4th International Conference on
Earthquake Geotechnical Engineering
June 25-28, 2007
Paper No. 1698

STRESS REDISTRIBUTION IN LIQUEFIED GROUND UNDER AND AROUND SHALLOW FOUNDATIONS: EXPERIMENTAL EVIDENCE AND NUMERICAL REPLICATION

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ABSTRACT

Since soil behaviour is mostly governed by the existing effective stress, its correct evaluation is vital in geotechnical problems. This is particularly true in the case of shallow foundations under the effects of earthquake-induced liquefaction. This paper considers the phenomenon of stress redistribution occurring in liquefiable ground during and after an earthquake. Dynamic centrifuge modelling was used to identify the main characteristics of effective stress variation under and around a shallow foundation, which is obtained from measuring the variations of excess pore pressure and total stress at specific instrumented locations. Numerical modelling was used to extend the observations obtained in the centrifuge model and to evaluate the ability of advanced numerical tools to reproduce the phenomenon of stress redistribution. The results obtained show that effective stress redistribution is a complex phenomenon. The experimental data suggests that accurate assessment of the effective stress variation under a shallow foundation requires proper evaluation of both the excess pore pressure and the total stress variations in the ground. In fact, during an earthquake, the vertical effective stress under a footing can even increase as a result of the total stress increase. In contrast, foundation performance is extensively affected by post-earthquake excess pore pressure migration. The processes of total stress redistribution and excess pore pressure generation and migration are suitably replicated by the numerical tools. This supports their use in performance-based liquefaction resistant design.

Keywords: liquefaction, earthquake, footing, stresses, centrifuge, numerical

INTRODUCTION

Liquefaction analyses are still predominantly based on semi-empirical methods, which, in view of the performance of structures during most recent earthquakes, seem to be satisfactory for most part of cases. However, increasing demand for the implementation of performance-based design in practice requires a more refined approach. In order to ensure a safe design using sophisticated numerical tools for liquefaction assessment, two aspects of the problem need further elucidation. Firstly, it is necessary to fully clarify all the mechanisms involved with to the development of liquefaction under and around foundations, which may be more complex than assumed in simplistic analysis. Secondly, the ability of current advanced numerical tools to accurately predict triggering, development and effects of liquefaction in the ground, under general conditions, needs to be verified.

Although simple liquefaction analyses consider that the effective stress variation occurring in the ground is a mere consequence of the earthquake-induced excess pore pressure generation, some experimental results suggest that the total stress may also change significantly. In the free-field, although the total vertical stress remains constant, the total horizontal stress may increase. This is

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revealed by undrained cyclic torsional tests performed by Ishihara & Li (1972) on laterally confined samples of saturated sand, which show total horizontal stress increase during the test. As a result, under loading conditions found in the free-field of a liquefiable deposit under seismic loading, the stress field in the ground tends towards an isotropic one. It is also hard to accept that the total vertical stress under shallow foundations remains constant, as centrifuge models representing their behaviour exhibit significant dilation in the soil under the footing during the earthquake (Liu & Dobry, 1997, Coelho et al., 2004). Since non-transient dilation cannot be induced solely by cyclic loading, it seems that additional static shear stress is imposed to the region under the footing when liquefaction occurs.

This paper describes the use of centrifuge and advanced numerical modelling to investigate the phenomenon of stress redistribution in liquefiable ground during and after an earthquake. Centrifuge modelling is employed to elucidate the stress variations under and around a shallow foundation built on liquefiable ground during an earthquake. Numerical modelling is used to assess the ability of sophisticated numerical tools to replicate the behaviour observed in the physical models, which are supposed to yield a realistic behaviour. The importance of understanding the phenomenon of stress redistribution in liquefiable ground and to suitably model using numerical tools is clear, since the soil strength and stiffness are a strong function of the effective stress. Therefore, appropriate evaluation of the performance of a shallow foundation built on liquefiable ground depends not only on a correct prediction of the excess pore pressure generation, but also on a proper assessment of the concurrent total stress variation.

CENTRIFUGE MODELLING

Centrifuge modelling is an effective tool for investigation on earthquake-related problems. The merit of this technique derives from its ability to generate truthful mechanisms under realistic loading conditions, as the stress in the ground and the loading can be correctly replicated. This is particularly relevant in liquefaction problems, as full-scale observations in the field have limited value. Centrifuge modelling is used in this research to assess the mechanism of stress redistribution occurring in liquefiable ground during an earthquake. All the results presented are shown in prototype (real) scale.

Model bridge

A centrifuge model representing a shallow foundation of a deck-type bridge built on liquefiable sand was tested in Cambridge University's beam centrifuge. Figure 1 shows the geometry of the bridge, whose decks stand on a single central pier and lateral low-friction bearings. The ground surface coincides with the top of the footing, which induces a plain strain condition in the soil foundation.

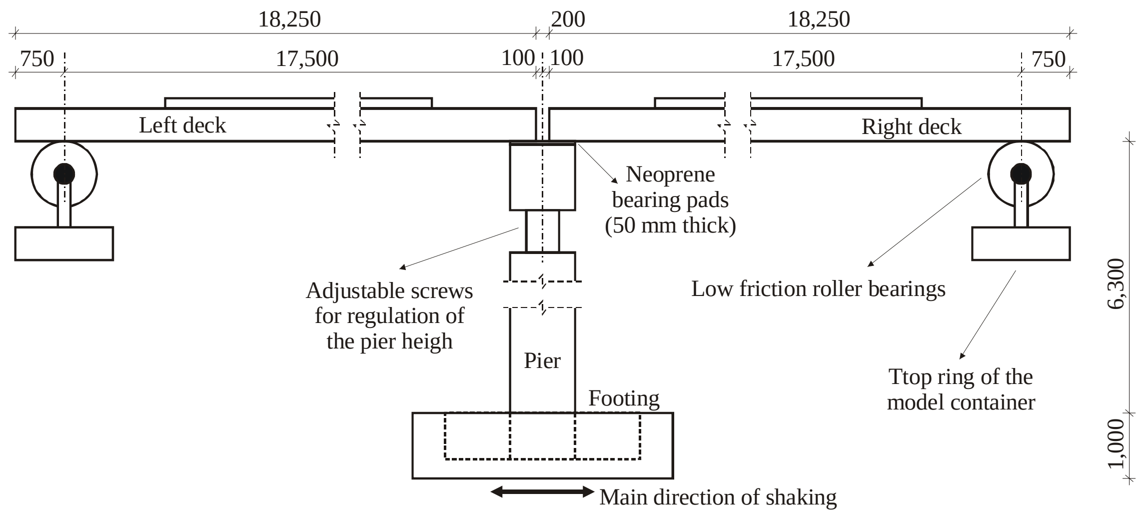
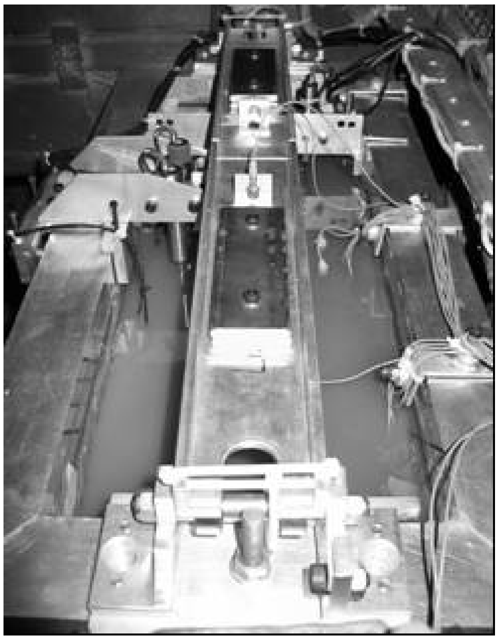
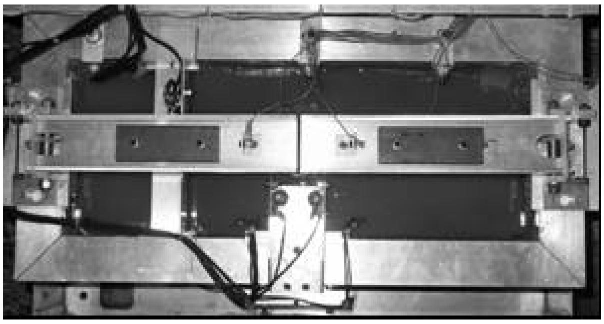


Figure 1. Geometry of the model bridge used in the centrifuge experiment (prototype scale)

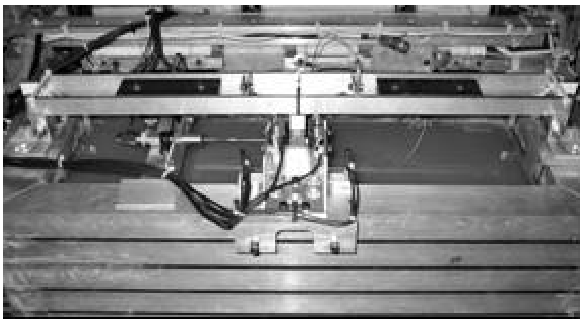
a) model placed in the arm of CUED's beam centrifuge



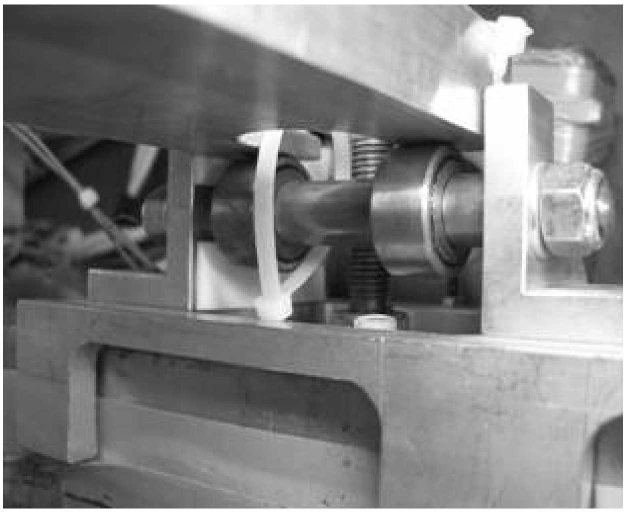
b) longitudinal view of the centrifuge model



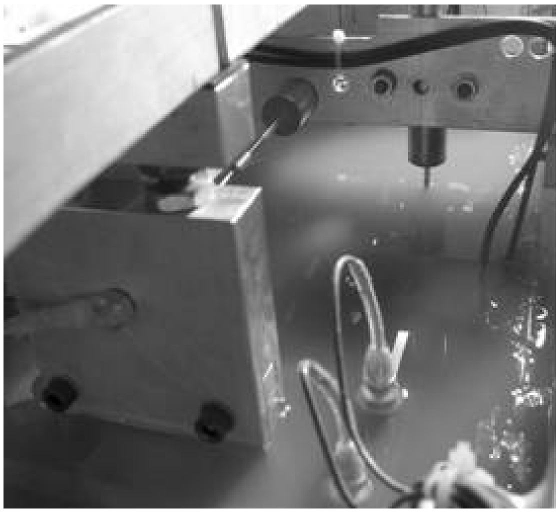
c) plan view of the model



d) front view of the model and ESB container



e) detail of the lateral low-friction bearings supporting the decks above the container walls



f) instruments to assess the behaviour of footing, pier and ground surface

Figure 2. Photographs of the centrifuge model loaded in the beam centrifuge and ready to test

Model preparation

The loose deposit of Fraction-E silica sand (D_R= 50 %) was prepared by air pluviation of dry sand. The bridge's footing was installed in the model during sand pouring, after ensuring proper levelling of the ground. The model was prepared and tested inside the boundaries of an Equivalent Shear Beam (ESB) container (Brennan & Madabhushi, 2002), in order to minimize the boundary effects. These are expected to have limited magnitude in the central region under consideration in this work (Coelho et al., 2003). To perform the so-called viscosity scaling, the model was saturated with a high-viscosity pore fluid (methylcellulose solution). The viscosity of the fluid (50 cSt) was chosen according to the centrifuge acceleration used in the test (50-g). In order to reduce model disturbance during the loading stage, the components of the bridge apart from the footing were only mounted in the model after installing it in the arm of the beam centrifuge. Figure 2 illustrates different aspects of the centrifuge model tested as part of this research work.

Instrumentation

Various instruments were placed inside and on the physical boundaries of the centrifuge model to assess its behaviour during the dynamic test. These include accelerometers, LVDTs, PPTs and stress cells, which measure, respectively, accelerations, linear displacements, pore-pressure generation and total stress variation in the model at different locations. Figure 3 identifies the locations of the instruments installed in the model.

This paper is mostly based on the analysis of the variations of the excess pore pressure and stresses recorded during the test. If PPTs tend to yield accurate measurements as long as their saturation is guaranteed, the performance of stress cells is much more problematic, due to the developing of arching around the stress cells. Therefore, the absolute values of stress variations measured must be considered carefully, though the qualitative variations are expected to be truthful.

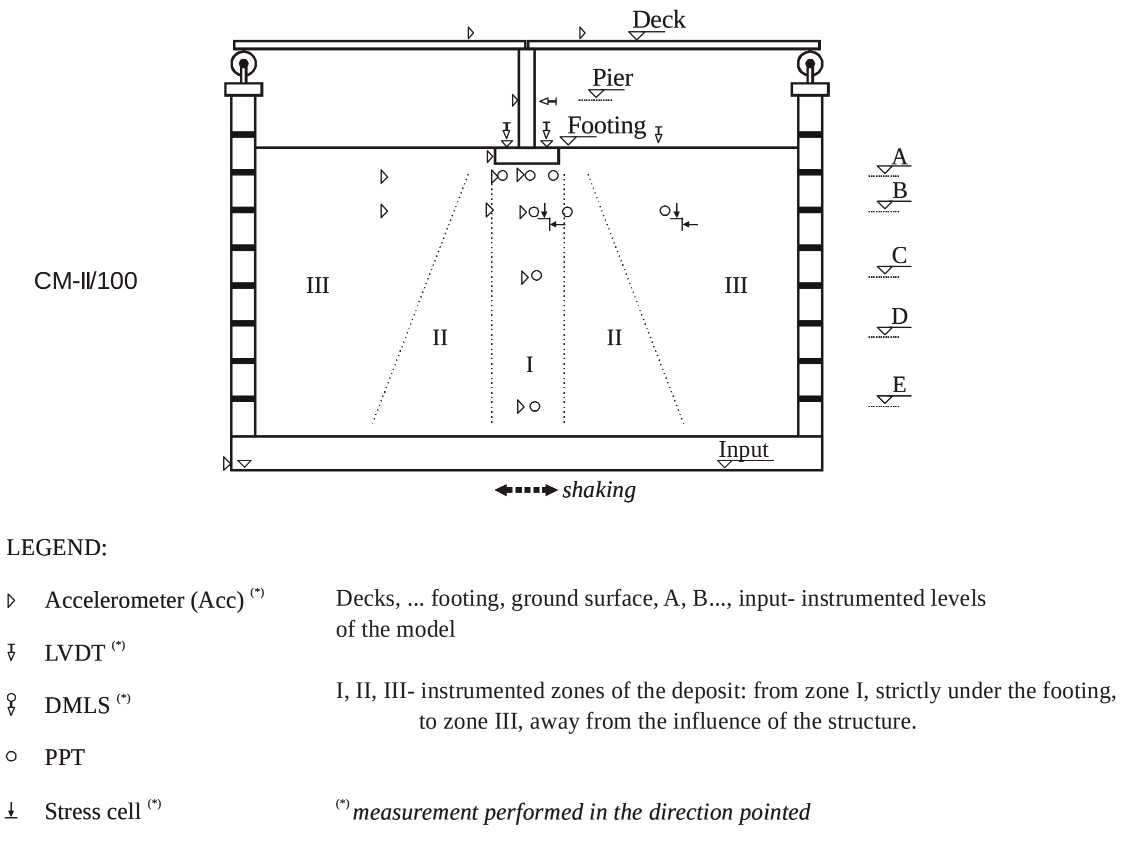


Figure 3. Location of the instruments installed in the centrifuge model to assess its behaviour during the test

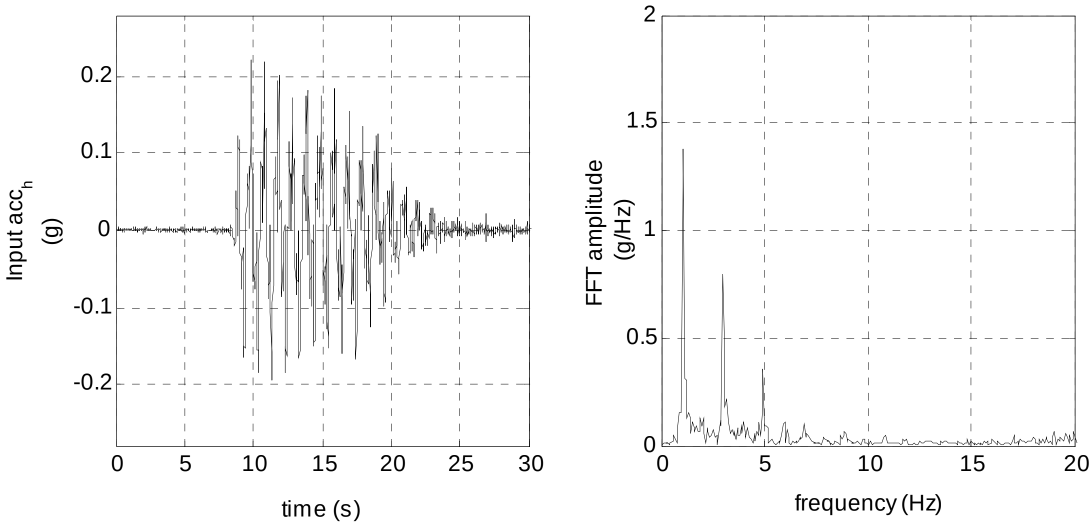


Figure 4. Characteristics of the earthquake simulation applied to the centrifuge model

Seismic loading

The seismic simulation applied to the centrifuge model was generated by the Stored Angular Momentum (SAM) actuator, a simple but reliable actuator developed at Cambridge University's Schofield Centre (Madabhushi et al., 1998). This mechanical seismic actuator is able to reproduce quasi-sinusoidal input motions, which can be more useful in liquefaction investigations than replication of more realistic multi-frequency events.

The dynamic loading applied to the centrifuge modelling was intended to simulate an earthquake lasting about 10 s, with a predominant frequency of 1 Hz and inducing peak horizontal accelerations at the bottom of the model close to 0.2-g. Figure 4, which details the characteristics of the earthquake simulation effectively generated by the SAM actuator, proves that the seismic motion applied to the model is quite close to the one projected.

NUMERICAL MODELLING

The accuracy of the solutions provided by the numerical tools available for liquefaction analysis is an essential requirement for the effective implementation of performance-based design in current design practice. The numerical work performed in this research to evaluate the reliability of advanced numerical tools was carried out with Swandyne dynamic FE code, using Pastor-Zienkiewicz-III as the soil model.

Swandyne FE code

DIANA-SWANDYNE-II (Dynamic Interaction And Nonlinear Analysis-SWANsea DINamic version II), or simply SWANDYNE, is a two-dimensional FE code created to perform static, consolidation and dynamic analysis in Geomechanics (Chan, 1988). The code uses a full effective stress-based framework to properly model the dynamic behaviour of saturated soil. The solid and pore-fluid dynamic interaction is established through a simplified form of the fully-coupled large-strain equations, termed dynamic u-p formulation. Integration is performed using the Generalized Newmark Single-Step integration scheme.

The performance of SWANDYNE, employing P-Z-III as the soil model, when carrying out liquefaction analysis has been satisfactorily validated by simulating the dynamic behaviour of different centrifuge experiments (Zienkiewicz et al., 1999). The value of SWANDYNE was particularly demonstrated when modelling centrifuge experiments performed in VELACS project.

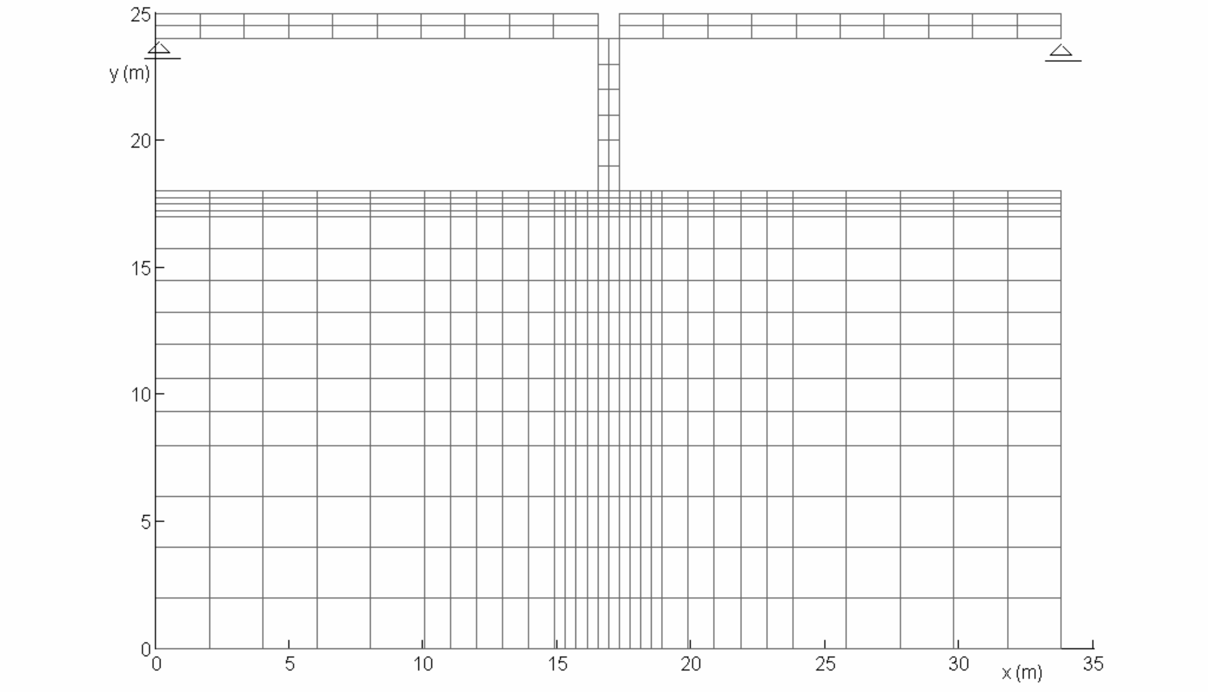


Figure 5. Discretization of the problem for the FE analysis

Pastor-Zienckiewics Mark-III soil model

Pastor-Zienckiewics Mark-III (P-Z-III) is a non-linear cyclic soil model that was proposed by Pastor et al. (1985, 1990) to model the behaviour of a large variety of soils under monotonic and static loading. It is based on the use of the bounding surface variant of the generalized plasticity theory. This model can more realistically simulate the behaviour of soils, as the transition from elastic to plastic behaviour is smooth and the irreversible straining generated during stress reversals can be replicated. Furthermore, explicit definition of yield and plastic potential surfaces is not required, which often facilitates the fitting of experimental data.

In its more complex form, the model requires 15 parameters, 5 of which are used to describe the soil pseudo-elastic properties. Some of the model parameters can be measured directly from experimental results, while others can only be obtained by fitting of experimental data.

Finite element mesh

The numerical simulation of the model presented in this paper employs the discretization shown in Figure 5. The FE elements are composed of 9 solid nodes and 4 fluid nodes and their size increase in the region of the deposit under the influence of the structure and near the drainage boundaries (ground surface).

Identification of P-Z-III model parameters

The parameters for P-Z-III soil model used in this research, which are shown in Table 1, were identified through an extensive element testing programme, including different types of triaxial tests. These values were successfully validated by means of numerical simulations of the behaviour of uniform deposits of liquefiable sand under earthquake loading.

Table 1. Values of P-Z-III soil model parameters used in the numerical analysis

Depth of layer (m)	H_{ev0} [MPa]	α_{ev} [1]	H_{es0} [MPa]	α_{es} [1]	p'_{ref} [kPa]	M_g [1]	α_g [1]	M_f [1]	α_f [1]	H_0 [1]	β_0 [1]	β_1 [1]	γ_{Dm} [1]	H_{U0} [MPa]	γ_U [1]
0-6 m	40	0.65	120	0.65	100	0.97	0.02	0.70	0.40	700	2.60	0.19	7	26	6.8
6-10 m	40	0.65	120	0.65	100	0.97	0.02	0.70	0.40	525	2.60	0.19	7	23	3.65
10-18 m	40	0.65	120	0.65	100	0.97	0.02	0.70	0.40	350	2.60	0.19	7	20	0.5

STRESS REDISTRIBUTION IN LIQUEFIED GROUND

Centrifuge and numerical modelling were used to investigate the existence of stress redistribution in the ground due to occurrence of earthquake-induced liquefaction, namely when a shallow foundation is built on the ground surface.

Experimental evidence

The centrifuge model tested in this research demonstrates that substantial redistribution occurs in liquefiable ground following an earthquake, its magnitude depending on the location considered.

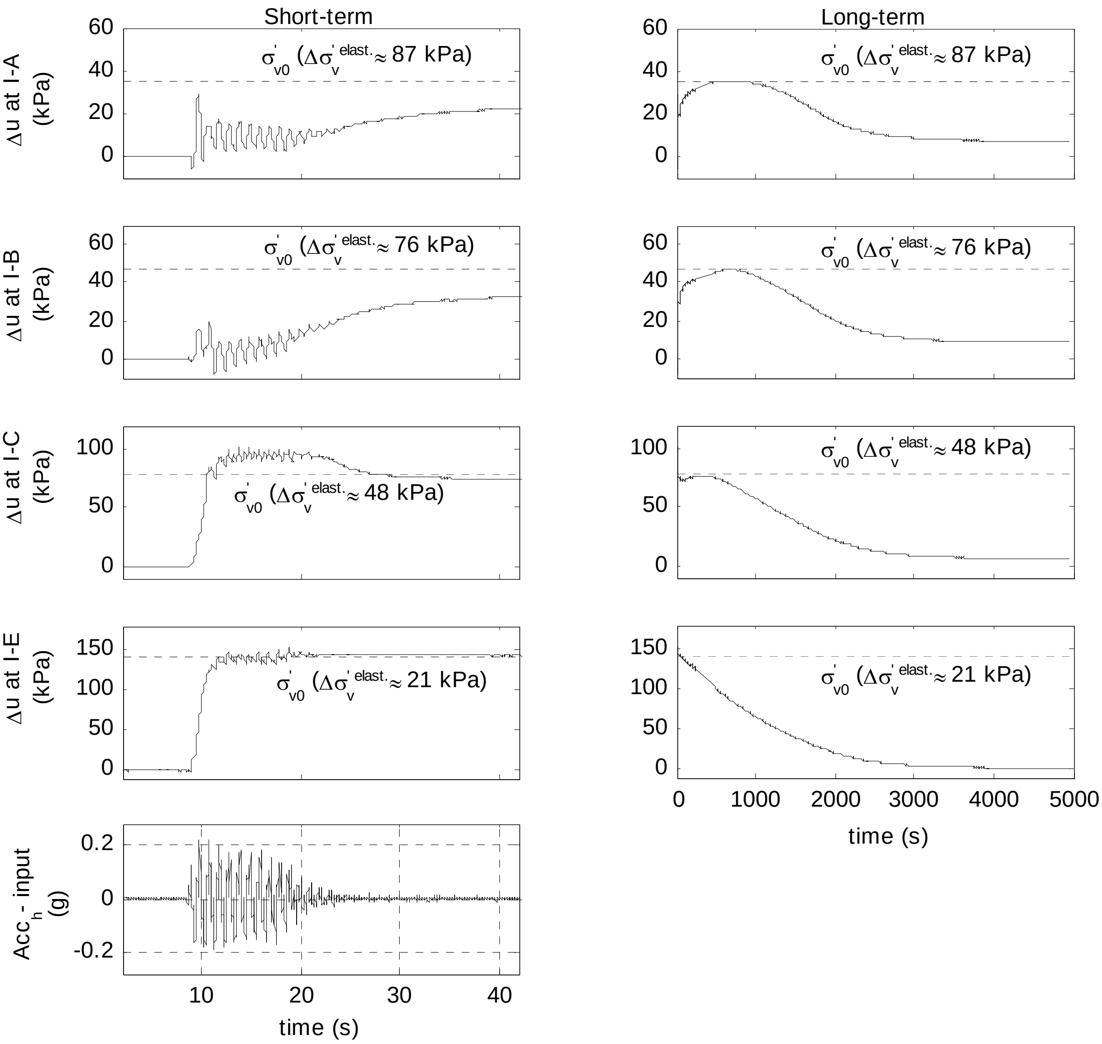
Figure 6 illustrates the excess pore pressure variation in the ground during and after the earthquake. It is shown that, in the region under the influence of the structure, the excess pore pressure generation is considerably less than in the free-field. The influence of the structure on the co-seismic generation of excess pore pressure in the ground is particularly significant at shallower depths under the footing (levels A and B), where the excess pore pressure variation in each instrumented location shows similar features. During the earthquake, after the initial loading cycles that cause some positive excess pore pressure, the soil starts dilating possibly due to a local increase of the total vertical stress. This causes the excess pore pressure to reduce in some cases to near zero values. After some more cycles, especially as the magnitude of shaking starts to decay, the excess pore pressure starts increasing again. The rate of excess pore pressure increase becomes more intense once the shaking stops, the maximum values of excess pore pressure tending towards the values occurring in the fully liquefied free-field. This is clearly shown by the fact that the excess pore pressure approaches the initial vertical effective stress in the free-field, which liquefies under the loading applied. Therefore, the excess pore pressure migration assumes an important role in the effective stress degradation under the footing, which is particularly visible after the end of the earthquake.

However, the variations in effective stress are not exclusively determined by the co-seismic excess pore pressure generation and subsequent excess pore pressure migration. As Figure 7 shows, the total stresses measured by the stress cells do not remain constant during the test. Despite the unfortunate failure of two the stress cells, the most important data was acquired, namely the total vertical stress variation under the footing and the total horizontal stress variation in the free-field. In fact, the total vertical stress in the free-field is not expected to vary at all, while the variation of the total horizontal stress under the footing should be much less important that the total vertical stress variation.

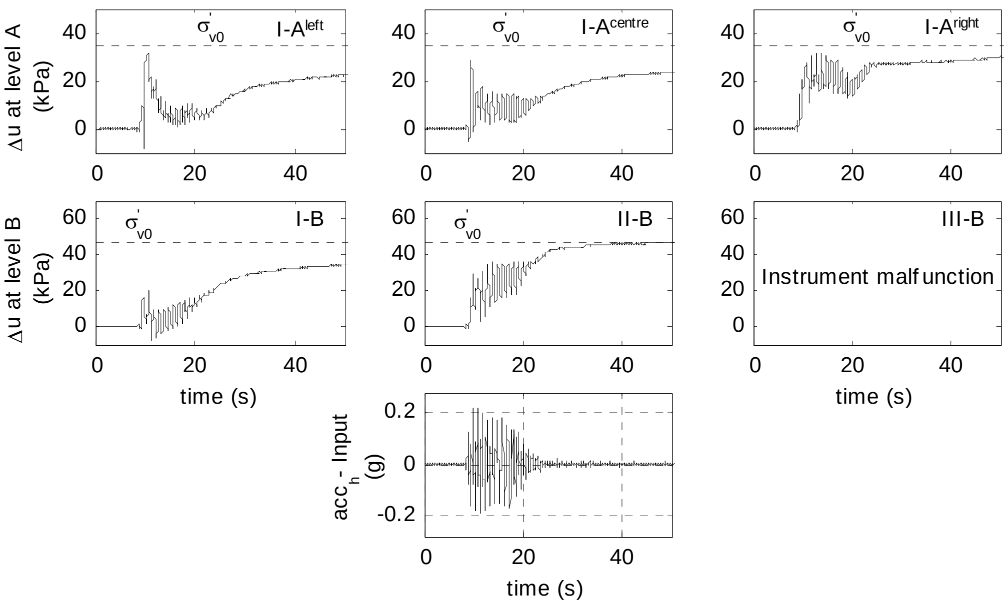
Under the footing (Figure 7a), the total vertical stress starts increasing from the first cycle. This is possibly caused by the fact that, due to massive excess pore pressure generation in the free-field, the disparity of stiffness between the soil under and around the footing tends to increase. But as excess pore pressure migration starts to affect the strength and stiffness of the ground under the footing, some total vertical stress is redistributed to the soil surrounding the footing. Since the surrounding fully liquefied soil has very low strength and stiffness, this process is again reversed and further accumulation of total vertical stress under the footing is induced.

As a result, the vertical effective stress under the footing is not degraded during the earthquake as strongly as suggested by the excess pore pressure increase, since the increase in total vertical stress partially compensates for the increase in pore-pressure. In fact, during most part of the earthquake, due to the combination of a marginal excess pore pressure generation with a significant increase in the total vertical stress, the vertical effective stress under the footing even tends to increase. Thus, the important post-earthquake degradation of vertical effective stress is induced by excess pore pressure migration from the free-field. The vertical effective stress in the ground only increases again once the excess pore pressure generated in the free-field starts to dissipate.

With respect to the total horizontal stress in the free-field, it increases during the earthquake (Figure 7b). Therefore, an isotropic stress condition is induced in liquefied free-field, as suggested by Ishihara & Li (1972) based on undrained cyclic element tests performed on laterally confined samples.

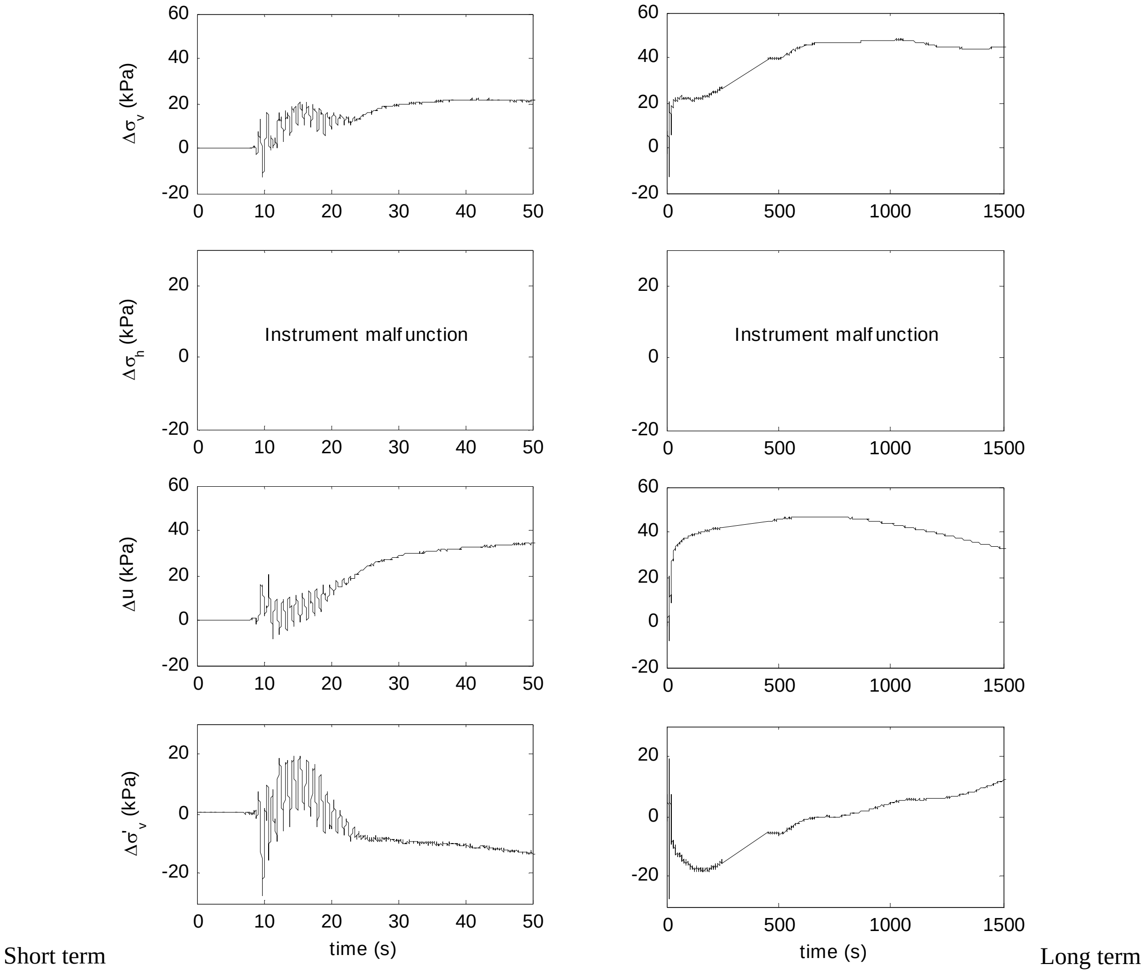


a) excess pore pressure variation at various depths under the centre of the footing

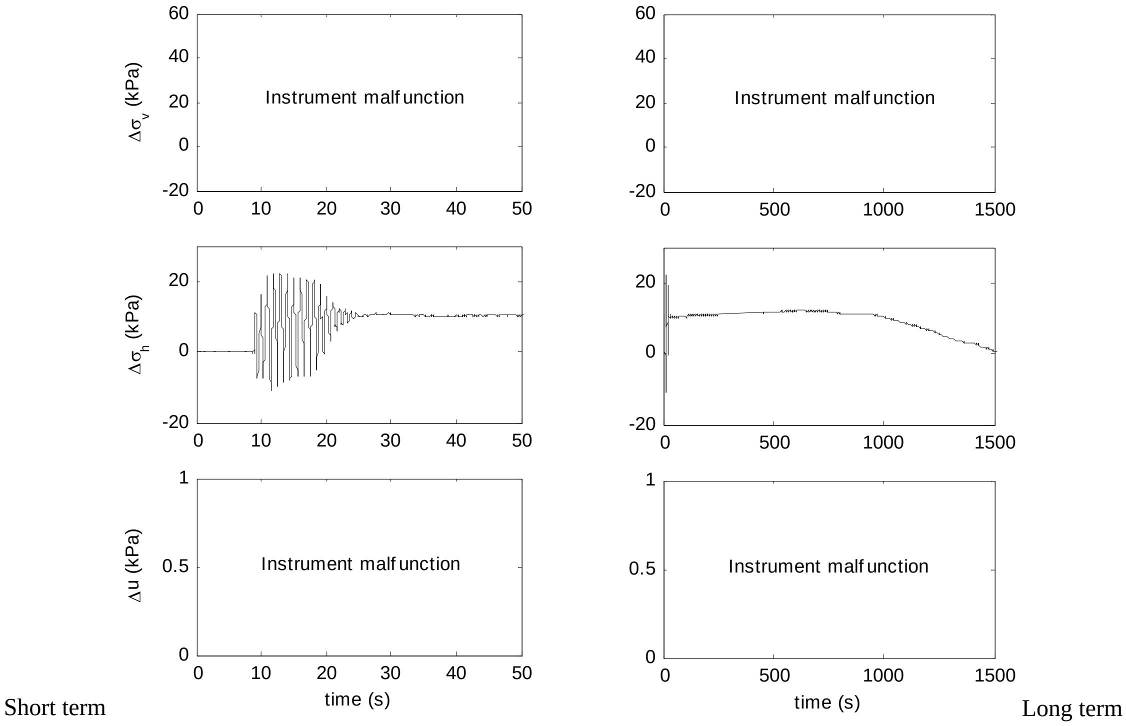


b) excess pore pressure variation at shallow depths under the footing and in the free-field

Figure 6. Excess pore pressure variation in the ground during and after the seismic simulation



a) under the footing



b) in the free-field

Figure 7. Stress variations in the ground at level B during and after the seismic simulation

Numerical simulation

Due to the influence of effective stress on soil behaviour, the behaviour observed in the centrifuge model must be fully captured by numerical tools aiming at reproducing the behaviour of shallow foundations built on liquefiable ground. A numerical simulation was performed with Swandyne using P-Z-III model to assess their ability to assess this phenomenon. The seismic simulation applied to the numerical model closely replicates the real dynamic loading used in the centrifuge model.

The qualitative variations of the total vertical stress under the footing and the total horizontal stress in the free-field observed in the centrifuge model are correctly reproduced in the numerical simulation at corresponding locations. Because the most important stress variation in the ground is the variation of the vertical effective stress in the soil supporting the shallow foundation, the analysis of the numerical results in this research concentrates on that particular aspect of the problem. Figure 8 illustrates the vertical effective stress remaining in the ground during and after the earthquake, according to the numerical prediction.

The stress distribution in the ground (0 s) is typical of that occurring, in static conditions, under a shallow foundation. Accordingly, some concentration occurs under the footing near the surface, the area of influence of the loading increasing with depth.

Immediately after the earthquake strikes, large excess pore pressure is generated in the free-field. As a result of the increasing difference in soil stiffness, vertical effective stress redistribution occurs in the ground, which causes a uniformly-loaded narrow column of relatively stiff soil to form under the footing. This process is mostly governed by the increase in total vertical stress under the footing. At about 10 s, when except for the deepest levels of the deposit the vertical effective stress do not decrease at any level, some minor enlargement of the loading area with depth is still perceptible. This instant corresponds approximately to the maximum vertical effective stress observed under to footing at shallow depths.

In the period between about 15 and 50 s, which coincides with the stage of more intense post-earthquake excess pore pressure migration, further degradation of the vertical effective stress is induced in the narrow column of stiffer soil under the footing. However, the vertical effective stress under the footing never reaches zero values. During this stage, the boundaries of the column under the shallow foundation also become slightly narrower and more vertical. The minimum level of vertical effective stress occurs sometime between 25 and 50 s, which probably coincides with the critical situation in terms of the stability of the foundation. Although this behaviour is qualitatively comparable to the one shown by the centrifuge model, the critical instant predicted by numerical prediction seems to occur before.

After about 50 s, the vertical effective stress in the soil under the footing slowly starts to increase, due to the excess pore pressure dissipation in the deposit, especially at deeper levels. During this period, the vertical effective stress in the narrow column increases while its boundaries become wider. The rate of stress degradation with depth also increases as the soil regains shear strength and stiffness, which is shown by the faster increase of the column width at deeper levels. At 250 s, the tendency of the stress distribution in the ground to approach the one existing before the occurrence of earthquake-induced liquefaction is perceptible.

Figure 8 also illustrates the excess pore pressure ratio in the ground, which compares the excess pore pressure with the initial vertical effective stress (including footing's contribution) at each location:

$$r_u = \Delta u / \sigma'_{v0} \,. \qquad (1)$$

The plot confirms the main features of behaviour of the soil under the footing, like the low r_u during the earthquake, the critical condition between 25 and 50 s and the final regain of effective stress.

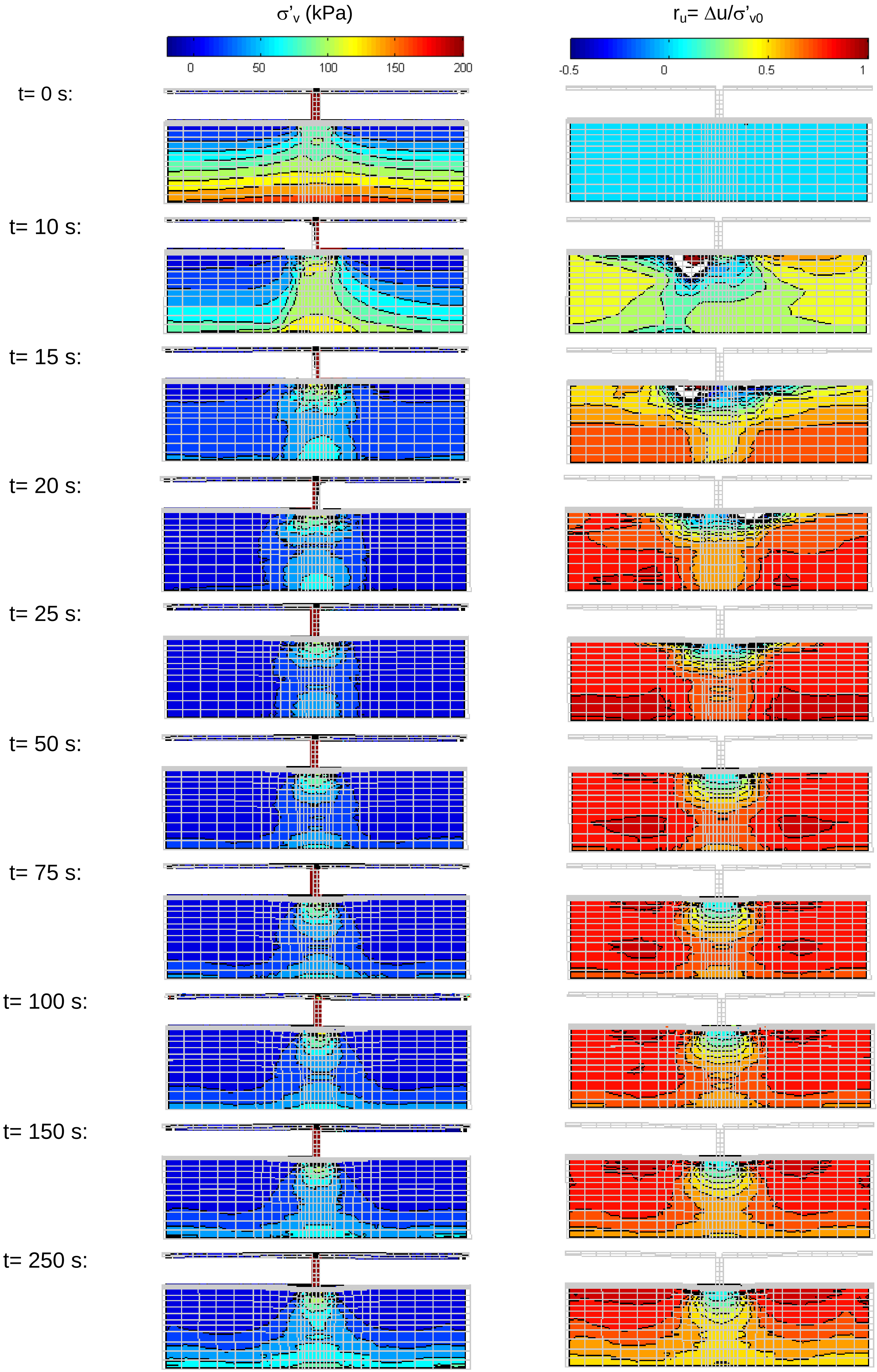


Figure 8. Numerical estimate of vertical effective stress and e.p.p. ratio variations in the ground

CONCLUSIONS

The results presented in this paper, obtained through centrifuge and numerical modelling of the behaviour of a shallow foundation built on liquefiable ground, suggest that the importance of stress redistribution cannot be neglected in accurate liquefaction analysis.

The centrifuge experiment shows that, under the footing, the vertical effective stress never reaches zero values. During the earthquake, the vertical effective stress under the footing even increases at shallow depths, due to the important contribution of the total vertical stress increase induced during this stage, in addition to modest or negative excess pore pressure generation. The critical condition in the ground, which is determined by large excess pore pressure migration from the fully liquefied free-field, occurs some time after the end of the earthquake.

Swandyne FE dynamic code used in conjunction with Pastor-Zienkiewicz-III soil model acceptably reproduces the phenomenon of total and effective vertical stress redistribution occurring in liquefiable ground supporting a shallow foundation. The numerical results improve the understanding of the problem, as the isolated observations in the physical model are extended to the all deposit. In addition, validation of these tools encourages their use in performance-based design. Further validation should be carried out to check if these tools can accurately reproduce other relevant physical phenomena.

ACKNOWLEDGEMENTS

The authors would like to thank the technicians of Schofield Centre for their support in performing the centrifuge experiment, and Prof. A. Chan for his assistance with Swandyne. This project was carried out with support from EPSRC Grant GR/R20328/01 and Mott MacDonald, UK.

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