Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering

doi:10.3233/978-1-61499-656-9-2543

Void redistribution research with 1-g and centrifuge modeling

Recherche de redistribution de vides à 1-g et modélisation de centrifugeuse

E.J. Malvick, B.L. Kutter & R.W. Boulanger
Department of Civil and Environmental Engineering, University of California, Davis, California, United States of America
K. Kabasawa & T. Kokusho
Department of Civil Engineering, Chuo University, Tokyo, Japan

ABSTRACT

A U.S.-Japan cooperative research project enabled researchers from Chuo University in Tokyo and University of California in Davis to collaborate on a project studying the effects of void redistribution and water film formation on shear deformations due to liquefaction in layered soils. It has been shown that softening associated with void redistribution can contribute to liquefaction-induced lateral spreading and flow slides. Examples are presented of 1-g model tests at Chuo University and centrifuge tests at UC Davis. Common findings are summarized and differences are discussed. The key implication of these complementary testing programs is that the residual shear strength of liquefied soil in the field is not solely a function of the pre-earthquake state of the soil, but rather is dependent of those conditions affecting void redistribution and water film formation.

RÉSUMÉ

Des chercheurs de Chuo University à Tokyo et de University of California à Davis ont collaboré sur un projet de recherche commun aux Etats-Unis et au Japon afin d'étudier les effets de redistribution de vides et de formation de films d'eau sur les déformations en cisaillement causées par la liquéfaction dans des sols stratifiés. Il a été démontré que l'amollissement associé à une redistribution de vides peut contribuer à des glissements et à la propagation latérale induite par liquéfaction. On montre des exemples d'essais sur un modèle à 1-g effectués à Chuo University et des essais de centrifugeuse à UC Davis. On résume et discute les résultats communs. La conséquence principale de ces programmes d'essais complémentaires est que, sur le terrain, la résistance résiduelle au cisaillement d'un sol liquéfié n'est pas seulement une fonction de l'état pré-sismique du sol. Elle dépend plutôt des conditions affectant la redistribution de vides et la formation de films d'eau.

1 INTRODUCTION

Seismic performance and instability in slopes with liquefied soils may be affected by shear strain localization or water film formation driven by void redistribution (pore pressure redistribution) during and/or after earthquake shaking. The practical signficance of void redistribution mechanisms was conceptually outlined by Whitman (1985). Only recently have detailed experimental studies been performed.

This paper provides examples of model tests performed as part of a collaborative research program between Chuo University and the University of California, Davis (UC Davis) to study void redistribution on a 1-g shake table and two geotechnical centrifuges. Common findings from experiments at both institutions are briefly summarized, and some differences between experimental testing environments are discussed.

Outcomes of this collaborative research effort are summarized. The primary purpose of the research is to study the factors that contribute to loosening (dilation) in a potential shear zone and the timing of deformations due to this loosening or in some cases water film formation. This US-Japan research project facilitated progress toward this goal by enabling graduate student researchers to work at the other institution, thereby fostering the exchange of ideas and experimental methods.

2 MODEL TESTING EXAMPLES

Comprehensive testing programs have been performed on the 1-g shake table at Chuo University and the two geotechnnical centrifuges at UC Davis as described in various publications referenced later. The typical shake table model had a 4:1 slope that was 0.3 m high and consisted of Tokyo Bay sand. Models were typically shaken transverse to the slope by a harmonic motion (e.g., Kokusho 2003). The typical centrifuge model had a prototype 2:1 slope that was 6 m high and consisted of Nevada sand. Models were typically shaken along the slope by a modified earthquake ground motion (e.g. Kulasingam et al 2004).

A few tests were performed at both institutions with the collaboration of a visiting graduate student researcher from the other institution. The emphases of the tests were to facilitate the exchange of experimental methods and explore factors affecting the consistency of results from the two modeling techniques.

Figure 1 shows photographs of a shake table test completed at Chuo University with the help of a researcher from UC Davis. Figure 1(a) shows the model configuration before shaking. This model consisted of a loose slope of Tokyo Bay sand with embedded silt arc. Figure 1(b) shows the model after being shaken transverse to the slope (normal to the view shown) by a 3 Hz harmonic motion for 1 s with a peak base acceleration of 0.3 g. Approximately 50% of the deformations and localization occurred for 9 seconds after shaking stopped.

This shake table test is similar to other tests completed at Chuo University and described in Kokusho (1999 & 2000), Kokusho and Kojima (2002), Kokusho (2003). For comparison, some of the tests described in these references showed 50% to 85% of the movements occurring up to 20 s after shaking stops. The base acceleration during shaking for these models ranged from approximately 0.15 g to 0.35 g.

Figures 2 and 3 show photographs of two centrifuge tests completed at UC Davis by a researcher from Chuo University. The figures show before and after photos of the centrifuge tests, and the results are discussed in terms of prototype values unless otherwise noted. The test shown in Fig. 2 consists of a model of Nevada Sand dry pluviated to an initial relative density, $D_{r,0}$, of 20% with an imbedded silt arc similar to other tests conducted

Table 1: Factors Influencing Void Redistribution and Water Film Formation

Factor	Influence	References
Shape of low-permeability barrier	• When the shape of the low-permeability layer coincides with a kinematically admissible failure surface, it is more likely to contribute to localization and large deformations.	1, 2, 7, 8, and 11
Relative density of the liquefied layer	• Looser soils trigger liquefaction sooner during shaking. • Looser soils experience larger consolidation strains, thereby expelling more water that can drive localization or water film formation elsewhere in the slope. • Looser soils require less water inflow (dilation) at the contact with a low permeability layer before they will localize and/or form a water film. • Looser soils develop larger shear strains during shaking and larger total displacements (includes displacements along localizations or water films). • The magnitude of ground displacement depends on whether or not localization forms with the transition between these cases occurring over a small range of relative density.	1, 2, 7, 11, and 12
Thickness (volume) of the liquefied layer	• Thicker layers expel more water to drive localization or water film formation beneath an overlying low-permeability barrier layer. • Thicker layers take longer to reconsolidate, which increases the potential for localization or water films to form after shaking.	1, 5, 7, 9, 11, and 12
Hydraulic impedance of barrier layer • Permeability contrast between liquefied and barrier soils • Thickness of barrier layer	• The hydraulic impedance of the barrier layer increases with increasing thickness and decreasing permeability. • Greater hydraulic impedance restricts pore water flow across the interface between the liquefied soil and the overlying barrier soil. This allows more water to accumulate, thereby making localization or water film formation more likely.	1, 2, 3, 6, and 9
Permeability of liquefying layer	• A lower permeability for the liquefied layer reduces the rate of pore pressure dissipation and consolidation, which can increase the potential for localization or water films to form after shaking. • A lower permeability for the liquefied layer reduces the permeability contrast with the overlying barrier layer, and could reduce the potential for water to accumulate at the interface if the contrast is small enough.	1, 6, and 7
Earthquake		
• Frequency content	• The proportion of the total ground displacement that occurs after shaking depends on how much displacement is induced during shaking versus how much occurs due to pore water flow after shaking.	1, 2, and 7
• Amplitude and duration of motion	• Delays of ground displacement until after shaking were most dramatic when the ground motion was small enough to minimize earthquake-induced deformations but strong enough to trigger high excess pore pressures throughout the slope.	1, 2, 5, and 9
	• Larger amplitude and/or duration motions increase shear strains, which increases volumetric strains in the liquefying layer, thereby making localization more likely.	4
• Direction of shaking	• Shaking transverse to the slope direction may reduce inertial stresses downslope which could reduce deformations during shaking	1, 2, 6, and 7
• Shaking sequence and history	• Prior shaking can increase the cyclic resistance of the liquefying sand, thereby reducing the potential for localization. At the same time, prior shaking can cause loosening below the barrier layer , which increases the potential for localization in subsequent shaking events.	5, 7, and 9

1. Kokusho (1999), 2. Kokusho (2000), 3. Kokusho & Kojima (2002), 4. Kokusho (2003), 5. Kulasingam et al. (2001), 6. Kulasingam (2003), 7. Kulasingam et al. (2004), 8. Kutter et al. (2002), 9. Malvick et al. (2002a), 10. Malvick et al. (2002b), 11. Malvick et al. (2003), 12. Malvick et al. (2004)

at UC Davis (e.g., Kulasingam et al. 2004). This model was shaken lengthwise along the container (with the slope) by a prototype harmonic ground motion of 0.5 Hz over 6 cycles with a peak acceleration of approximately 0.15 g. This was done to observe the behavior of a typical UC Davis model geometry under the influence of a ground motion typical of a Chuo University shake table test. The difference in input base motion frequency and number of cycles between the 1-g and centrifuge model tests reflects the desire to match the frequency response of the centrifuge model slope with that of the typical shake table model slope. The extra cycles were added to compensate for the centrifuge's displacement limit that in turn limits the acceleration at low ground motion frequency.

The model shown in Fig. 2 had approximately 40% of the total movement occur for 200 s after shaking stopped. It is notable that the large localization did not initiate until 75 s after shaking stopped. In comparison, a similar model slope tested on the centrifuge but subjected to a non-harmonic (earthquake) ground motion of 80 s duration and 0.3 g peak amplitude had 45% of the total movement occurring for 120 s after shaking (Kulasingam et al. 2004). In that instance, localization was initiated during shaking. Other centrifuge tests showed 0-25% of movement occurring after shaking, depending on the various configurations of the model tests.

The centrifuge model shown in Fig. 3 was designed to approximate a model geometry used in 1-g model tests at Chuo University. This model was tested at a centrifugal acceleration of 80 g and subjected to the same ground motion as the model in Fig. 2. This model showed similar results to the model in Fig. 2 in that 40% of the movement occurred after shaking, over a longer time frame than observed in the 1-g models. Close observation of Fig. 3 also shows that there were some upslope strains on the left side. The upslope strains are due to the prototype slope curving downhill at the left side of the container under the radial g-field of this small radius centrifuge.

In these models, the presence of a low permeability silt arc at a potential shear zone amplifies the effects the void redistribution on shear localization. The silt layer impedes the flow of water that occurs due to liquefaction induced excess pore water pressure. This flow impedance allows the soil directly under the silt arc to loosen with an associated loss of shear strength. If the soil loosens enough, a water film may be observed beneath the low permeability layer and shear localization occurs.

The tests discussed show that localization can occur during and after shaking. Figure 4 plots displacement vs. time for a shake table model and the centrifuge model of Fig. 2. For both plots, the displacements were recorded above the silt arc under which localization were observed to occur. The two plots show similar displacement proportions. The difference in timing and

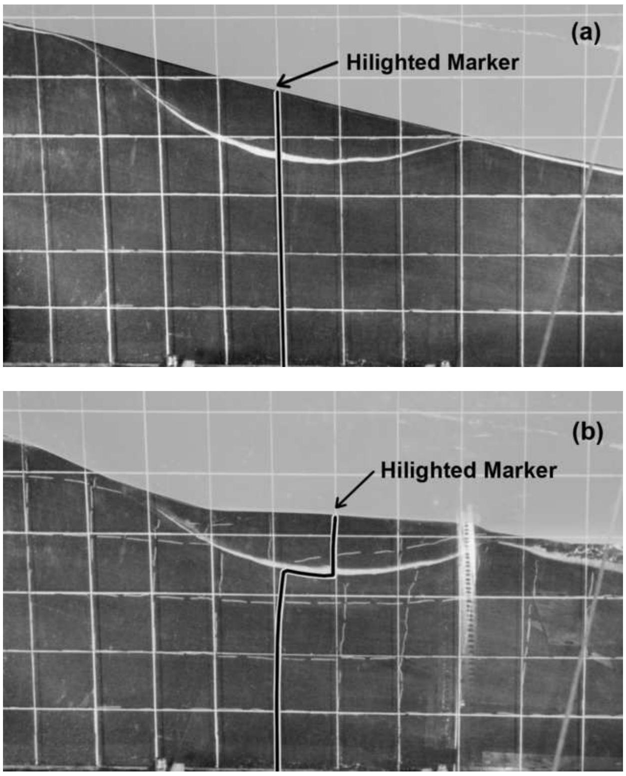

Figure 1: Shake table model at Chuo University tested with visiting researcher from UC Davis (a) before testing and (b) after testing.

magnitude of the displacements can be mostly attributed to the different modeling conditions (1-g vs. 80-g).

3 FACTORS INFLUENCING VOID REDISTRIBUTION

Table 1 summarizes the key factors that have been experimentally observed to directly or indirectly influence void redistribution and water film formation in layered soil profiles. Some of these factors were illustrated by the model tests shown on Figs. 1, 2 and 3 while other factors are based on 1-g and centrifuge model tests presented elsewhere and referenced in Table 1.

For instance, the geometry of the low permeability barrier layer (e.g. silt arc) was shown to affect the magnitude of ground displacements, with larger displacements occurring when the shape of the barrier layer most closely corresponded to a kinematically admissible (and even optimal) failure plane. In addition, the centrifuge tests showed greater proportions of ground displacement occurring after shaking when the shape of the silt arc was more circular and steeper (an optimal failure surface), versus those tests with silt planes at flatter inclinations. This pattern is consistent with the fact that the 1-g shake table tests had some of the larger proportions of ground displacement being after shaking, since the silt arcs in those tests were more circular (e.g., Fig. 1).

The thickness and volume of the liquefying layer is a key factor that affects the potential for and timing of void redistribution or water film formation. Thicker liquefying layers expel more water, which increases the potential for localization beneath the overlying barrier layer, and they take longer to reconsolidate which increases the potential for a large proportion of the ground displacements to occur after shaking. The lateral dimensions of the liquefied layer are also important when the presence of other low permeability layers produce preferential horizontal flow towards the potential failure surface. This effect was demonstrated in the large centrifuge test described by Malvick et al. (2004), wherein a large localization formed with nearly 75% of localization occurring for 400 s after shaking.

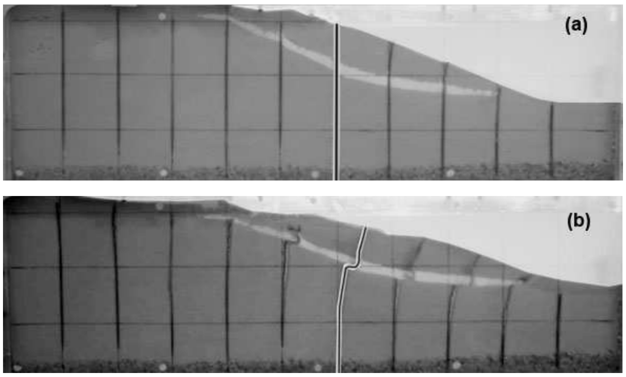

Figure 2: Centrifuge test at UC Davis conducted by visiting researcher from Chuo University, (a) before testing and (b) after testing.

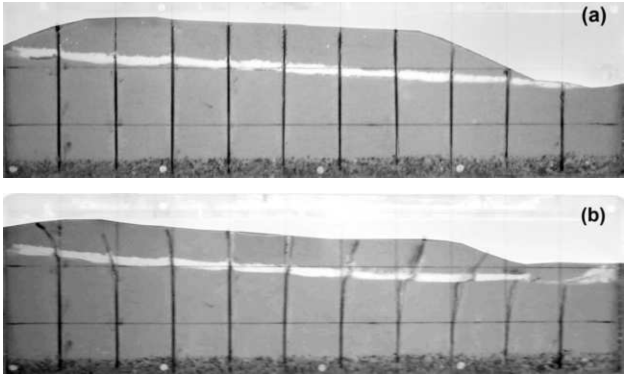

Figure 3: Centrifuge model of a 1-g model tested at UC Davis by Chuo University researcher. (a) before testing and (b) after testing.

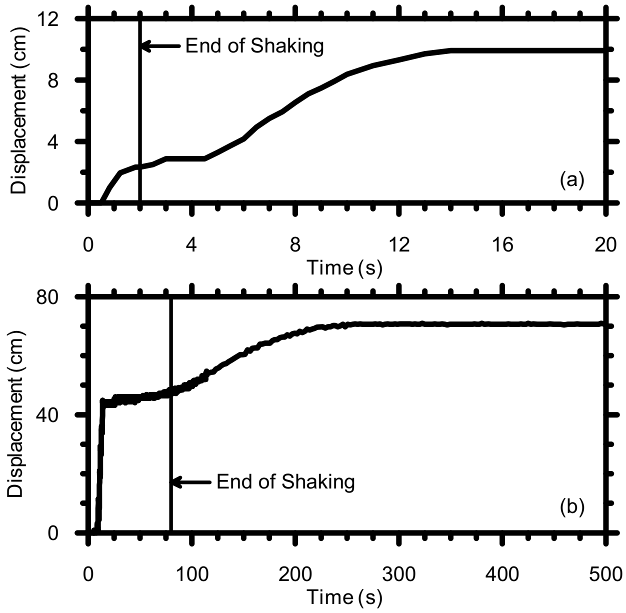

Figure 4: Displacement above silt arc in models: (a) A 1-g shake table test at Chuo University and (b) An 80-g centrifuge test at UC Davis.

Relative density is another key factor that model tests show to influence void redistribution. The 1-g model tests that showed localization all had a $D_{r,0}$ less than about 40%. The centrifuge tests showed localizations for $D_{r,0}$ less than 40-50% (depending on ground motion) and an absence of localization for $D_{r,0}$ greater than 50%. The effect of $D_{r,0}$ on model behavior is consistent with column tests by Kokusho (1999) that show water film size and duration reduced with increasing $D_{r,0}$.

Earthquake characteristics such as frequency content, duration, amplitude, direction, and history have been shown to affect void redistribution and localization. The 1-g model tests mostly used 3 Hz sinusoidal motions with peak acceleration between 0.15 and 0.35 g. The centrifuge models mostly used modified earthquake ground motions, with durations between 7 to 80 s. Longer duration motions increased localization potential in the centrifuge tests despite the generation of similar excess pore pressure ratios for short and long duration motions. The longer duration motions also made it more likely for a larger proportion of ground displacement (including localization) to occur during shaking.

One 1-g model test showed localization and larger post shaking movements when the base acceleration was reduced to 0.18 g (Kokusho 2003). This may be attributed to smaller strains during shaking, while the motion was still adequate to generate the high excess pore pressures necessary for the localization to occur after shaking (as pore pressures redistributed).

A comparison can be made of a centrifuge test shown (Fig. 2) where a sinusoidal motion was used to mimic the motion of a 1-g model. The resulting characteristic timing and fraction of movement after shaking was similar to the 1-g shake table tests at similar densities and peak accelerations (Fig. 4).

The 1-g and centrifuge model test results were generally consistent as summarized in Table 1, but there were some areas where the quantitative measures of behavior (e.g., magnitude of displacement and its timing) were not directly comparable. The problem with comparisons stemmed from difficulties in designing 1-g and centrifuge models that were identical in all major aspects. For example, the 1-g tests used Tokyo Bay sand pluviated through water, whereas the centrifuge tests used Nevada sand pluviated through air and subsequently vacuum saturated. The effect of using two different sands, with different placement methods and different degrees of saturation are potentially significant. Furthermore, the 1-g shaking table was configured to shake models transverse to the slopes, while the centrifuges were configured to shake the models longitudinally with the slope. One centrifuge model was constructed sideways in its container with water pluviation to try and mimic the 1-g tests, but this required reducing the model size to the point where complications in constructing the silt arc and placing instruments rendered the results questionable. Despite the differences between the two physical modeling programs, the overall results and findings were consistent in showing that void redistribution and/or water film formation can be a major contributor to the occurrence of liquefaction-related deformations or instabilities.

4 SUMMARY AND CONCLUSIONS

A collaborative research program between Chuo University and the University of California, Davis has been studying void redistribution and water film formation in layered soil profiles that experience liquefaction during earthquakes. This program has involved a series of physical model tests on a 1-g shake table (Chuo University) and in two centrifuges (UC Davis). Three models tested by visiting researchers from each university were summarized herein.

Several key parameters that affect the severity and consequences of void redistribution or water film formation were identified, as summarized in Table 1. These key parameters include the shape of the low-permeability barrier layer; the relative density of the liquefied layer; the thickness/volume of the liquefied layer; the hydraulic impedance of the barrier layer; the permeability of the liquefied layer; and the earthquake characteristics (frequency content, amplitude, duration, direction of shaking, sequence and history). This summary table lists includes references to publications where further details can be found regarding the tests that demonstrated these factors.

This collaborative US-Japan research project facilitated progress on the technical research at both institutions, with a particular important component being the exchange of graduate student researchers. This exchange provided a more efficient means of communicating different experimental techniques as well as providing extended opportunities to exchange ideas on the interpretation of the observed behaviors. A few examples of the tests performed at each institution with their visiting researcher were presented herein.

In conclusion, the combined findings from both institutions show that void redistribution and water film formation can have a major effect on the magnitude and timing of displacements associated with earthquake-induced liquefaction. Consequently, the residual shear strength of liquefied soil that would be appropriate for use in a stability analysis does not depend solely on the soil's pre-earthquake state (i.e., density and confining stress), because instability may form along a zone of soil that has become loosened during void redistribution or along interfaces that have trapped water films.

ACKNOWLEDGMENTS

The University of California, Davis portion of the research project was supported by the National Science Foundation under grant CMS-0070111 as part of the US-Japan Cooperative Research in Urban Earthquake Disaster Mitigation program. The Chuo University portion of the research project was supported by the Japanese Government under the same cooperative research program.

REFERENCES

Kokusho, T. 1999. Water film in liquefied sand and its effect on lateral spread. *J. Geot. Geoenv. Eng.,* ASCE, 125(10), 817 – 826.

Kokusho, T. 2000. Mechanism for water film generation and lateral flow in liquefied sand layer. *Soils & Foundations*, 40(5), 99-111.

Kokusho, T & Kojima, T. 2002. Mechanism for postliquefaction water film generation in layered sand. *J. Geotech. Engrg.*, ASCE, 128(2), 129-137.

Kokusho, T. 2003. Current state of research on flow failure considering void redistribution in liquefied deposits. *Soil Dynamics and Earthquake Engineering*, 23(7), 585-603.

Kulasingam, R., Malvick, E. J., Boulanger, R. W., & Kutter, B. L. 2001. Void redistribution and localization of shear strains in model sand slopes with silt seams: report on first year activities. *Proc. U.S. – Japan Joint Workshop and 3rd Grantees Mtg, U.S.- Japan Cooperative Research in Disaster Mitigation*, Seattle, WA, pp. 117-128.

Kulasingam, R. 2003. *Effects of Void Redistribution on Liquefaction-Induced Deformations.* Ph.D. thesis, Univ. Calif., Davis, 460 pp.

Kulasingam, R., Malvick, E. J., Boulanger, R. W., & Kutter, B. L. 2004. Strength loss and localization at silt interlayers in slopes of liquefied sand. *J. Geotech. Geoenviron. Eng.* 130(11), 1192-1202.

Kutter, B. L., Malvick, E. J., Kulasingam, R., & Boulanger, R. W. 2002. Interpretation and visualization of model test data for slope failure in liquefying soil. *Proc. 8th U.S.-Japan Workshop on Eqk Resistant Design of Lifeline Facilities and Countermeasures against Liquefaction,* Tokyo, Japan.

Malvick, E. J., Kulasingam, R., Kutter, B. L. and Boulanger, R. W. 2002a. Void redistribution and localized shear strains in slopes during liquefaction. *Physical Modeling in Geotechnics, ICPMG '02*, R. Phillips, P. Guo, R. Popescu, eds., A. A. Balkema, 495-500.

Malvick, E. J., Kulasingam, R., Kutter, B. L. & Boulanger, R. W. 2002b. Effects of void redistribution on liquefaction flow of layered soil: Centrifuge data report for EJM01. *Report No UCD/CGMDR-02/02, 2002.*

Malvick, E. J., Kulasingam, R., Boulanger, R. W., & Kutter, B. L. 2003 Analysis of a void redistribution mechanism in liquefied soil. *Proc. 12th Panam Conf. Soil Mech. & Geotech. Engrg,* Cambridge, MA. Vol. 2, 955-961.

Malvick, E. J., Feigenbaum, H. P., Boulanger, R. W., & Kutter, B. L. 2004. Post-shaking failure of sand slope in centrifuge test. *Proc. 11th Intl. Conf. on Soil Dyn. & Eqk. Engrg & 3rd Intl. Conf. on Eqk. Geotech. Engrg,* Berkeley, CA. Vol. 2, 447-455.

National Research Council. 1985. *Liquefaction of soils during earthquakes*. National Academy Press, Washington, D.C., 240 pp.

Whitman, R. 1985. On liquefaction. *Proc. 11th Inter. Conf. Soil Mech.& Fdtn. Eng.* San Francisco, Balkema, Rotterdam. pp1923-1926.