# THE INFLUENCE OF STRESS DENSIFICATION AND CENTRIFUGE MODEL PREPARATION METHOD FOR SOIL LIQUEFACTION

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ABSTRACT
Centrifuge tests have shown that a uniformly placed sand layer will first initiate liquefaction near the surface and that liquefaction will progress downward during shaking. This appears to be in conflict with the overburden stress effect on soil liquefaction (i.e. $K_\sigma$ effect) observed in laboratory testing. This discrepancy can be explained by stress-induced densification at depth which overcomes the effect of confining stress on liquefaction resistance. Stress densification occurs in centrifuge model tests but its effect has generally not been considered when preparing or evaluating centrifuge models. A new centrifuge model preparation method is proposed by considering stress-induced densification upon spin-up. The proposed method can be used to explore $K_\sigma$ effects. The method is supported at this stage by numerical predictions only. Centrifuge tests are planned to verify the proposed method.

RÉSUMÉ
Les tests de centrifugeur ont montré qu'une couche de sable uniformement placée fera premièrement inaugure la liquéfaction près de la surface et cette liquéfaction progressera descendant pendant la secousse. Ceci a l'air d'être dans le conflit avec le surcharge l'effet de tension sur la liquéfaction de sol (le j'.e. l'effet de $K\sigma$) observé dans l'essai de laboratoire. Ce désaccord peut être expliqué par densification tension-persuadé à la profondeur qui surmonte l'effet de limiter de tension sur la résistance de liquéfaction. Densification de tension arrive dans le centrifugeur tests modèles mais son effet n'ont pas été généralement considérés en préparant ou évaluer les modèles de centrifugeur. Un nouveau centrifugeur une méthode de préparation modèle est proposée densification en considérant tension-persuadé sur rotation-en haut. La méthode proposée peut être utilisée pour explorer les effets de $K\sigma$. La méthode est soutenue à cette étape par les prédictions numériques seulement. Les tests de centrifugeur sont eus l'intention de vérifier la méthode proposée.

## 1. INTRODUCTION

Geotechnical centrifuge modelling can simulate the actual stress condition in the field by increasing the unit weight of a small-scaled model. In addition, the soil conditions, the loading and the response measurements can be much better controlled in the centrifuge. Because of this advantage over observed field behaviour, instrumented dynamic centrifuge model tests have been used for constitutive model verification. Arulanandan et al. (1982) were the first to verify numerical procedures using dynamic centrifuge tests. Various centrifuge model tests have been used to study the mechanism of soil liquefaction and verify numerical models since the VELACS project (Arulanandan and Scott 1993). Constitutive models require input parameters such as elastic bulk and shear moduli as well as plastic parameters such as plastic moduli and friction angle, which are primarily a function of soil density under a given stress level. The correct evaluation of soil density is, therefore, important for numerical modellers to capture in prescribing the behaviour of granular soils observed in centrifuge model tests.

For laboratory element tests, both the densities as placed, and after consolidation are known. It is the consolidated density corresponding to the applied stress state that is important as it controls sand behaviour. In centrifuge model tests, while the placement density is generally accurately known, the consolidation density after spin-up will vary with the non-uniform applied stresses and there is no simple direct way to measure this. Accordingly, stress densification is seldom taken into account in numerical modelling of centrifuge tests. Recently, Byrne et al. (2004) argued that the stress-induced densification at deeper depth changed the pattern of soil liquefaction. When the increased density was considered, the numerical prediction captured, very nicely, the excess pore pressure generation and movement of the liquefaction front (Byrne et al. 2004).

The possible implications of stress-induced densification on the results of element tests and dynamic centrifuge model tests are discussed. From these experimental observations, it is found that, without proper evaluation of density change in centrifuge modelling, an erroneous numerical verification would be achieved. To avoid this difficulty caused by stress-induced densification upon spin-up, a new centrifuge model preparation method is proposed. The new method can make an in-flight uniform model for dynamic centrifuge tests and increase our understanding of liquefaction response. While no physical testing has yet been carried out to verify the proposed method, excess pore pressures predicted from the proposed uniform model are compared against those measured from conventional increased density model.

## 2. INFLUENCE OF STRESS DENSIFICATION IN CENTRIFUGE TESTS

Centrifuge models are generally uniformly reconstituted under gravity condition and then subjected to an acceleration field 50 or 100 times the gravity field. Upon spin-up, a huge stress gradient builds up. For those tests the relative density increase was usually ignored or averaged within a sample by measuring the total volume and weight after consolidation. In fact, a high stress gradient results in a density state that increases with depth. In addition, there is a secondary effect, due to the increase in the radius arm of the centrifuge which causes the applied acceleration field to increase slightly with depth in the model. Schofield (1980) showed the effect of the variation of centrifugal acceleration with depth on vertical stress, which in the upper part of a centrifuge model would be lower and near the bottom higher than the corresponding prototype stress. Because of the high stress gradient induced upon spin-up, stress-induced densification becomes more significant at deeper depth. However, a direct measurement is currently not available. Bellotti et al. (1991) used the thermal probe method to check the uniformity of calibration chamber samples. They confirmed that it is a useful tool but it may not be available for centrifuge tests because of calibration difficulties. Centrifuge cone penetration tests have been used to measure the sample uniformity or relative density. However, a correlation based on centrifuge cone penetration tests has not been developed to the authors' knowledge. Most correlations between cone tip resistance and relative density are based on calibration chamber tests. This paper is not concerned with indirect measurement of relative density.

Centrifuge models listed in Table 1 all comprise of a uniform layer without surcharge. Prototype test conditions are listed in Table 1 and details can be found in each reference. Excess pore pressures versus depth profiles at different times are shown in Figures 1 to 4. Excess pore pressures corresponding to the initial vertical effective stress line, IVES, constitute 100 % pore pressure rise and liquefaction.

The applied cyclic stress ratio was essentially constant through an entire layer since measured maximum accelerations in each layer are the same before liquefaction occurs. All cases liquefied first near the surface and then the liquefaction front moved downward. Gonzalez et al. (2002) reported that the behaviour observed in Figure 3 (Model 1) was due to high confining stress. However, it cannot be explained by the $K_\sigma$ effect. If these samples are really uniform, bottom layers under higher stress condition should liquefy first. The authors propose that these samples have densified at deeper depths and, as a result, are less likely to liquefy at depth as shown in Figure 3.

Test 1 and Test 2 (Taboada and Dobry 1993) in Figures 1 and 2 used water as a pore fluid, where the others used a fluid more viscous than water. The difference in fluid viscosity does not seem to influence the pattern of liquefaction. Most of the tests have an effective stress of 100 kPa at the base. Even this low stress is large enough to cause densification, especially on compressible sands such as Nevada sand. Model 1 (Gonzalez et al. 2002) in Figure 3 was comprised of a uniform Nevada sand layer with a placed relative density of $D_r$ = 55 %. The maximum initial effective stress at the base was 380 kPa upon spin-up. In such high stresses conditions, stress-induced densification cannot be avoided and the bottom layer becomes denser and more resistant to liquefaction as clearly demonstrated in Figure 3.

On the other hand, a similar response of liquefaction propagation (top to bottom) was also observed from several shaking table tests (Florin and Ivanov 1961). However, it is not known whether this is due to stress densification or other factors. It is difficult to derive any conclusion from 1g shaking table tests because of extremely low stress levels, resulting in excessive dilation.

Table 1. Excess pore pressure profiles of centrifuge tests.

| Sand | Height | Dr | Reference |
|---|---|---|---|
| Nevada sand | 10 m | 40% | Taboada & Dobry 1993 |
| Nevada sand | 10 m | 40 % | Taboada & Dobry 1993 |
| Nevada sand | 38 m | 55 % | Gonzalez et al. 2002 |
| Nevada sand | 10 m | 45 % | Sharp et al. 2003 |

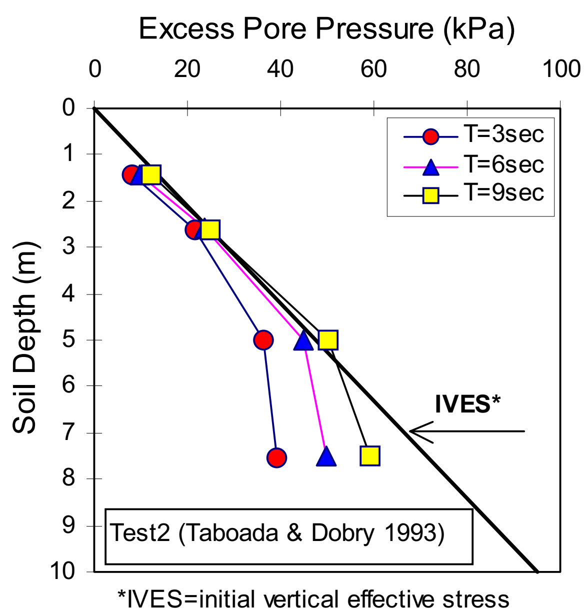


Figure 1. Excess pore pressure profiles during shaking of Test 1 (Taboada and Dobry 1993).

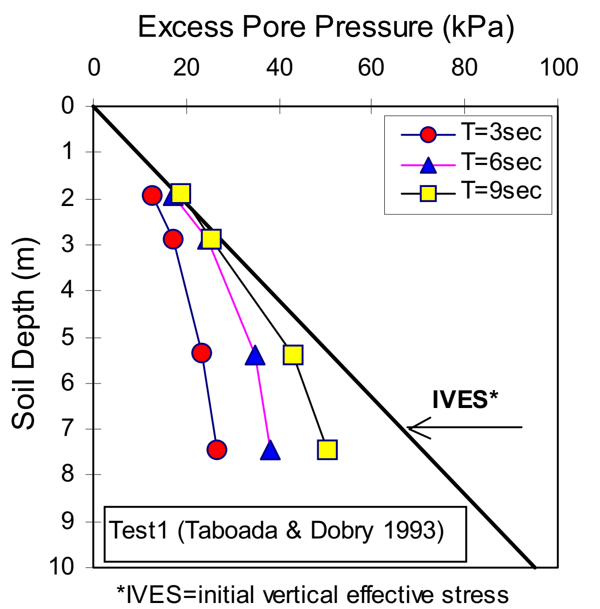


Figure 2. Excess pore pressure profiles during shaking of Test 2 (Taboada and Dobry 1993).

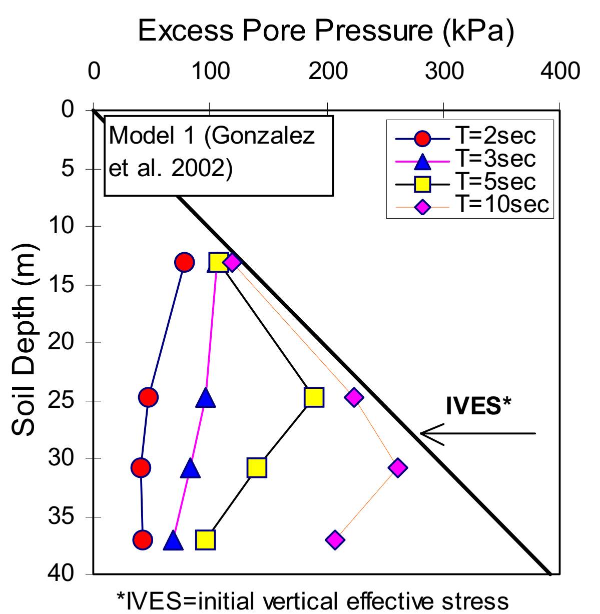


Figure 3. Excess pore pressure profiles during shaking of Model 1 (Gonzalez et al. 2002).

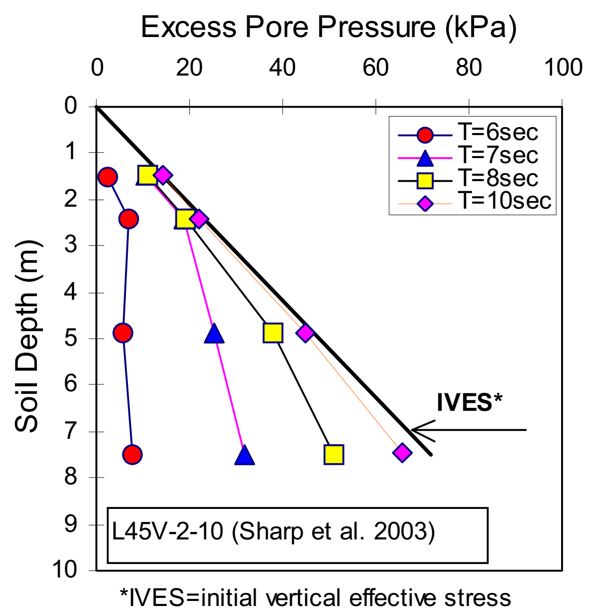


Figure 4. Excess pore pressure profiles during shaking of Test L45V-2-10 (Sharp et al. 2003).

## 3. CONVENTIONAL CENTRIFUGE MODEL PREPARATION METHODS

The importance of sample preparation methods in laboratory testing has been well documented by several researchers (Kuebris and Vaid 1988; Ladd 1974; Mulilis, et al. 1977; Vaid et al. 1999). In the case of triaxial tests, different triaxial sample preparation methods for sands result in different fabric states and consequently influence the undrained behaviour of laboratory tests. The density of these samples prepared by pluviation was proven by direct height measurement for element laboratory tests.

Research on centrifuge model preparation is not as abundant. Two sample preparation methods are mostly used in centrifuge tests: water pluviation and dry (air) pluviation. The dry pluviation method is most commonly used in tests since a target density can be easily controlled and for ease of transducer installation. Dry pluviation can be defined as pouring dry sands through the air. Three different methods can be used in centrifuge model preparation; spot, line, and plane types (Katagiri and Takemura 1998). A dry pluviation method controls the relative density by the flow rate and drop height. The flow rate is controlled by funnel opening size or shutter size. While keeping the flow rate constant, the falling height should be calibrated against relative density before sample preparation. With falling height corresponding to target relative density, the funnel is continuously raised to keep a constant falling height as the model is constructed. This is called a conventional centrifuge model preparation method and hereafter a conventional method in this paper.

The conventional placement method results in a uniform density with depth under gravity load, but develops an increasing density with depth profile upon spin-up as illustrated in Figure 5. Figures 5(a) and 5(b) show the stress and relative density distributions before and after spin-up by a conventional method. Recall that these models usually liquefy first near the surface. A new centrifuge model preparation method is proposed to make a uniform density with depth model after spin-up.

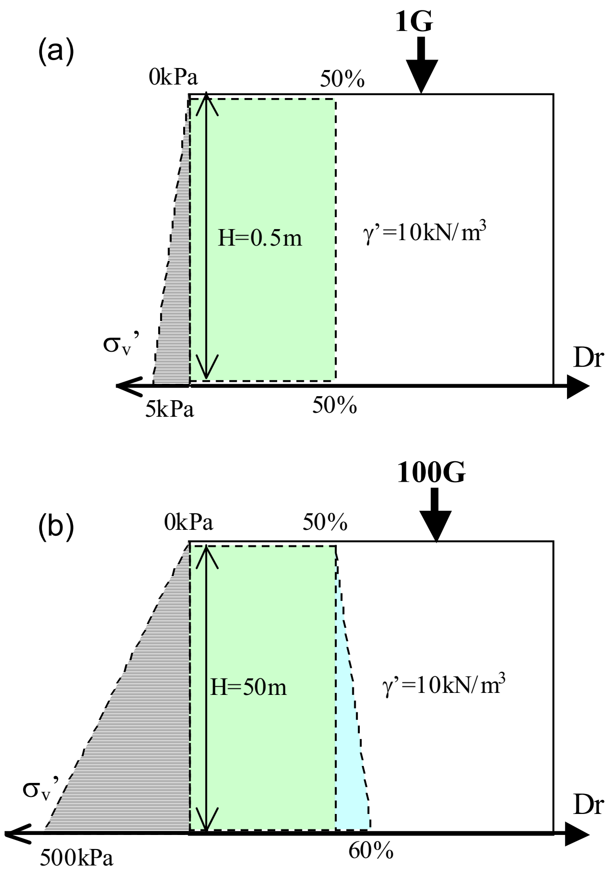


Figure 5. Density and vertical stress distributions by the conventional model preparation method in centrifuge testing: (a) before spin-up and (b) after spin-up.

## 4. NEW CENTRIFUGE MODEL PREPARATION METHOD

When high stress gradients are applied, non-uniform density distribution naturally occurs in centrifuge model tests prepared by the conventional method as animated in Figure 5(b). This may not be desirable for constitutive model verification purposes unless non-uniform density distributions are considered. Models prepared under gravity load will necessarily experience a stress increase upon spin-up.

In contrast to the conventional technique in Figure 5, a new model preparation method termed the reverse gradient sample preparation method is developed. This method produces a reverse gradient density with depth under gravity loading. This results in a uniform density model at centrifugal acceleration loading, such as 100 g as illustrated in Figure 6.

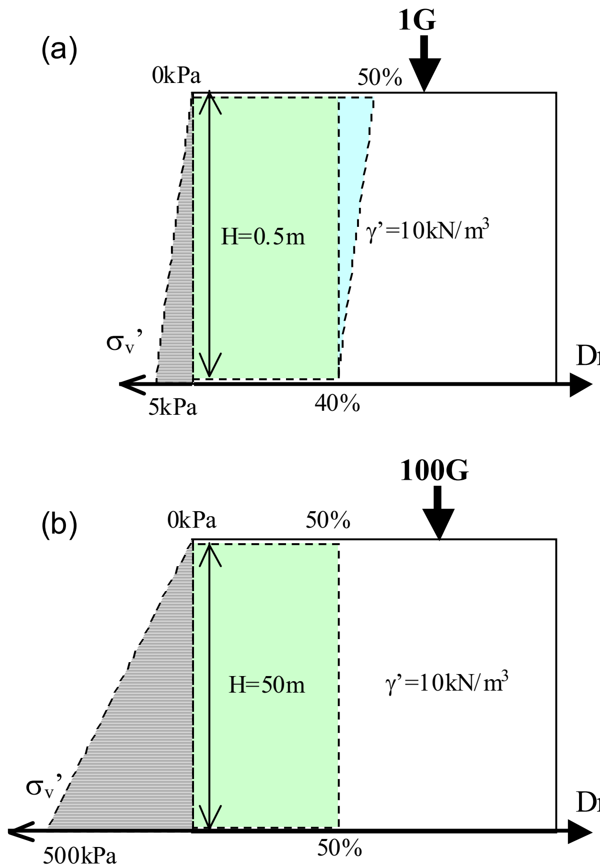


Figure 6. Density and vertical stress distributions by the new model preparation method in centrifuge testing: (a) before spin-up and (b) after spin-up.

### 4.1 Concept of reverse gradient sample preparation method

A reverse gradient sample preparation method uses the dry pluviation method controlled by pre-calibrated falling height. An example of a relative density calibration performed on air-pluviated Fraser River sand is illustrated in Figure 7. Any of the dry pluviation methods (Katagiri and Takemura 1998) can be used. A requirement for the new method is to predict the density increase upon spin-up. It can be obtained by using the stress densification equation, equation 1. This equation is based on examination of compression data on a number of sands (Park and Byrne 2004a). It indicates that all sands examined seem to behave in a similar manner and that the stress densification effect can be expressed by:

$$D_r = D_{r0} + \alpha \cdot \sqrt{\left(\frac{\sigma'_v}{P_a}\right)} \quad [1]$$

where $\alpha = \left[\frac{(1+e_{max})}{e_{max} - e_{min}} - D_{r0}\right] \cdot \frac{2 \cdot (1.5 - D_{r0})}{C}$, $D_{r0}$ is initial relative density at 0 kPa, C is a sand stiffness number that is independent of void ratio, $P_a$ is atmospheric pressure and $\sigma_v'$ is the vertical effective stress. From Eq. 1 the amount of stress densification corresponding to stress increase can be estimated. The test data from a range of sands was found to be in good agreement with measurements for vertical effective stresses less than 1000 kPa (Park and Byrne 2004a). For example; for Fraser River sand to achieve a target density $D_r$ = 50 % at stress level 500 kPa, a sample should be pluviated at $D_{r0}$ = 40 % under gravity. This follows from the fact that an element deposited at $D_{r0}$ = 40 % at zero gage stress is expected to increases to $D_r$ = 50 % at 500 kPa. The schematic concept at 1 g and 100 g is illustrated in Figure 6. The new technique requires a non-uniform density at 1 g and a continuously increasing fall height. The centrifuge model prepared by this new technique will be looser at the bottom and denser at the surface under 1 g loading as illustrated in Figure 6(a). However, this model will become uniform upon spin-up as illustrated in Figure 6(b). This method can produce a uniform model upon spin-up and create results consistent with those observed in laboratory element tests. It will be a benefit to numerical modellers, since density is uniform with depth and input parameters are only a function of stress level.

### 4.2 Example of reverse gradient sample preparation method

Two prerequisites for this method are an equation of stress densification and a relative density calibration for a given flow rate such as Figure 7. For demonstration purpose, Fraser River sand with depositional characteristics as depicted in Figure 7 is used. The two prerequisites are known for this sand. Assume that a sand model has the dimension of 1.0 m in length x 0.3 m in width x 0.5 m in height. As explained in the previous section, a target relative density is 40 % at bottom and 50 % near the surface under gravity loading. The conventional air pluviation method keeps the fall height constant with depth of placed sand as shown in Figure 8(a). However, the reverse sample preparation method needs to increase the fall height proportionally from 0.3 m to 0.5 m as the model sand depth increases from 0 to 0.5 m as shown in Figure 8(a).

This will result in a reverse gradient density under 1g as depicted in Figure 6(a). Upon spin-up stress densification will offset this and result in a uniform density model as shown in Figure 6(b).

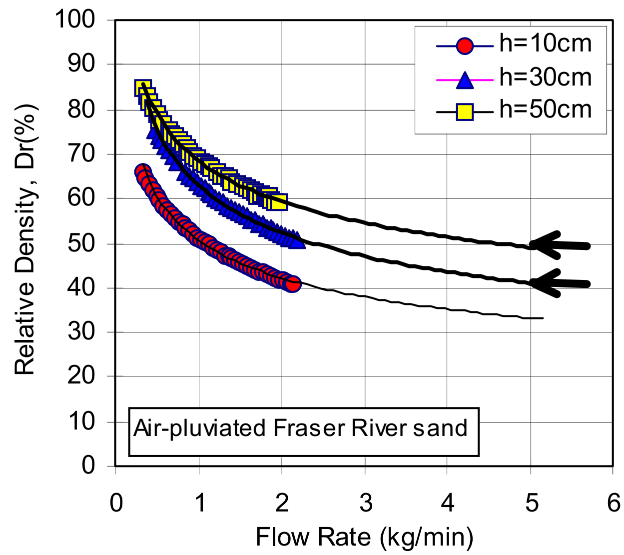


Figure 7. Variation of relative density as a function of flow rate and fall height (h) (modified from Sriskandakumar, 2004).

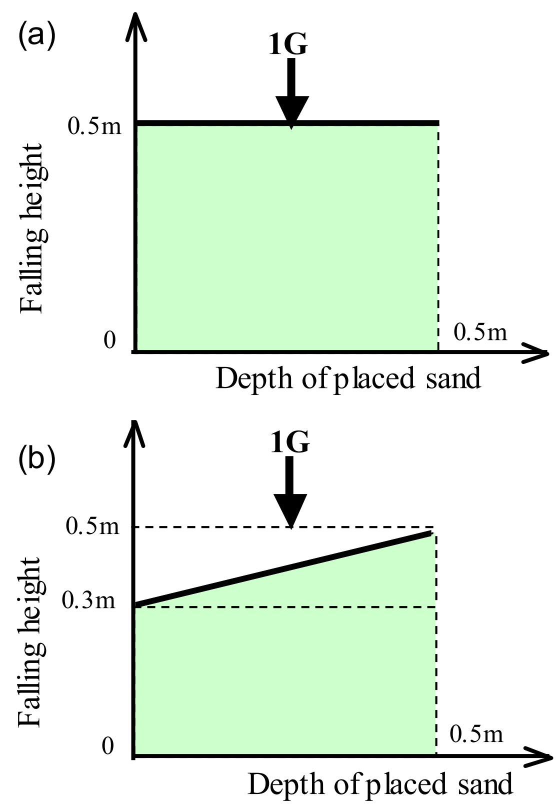


Figure 8. Comparison of (a) the conventional and (b) the reverse sample preparation methods.

5. COMPARISON OF CENTRIFUGE MODEL PREPARATION METHODS

Currently, the results of dynamic centrifuge tests prepared by this new method are not available. However, numerical analyses of dynamic centrifuge tests prepared by both methods are available. These numerical predictions are also compared with measurements from RPI Centrifuge Model 1 (Gonzalez et al. 2002) prepared by the conventional method. Measured and predicted excess pore pressures (EPP) are shown in Figures 9 and 10. A fully coupled dynamic effective stress analysis with a plastic constitutive model called UBCSAND was used for these numerical predictions. Details regarding the numerical procedure can be found in Byrne et al. (2004). This model has successfully predicted measurements of several dynamic centrifuge tests by considering stress-induced densification (Byrne et al. 2001; Byrne et al. 2004; Park and Byrne 2004b). One of those numerical predictions is shown in Figure 9 and is seen to be in generally good agreement with the measurements.

A numerical prediction of a centrifuge model test prepared with the proposed new method is shown in Figure 10. The assumption here is that the density after spin-up is constant with depth. The results in terms of excess pore pressure (EPP) are compared with RPI Centrifuge Model 1 (same as Figure 9). It shows an opposite pattern to typical observations in that the bottom layer liquefied first.

This suggests that the characteristic behaviour observed in centrifuge tests in which placement density is uniform is greatly modified by small density changes that occur due to stress densification upon spin-up. The stiffness of soil elements in terms of bulk and shear moduli usually increases as a function of mean stress and density. For the proposed uniform density model constructed with the new method, the stiffness will increase with depth due to only a stress increase. Additionally, a conventional density model has an extra increase of stiffness due to the density increase with depth. This is why a small density increase is important and the numerical model can capture a liquefaction pattern observed in most of the centrifuge tests. Without considering the increased density at depth, liquefaction always occurs at the bottom first and isolates the upper layer. This is demonstrated in Figure 10 and can be also simulated by the planned uniform centrifuge model. This is consistent with the $K_\sigma$ effect on soil liquefaction mentioned earlier. By using the new method we can investigate the effect of overburden stress ($K_\sigma$ effect) on soil liquefaction.

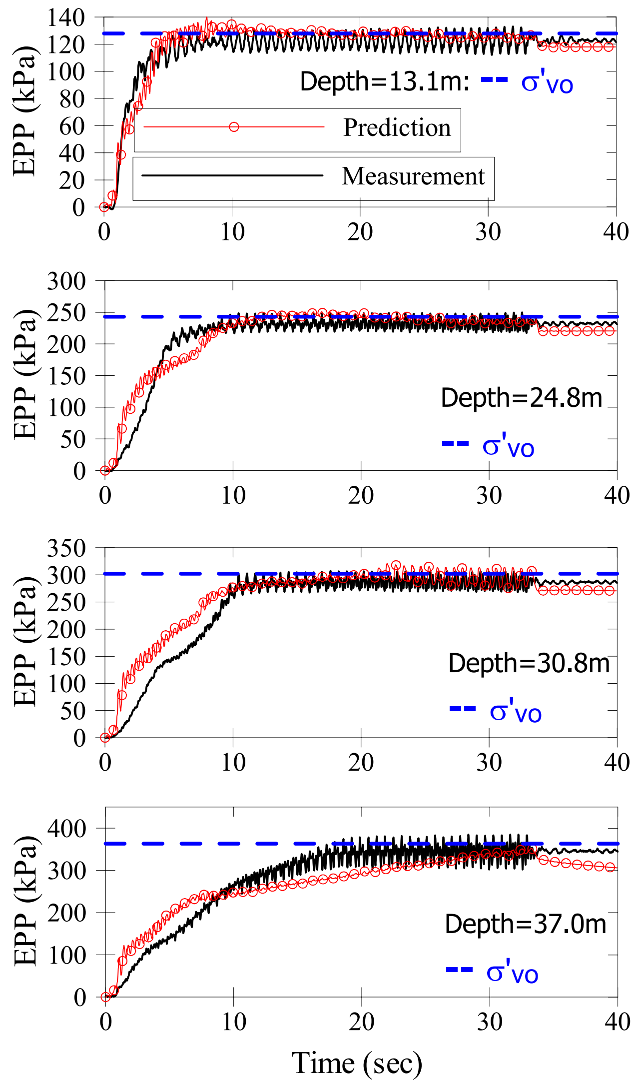


Figure 9. Measured and predicted excess pore pressure (EPP) of RPI Model 1 prepared by a conventional model preparation method (measurements from Gonzalez et al. 2002).

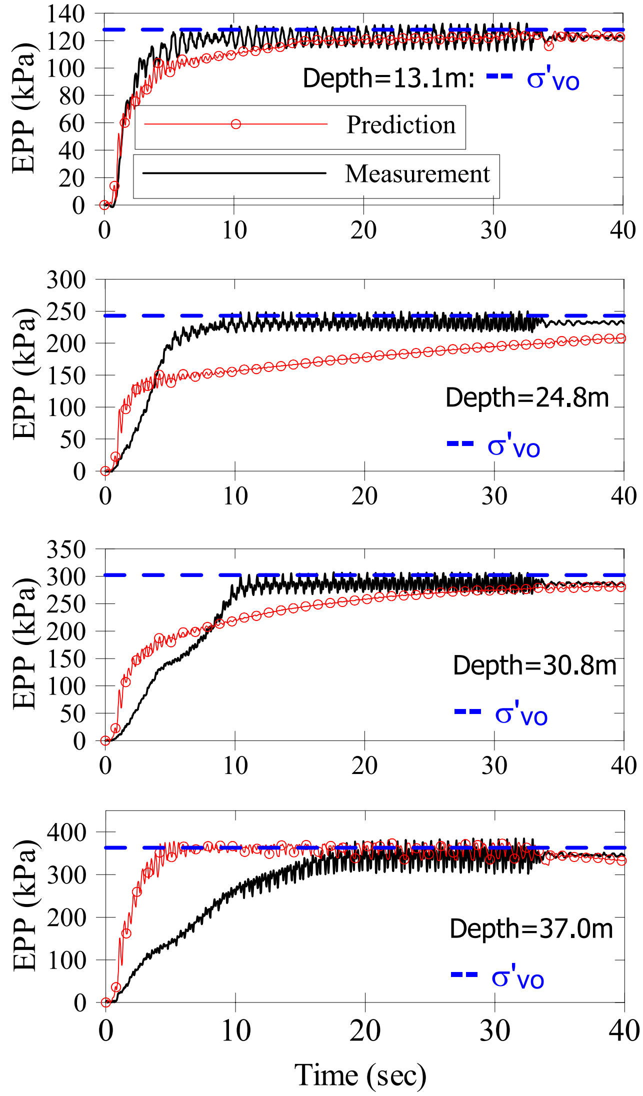


Figure 10. Measured excess pore pressure (EPP) of RPI Model 1 and predicted excess pore pressure (EPP) of assumed RPI Model 1 prepared by the proposed model preparation method (measurements from Gonzalez et al. 2002).

## 6. IMPLICATIONS FOR FIELD CONDITIONS

Stress densification will also occur in the field as nature deposits material. However, this is generally accounted for in conventional practice by the use of normalized penetration test data corrected for stress level and giving an indirect measure of in situ density and soil properties.

## 7. SUMMARY

The influence of stress-induced densification observed in element tests and dynamic centrifuge tests was presented. Even small increment changes in the relative density of a soil deposit can impact the soil liquefaction behaviour. Liquefaction response observed in centrifuge tests involving uniform placement density shows liquefaction is first triggered near the surface. However, stress densification upon spin-up results in higher density at depth and lower density at the surface, and analyses suggest that this is responsible for the observed response.

A new centrifuge model preparation method is proposed allowing a uniform density sample to be achieved after spin-up. This allows researchers to explore the $K_\sigma$ effect. Centrifuge results using the proposed method are not available at this stage. Numerical simulations of two methods suggest that small changes in density are important and that the new method could provide fundamental insights into liquefaction response. It is also consistent with current practice based on laboratory element tests.

## REFERENCES


Arulanandan, K., Anandarajah, A. and Abghari, A. 1982. Centrifuge modelling of soil liquefaction susceptibility. Physical modeling of soil dynamics problems, preprint 82-063, American Society of Civil Engineers, Las Vegas, NV, April 26-30.

Arulanandan, K., and Scott, R.F. 1993. Verification of numerical procedures for the analysis of soil liquefaction problems. *In* Proceedings of the International Conference on the Verification of Numerical Procedures for the Analysis of Soil Liquefaction Problems, Vols. 1 and 2, Balkema, Rotterdam, the Netherlands.

Bellotti, R., Ghionna, V. N. and Morabito, P. 1991. Uniformity tests in calibration chamber samples by the thermal probe method, *Geotechnical Testing Journal*, Vol. 14, No. 2, pp. 195-205.

Byrne, P.M., Beaty, M., and Park, S.-S. 2001. Analyses of ERDC centrifuge tests using UBCSAND. Report to Engineer Research Development Center, Dec. 2001.

Byrne, P.M., Park, S.-S., Beaty, M., Sharp, M., Gonzalez, L. and Abdoun, T. 2004. Numerical modeling of liquefaction and comparison with centrifuge tests, *Canadian Geotechnical Journal*, Vol. 41, No. 2, pp. 193-211.

Florin, V. A. and Ivanov, P. L. 1961. Liquefaction of saturated sandy soils, *In* Proceedings of the 5th International Conference on Soil Mechanics and Foundation Engineering, Vol. 1, pp 107-111.

Gonzalez, L, Abdoun, T., and Sharp, M.K. 2002. Modeling of seismically induced liquefaction under high confining stress, *International Journal of Physical Modelling in Geotechnics*, Vol. 2, No. 3, pp 1-15.

Katagiri, M. and Takemura, J. 1998. 2. Test programme, Centrifuge 98, Vol. 2, 1091-1094.

Kuebris, R. and Vaid, Y. P. 1988. Sand sample preparation-the slurry deposition method, Soils and Foundations, Vol. 28, No. 4, pp 107-118.

Ladd, S. R. 1974. Specimen preparation and liquefaction of sands. Journal of the Geotechnical Engineering Division, Vol. 100, GT10, pp 1180-1184.

Mulilis, J. P., Arulanandan, K., Mitchell, J. K., Chan, C. K. and Seed, H. B. 1977. Effects of sample preparation on sand liquefaction, Journal of the Geotechnical Engineering Division, Vol. 103, No. GT2, pp 91-108.

Park, S.-S. and Byrne, P.M. 2004a. Stress densification and its evaluation, *Canadian Geotechnical Journal*, Vol. 41, No. 1, pp. 181-186.

Park, S.-S. and Byrne, P.M. 2004b. Numerical modeling of soil liquefaction at slope site, *In* International Conference on Cyclic Behaviour of Soils and Liquefaction Phenomena, Bochum, Germany, pp. 571-580.

Schofield, A. N. 1980. Cambridge geotechnical centrifuge operations, Geotechnique, Vol. 30, No. 3, pp 227-268.

Sharp, M. K., Dobry, R., and Abdoun, T. 2003. Liquefaction centrifuge modeling of sands of different permeability. Journal of Geotechnical and Geoenvironmental Engineering, Vol. 129, No.12, pp 1083-1091.

Sriskandakumar, S. 2004. Cyclic loading response of Fraser River sand for validation of numerical models simulating centrifuge tests. MASc. Thesis, Department of Civil Engineering, University of British Columbia.

Taboada, V. M. and Dobry, R. 1993. Experimental results of Model No 1 at RPI. *In* Proceedings of the International Conference on the Verification of Numerical Procedures for the Analysis of Soil Liquefaction Problems, Vol. 1, Balkema, Rotterdam, the Netherlands. pp. 3-17.

Vaid, Y. P, Sivathayalan, S. and Stedman, D. 1999. Influence of specimen-reconstituting method on the undrained response of sand, Geotechnical Testing Journal, Vol. 22, No. 3, pp 187-195.