridge University's Schofield Centre at a centrifuge acceleration of 50 g and employing a similar input earthquake, characterised at prototype scale, by a predominant frequency of 1 Hz and a duration of 25 s. A comprehensive analysis of the experimental results shows that:

1) the generation of excess pore pressure due to the cyclic loading is very similar in the models of loose and dense sand, being characterized by a massive build up of excess pore pressure that rapidly extends from the top to the bottom of the deposit. Although the rate of pore pressure generation is slightly lower in the deposit of dense sand, the earthquake simulation causes, after a given number of loading cycles, the excess pore pressures to match, at each instrumented level, the values of the initial vertical effective stresses, which is commonly referred to as liquefaction;

2) the number of loading cycles required to achieve liquefaction increases with depth as a consequence of higher effective stress level, and the relative density of the sand, the beneficial effect of relative density being more significant at shallow depths;

3) the propagation of the horizontal accelerations through the deposit is strongly dependent on the relative density of the sand, but, in both cases, as soon as the shear stiffness of the sand is degraded to minimum values, the peak accelerations reaching the ground surface of the deposit are a modest fraction of the input, signalling an extensive attenuation of accelerations;

4) in the case of dense sand, immediately before the attenuation of the horizontal accelerations becomes substantial, large magnitude short duration acceleration spikes corresponding to amplifications of 100 % or more of the peak input accelerations were observed at shallow depths, causing concern on the effects these can have on structures with shallow foundations resting on the surface, as suggested by Mitchell et al (1998);

5) the total settlement of the ground surface resulting from the earthquake event is quite significant in both cases, but the fact that the relative density of the sand increases from 50 % to 80 % causes the average post-liquefaction volumetric strain (ε_v) to be reduced to about one third of the original value;

6) considering that the most significant part of the settlement occurs simultaneously with the shaking and also that the excess pore pressures remaining in the soil once the seismic event ends require a considerable time for full dissipation, it seems that the permeability of the sand increases significantly during the period of shaking.

In conclusion, based on the experimental work described here it can be seen that both loose and dense sand deposits exhibit very similar behaviour under earthquake loading, though there are some highly significant differences. Both loose and dense sand exhibit increasing pore-pressures leading to a state after a relatively small number of cycles that might be termed liquefaction, with excess pore-pressures being equal to the initial vertical effective stress. Whilst in loose sands there is a progressive attenuation of surface accelerations throughout the earthquake, in dense sands there is a period early in the earthquake where large amplification of input accelerations is seen at the surface due to the strain hardening behaviour of the liquefying soil. The higher initial density of the dense soil leads to a lower tendency to contract under cyclic loading, leading to significantly reduced volumetric strains and hence surface settlements.

Although the state attained in both models of sand during the earthquake simulation can be termed liquefaction, the dense model sustains a significantly reduced settlement as a result of the shaking. This fact is presumably the reason why, in general, reviews of case histories show that liquefiable ground improved by densification performs noticeably better than the contiguous non-improved ground (Mitchell et al, 1995, Hausler and Sitar, 2001). But the results shown also suggest that, whilst densification may be used as a remediation method against earthquake-induced liquefaction in that it will reduce the settlements experienced by structures, this may be at the expense of drastically increased surface accelerations.

ACKNOWLEDGMENTS

The authors would like to acknowledge the financial support provided to this project by the Engineering and Physical Sciences Research Council (EPSRC) and Mott Macdonald.

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