



Modelling pore fluid migration in layered, liquefied soils

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ABSTRACT: To date, most research on water films has been undertaken using relatively expensive, specialist equipment such as centrifuge models or large laboratory models. This paper describes a simple, inexpensive apparatus that allows the direct observation of pore-fluid migration within the liquefied soil. A review of other research on waterfilms and frames from digital video footage of the model in operation is presented. The model may prove useful in the study of water film formation as well as post-liquefaction settlement, consolidation of soils at very low effective stress and sediment transport within a liquefied mass.

1 INTRODUCTION

Liquefaction has been the subject of ongoing research for a number of decades. While much is understood about complete liquefaction in ideal soils, there remain a number of fundamental phenomena associated with liquefaction in real soils that are still not well understood. One such phenomenon is the development of water films.

Recent research on post-liquefaction behaviour of layered soils has demonstrated that a water film will develop beneath or within a less permeable sublayer under most circumstances. It has been suggested that the water film effect can cause liquefaction in otherwise non-liquefied layers closer to the surface, and that persistent water films can cause significant damage to infrastructure, such as bearing capacity failures, and flow failures on shallow slopes. The common occurrence of waterfilms in liquefied soils is of significance to both designers and theorists, as most existing methods for calculating liquefaction risk or post-liquefaction soil strength relies on the assumption that the soil is a continuum. Clearly this may not be the case and further work is required to determine the implications.

Sections 2 and 3 of this paper review the past work on water films and give a description of the mechanism of water film generation. Sections 4 and 5 describe a model developed by the authors, which allows direct observation of the water film generation process, and presents preliminary results from the model in operation.

2 PAST WORK

The earliest work on water films can be seen in investigations on the mechanisms for sand boils. Housner (1958) suggested the reservoir for sand boils might be a region of water and loose soil left behind after the sand particles in the liquefied soil have settled to form a more stable configuration. Scott and Zuckerman (1973) sought to explain how this reservoir found a path to the surface and in a series of simple laboratory experiments showed that an essential condition for the generation of sand boils is the presence of a suitably fine-grained capping layer. Liu and Qiao (1984) performed shake table tests, similar to those described in the present paper, where “water interlayers” were observed to form beneath minor layers of finer grained material within an otherwise homogeneous sand. More

recent research by Fiegel and Kutter (1994) confirms the earlier findings and provides a mechanism of liquefaction for layered soil.

It is now readily understood that sand boils are a porewater pressure dissipation mechanism, caused when there is a build-up of pressure beneath a lower permeability layer. The water finds an existing weakness in the overlying soil or the soil cap cracks and the water surges to the surface, taking sand and silt particles with it, often forming volcano shaped cones of loose sand and silt. A case study on the sand boils observed in the Marina District of San Francisco during the 1989 Loma Prieta earthquake (Bardet and Kapuskar, 1993), highlighted some remaining questions on the formation of sand boils; in particular the sediment transport process associated with them. A number of authors have noted that substantial quantities of soil from deep layers are often found in the cone of a sand boil and this process is still not understood (Bardet and Kapuskar 1993, Housner 1958).

Until recently, little research effort had focussed on the possible role of water films in lateral spreading and slope failures. Seed (1987) considered how the emergence of a water film might make calculating a reliable residual shear strength against slope failure difficult. Balakrishnan and Kutter (1999) performed centrifuge tests on layered soils, producing a water film which they cited as a low effective stress region on which lateral spreading might occur. Most recently, a number of papers have been authored by Kokusho (Kokusho, 1999; Kokusho, 2000; Kokusho and Fujita, 2001; Kokusho and Kojima, 2002) giving a mechanism for water film generation and investigating their effect on lateral spread.

Kokusho and his graduate students have shown that water films form readily under a variety of layering configurations, such that most liquefiable soils, both natural and manmade, might be shown to form stable water films when liquefied. They have shown that the water film may remain for many minutes and can exclusively explain a number of well-known lateral spreading failures, including the famous large lateral spread that occurred at the Meikun High School during the 1964 Niigata earthquake. Beaty and Byrne (2001) have similarly suggested the Lower San Fernando Dam may have failed due to a water film beneath the toe, drawing the general conclusion that evaluations of stability based entirely on undrained laboratory tests may be unconservative, particularly for highly stratified sites.

Kokusho (2000) has also suggested that subterranean rupture of silt seams due to water filming may cause destabilisation in sand layers closer to the surface. This has been suggested by earlier researchers, including Scott and Zuckerman (1973), who indicated that denser soils can be induced to liquefy from below by the behaviour of the underlying layer.

3 WATER FILM GENERATION MECHANISM

When the porewater pressure in a saturated, loose sand is raised to a value equal to the initial total stress, the soil is said to be completely liquefied. In this state of zero effective stress, the sand particles are held in suspension, eventually settling into a denser configuration. Meanwhile, the hydraulic gradient caused by the excess porewater pressure drives water toward the ground surface at a rate relative to the permeability of the surrounding soil. If the liquefied soil is capped by a lower permeability material, this dissipation process is slowed and a film of water will form immediately beneath the less permeable layer. The water film will remain until the porewater pressure has dissipated, either by seeping through or around the capping layer, or by breaching it.

Real soils, whether natural or man-made, typically consist of layers or conglomerations of differing grain sizes and permeabilities. Soils prone to liquefaction are readily found to have seams of lower permeability within the soil column, either sandwiched within the liquefiable layer or capping it. Kokusho (1999, 2000) has shown that a water film will form beneath a layer of only a few millimetres in thickness, and of only a slight difference in permeability. Kokusho's results also suggest that greater settlements can be expected from soils where a water film has lingered than for a soil where pressures have been dissipated quickly. Therefore, it can be seen that water film generation might play an

important role in post-liquefaction behaviour for most real soils.

Theoretical soils, or those used in liquefaction theory and most laboratory experiments, typically consist of a homogeneous soil structure with homogeneous or graded strength and permeability characteristics. This assumption is largely necessary for experimental repeatability. However, the methods that are commonly used for determining liquefaction risk and post-liquefaction soil strength do not generally allow for the type of strength discontinuity provided by a persistent water film and may therefore be a poor generalisation for real soils. To determine the implications of water film generation on liquefaction of stratified soils and post liquefaction performance, further research is clearly required. To that end, the authors have developed a simple, inexpensive apparatus that allows direct observation of pore-fluid migration within the liquefied soil.

4 MODEL DESCRIPTION

The model consists of a small plywood box with a Perspex window, filled with saturated sand in which a thin silt seam, or other lower permeability material, is sandwiched (Figure 1). The sand is liquefied instantaneously by releasing a compressed-air piston against the model. The water film that forms against the Perspex is recorded with digital video or a digital camera.

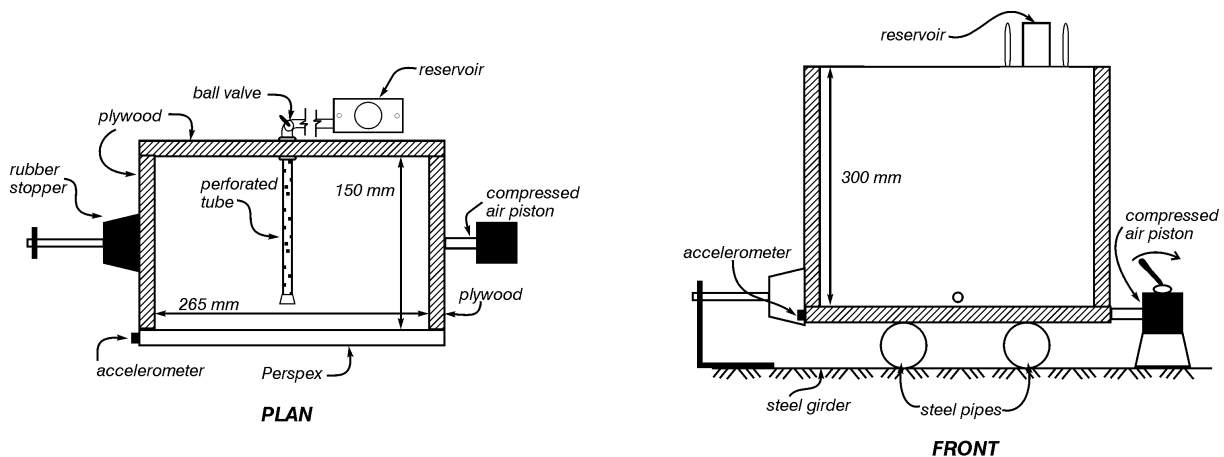


Figure 1. Plans for the model

The box has internal dimensions 265mm x 150mm x 300 mm. The back, base and sides are plywood, and the front wall is Perspex. The edges are screwed together and the wooden surfaces are coated with a marine sealant. A small, perforated tube in the base of the box is connected to a reservoir via a ball valve at the back. The reservoir can be raised or lowered to control the water pressure inside the model.

To allow one-dimensional movement only, the box is mounted on steel rollers on a steel girder. On one side of the model, a compressed-air piston is released to provide the simulated seismic input in the form of a single pulse. At the other, a rubber stopper holds the box in place and an accelerometer attached to the box measures the magnitude of the seismic pulse. To achieve an acceleration in the order of 0.4g the rubber stopper was wound tight against the model and the air compressor was reduced to the lowest repeatable level. Improved control of the seismic input might be achieved by securing the model to a shake table.

To prepare the model, the box is first filled with water, with the ball valve open, and allowed to stand until the water level equalises. Then a thin layer of coarse gravel and sand is spread in the bottom of the box to cover the drainage pipe. A thick layer of pluviated, fine sand follows, poured so the particles settle in a similar way to a natural, loose sand deposit. If a domed surface is required, it is formed in the loose sand. Next, a thin silt seam is included by carefully pouring a silt slurry into the water. Alternatively, an impermeable material such as a piece of geomembrane or plastic may be laid

on the sand. At this stage it is important to avoid disturbing the model and to allow ample time for the sample to consolidate and to attain hydraulic equilibrium. In the sample discussed below, the samples were left overnight before testing. To assist in the consolidation of the low permeability layer, another layer of sand is placed on the top. Once the sample is ready for testing, the ball valve is closed to simulate undrained conditions.

The model works on the assumption that the pore fluid migration and soil particle movements against the Perspex window are representative of any other slice through the model. While particles in contact with the window encounter less frictional resistance than those deeper within the model, there is still sufficient friction to ensure a competent seal, allowing a water film to form and then dissipate through the silt layer without failing it, as the following results show. However, the lower friction does ensure sand boils occur adjacent to the window in preference to any other location, allowing direct observation of the sediment transport paths within the soil column.

5 RESULTS

A series of preliminary tests were performed to ascertain the model's effectiveness in allowing a direct view of the processes involved in the generation of water films and sand boils. The results described here concern a domed sand deposit, overlain by a silt seam which varies in thickness from 3mm at the top of the dome, to as much as 25mm near the side walls of the model. A layer of sand was pluviated on top of the silt to help consolidate it and the model was left overnight before the first test.

Four tests were performed on this sample and received peak accelerations of 0.4g, 0.4g, 0.3g and 0.6g for tests A, B, C and D respectively. Tests A, B and C produced a stable water film and caused some damage to the silt layer, but did not rupture it. The sample was allowed to stand between each test until the water film had dissipated. Test D produced a thin water film which dissipated immediately when a sand boil ruptured the silt layer, and no appreciable water film was observed after the silt had failed.

Photos for tests A and D are presented below. Test A (Figure 2) produced a clean water film which persisted for between 10 and 30 minutes from the seismic pulse. Maximum thickness of the water film was 1.1mm. Total post liquefaction settlement achieved was 2.0mm. Test D (Figure 3) produced a sand boil that dissipated the porewater pressure beneath the silt layer in approximately 1 to 2 minutes. Total post liquefaction settlement for this test was 1.0mm, and the total combined settlement for Tests A, B, C and D was 5.7mm. While little numerical data can be gleaned from these photographs, they do show that with well positioned photographic or video equipment, technologies such as PIV (Particle Image Velocimetry) might be applied to determine migration of voids or particle transport within the lower sand (White et al. 2001).



Figure 2a, Test A. Hydraulic equilibrium before the ~0.4g shake.



Figure 2b, Test.A. The soil has completely liquefied and settled. Maximum water film thickness of 1.1mm.



Figure 2c, Test A. The water pressure has dissipated through or around the silt layer, a process which took between 10 and 30 minutes. Total post-liquefaction settlement of 2.0mm.



Figure 3a, Test D. Hydraulic equilibrium before the $\sim 0.6g$ shake. The sample has been tested 3 times before and the silt layer is visibly damaged.



Figure 3b, Test D. Soil is completely liquefied. The silt layer appears to “blur” as the pressurised water churns up the silt particles in the poorly defined water film.



Figure 3c, Test D. The silt layer fails and two plumes of water surge toward the surface.

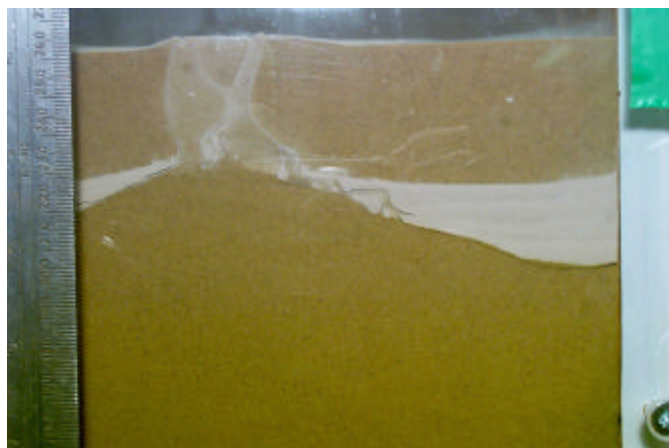


Figure 3d, Test D. The sand boil breaks the surface, taking silt and sand particles with it.



Figure 3e, Test D. Between 1 and 2 minutes later the water pressure has dissipated completely. Post-liquefaction settlement of 1.0mm for Test D. Total combined post-liquefaction settlement for Tests A (0.4g), B (0.4g), C (0.3g) and D (0.6g) is 5.7mm.

6 DISCUSSION

The model described above was built as a first attempt to directly observe the process of water film generation in a liquefied, layered soil. It can be used to investigate the migration of voids and sediment transport within the liquefied soil, and to determine the effect of a water film forming beneath a geomembrane. Research recently completed at the University of Cambridge has made use of the model to examine the effect drainage columns have on liquefied soils (Brennan, 2002). Other possibilities include testing different density sands to determine if the presence of a less permeable layer makes a “border-line” soil more likely to liquefy. A similar test using multiple silt layers could be devised to determine if the formation of a water film in a lower layer increases the risk of liquefaction for an overlying, denser layer.

Another suggested use of the model is to investigate post liquefaction settlement and consolidation of soils at low effective stress. Recent research at the University of Cambridge on the micro-mechanics of soil during one-dimensional compression noted that at very low effective stresses there is a distinct drop in void ratio (Cheng, 2001). A literature review revealed little explanation of why this occurs. Adalier and Elgamal (1992) demonstrated that the initial part of post-liquefaction settlement is due to sedimentation rather than consolidation. However, earlier research by Yoshimi et al (1975) concluded that; “Even under very low confining stress...the sand that had not undergone liquefaction was considerably less compressible than the sand that had been liquefied.” And Kokusho’s results (1999) suggest that greater settlements can be expected from a soil where a water film has lingered, than for a soil where the water pressures have dissipated quickly. This suggests there may be other mechanisms also involved and further research is required.

A number of adjustments could be made to the design to expand the range and quality of information that might be gathered from it. For example, additional instruments could be added, such as piezometers, to measure the porewater pressure at specific depths within the liquefied sand layer. More control of the input motion might be gained if the model were fixed to a shake table. For site-specific analyses or slope stability problems, larger models could be built to accommodate a scaled site. And seepage loss might be reduced by slightly abrading the lower friction Perspex wall, but care should be taken, as it is important to maintain optical clarity.

7 CONCLUSION

A simple, inexpensive model is described which allows the direct observation of porewater migration within a liquefied soil. The authors have demonstrated that the low technology apparatus gives some interesting results which, when combined with high technology recording equipment and data analysis tools, might help answer remaining questions about the mechanisms of liquefaction in layered soils.

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