

LATERAL SPREADING DURING CENTRIFUGE MODEL EARTHQUAKES

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ABSTRACT

Lateral spreading of gently-sloping deposits of liquefiable sand is a cause of much damage in earthquakes, reportedly more than any other form of liquefaction-induced ground failure. Estimation of the forces induced on structures such as pile foundations within these deposits requires a knowledge of both the magnitude of spreading occurring and the distribution of displacement through the liquefied layer.

This paper concerns itself with measuring the displacement profile through a laterally spreading slope by means of coloured sand marker lines within centrifuge models. A series of dynamic centrifuge model tests have been carried out on gently sloping sand beds containing instrumentation for measuring pore pressures, accelerations and displacements. The results of these experiments are presented in the paper.

It can be concluded that the surface displacements relatively easily measured in the field by such techniques as aerial photogrammetry do not necessarily indicate the magnitude of lateral spreading occurring at depth. Surface layers above the phreatic surface may rotate, causing increased displacement with depth. Alternately they may shear on the boundary with the underlying liquefied layer by virtue of support received from the toe, giving a displacement discontinuity.

INTRODUCTION

Liquefaction and lateral spreading of saturated, gently sloping, loose, fine sand deposits is a matter of concern during earthquakes. Investigation of the Niigata earthquake of 1964 revealed extensive lateral spreading with up to 10m of surface displacement being seen close to the Shinano river. The damage in this earthquake was extensively studied by Hamada (1992) who gives details of much of the damage caused. Ground movements of this magnitude obviously cause great damage to the structures founded upon them, more than any other form of liquefaction induced ground failure, National Research Council (1985). This damage can include movement of quay walls, axial buckling of bridge decks and railways spanning between spreading slopes and bending failure of piles passing through laterally spreading liquefiable layers.

Lateral spreading especially occurs close to free boundaries such as rivers, the shore or quay walls, as here the water table is high and the boundary conditions favourable. A large volume of case study data is available on lateral spreading towards these free boundaries from previous earthquakes. Dynamic centrifuge modelling was carried out using sloping laminar boxes at RPI by Abdoun (1997), and finite element modelling at Cornell by Meyersohn (1994). Much of the data from field studies of the extent of lateral spreading is based on aerial photogrammetry or satellite imaging, comparing photographs from before and after the earthquake and measuring the movement of objects dragged with the lateral flow, such as manholes and some buildings, relative to certain fixed points. Unfortunately this technique can only give surface displacements for the soil.

This paper details a series of centrifuge tests carried out at Cambridge University, investigating the lateral spreading of gently sloping ground subjected to earthquake loading. By using marker lines of coloured sand in centrifuge models, it has proved possible to measure both surface and sub-surface movements of the liquefied sand bed. This has shown a significant increase in displacement with depth. As the forces exerted on structures such as piles within the flowing soil layer are dependant on the magnitude of the movement of the soil relative to the structure, increased movement with depth may seriously alter the forces exerted on the structure.

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Lateral spreading past bridge foundations was observed in the 1999 Chi-Chi earthquake in Taiwan. The situation is illustrated schematically in Figure 1, and the resulting damage is shown in Figures 2 and 3. A non-liquefied surface layer at the Nantou new bridge flowed downslope relative to the bridge pier. Figure 3 shows the build-up of non-liquefiable soil at the up-slope face of the pier and the resulting void at the down-slope face. The bridge piers did not fail during the earthquake, but were subjected to significant lateral spreading.

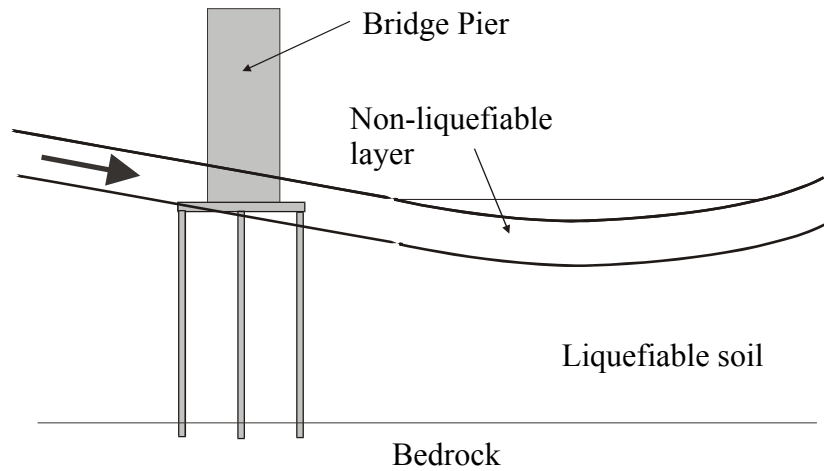


Figure 1 : Schematic of layout at Nantou new bridge, Taiwan.



Figure 2 : Nantou New bridge after the 1999 Ji-Ji earthquake showing arrangement of piers relative to the river.



Figure 3 : Nantou new bridge pier after the Ji-Ji earthquake showing build-up of soil on the upslope face and gap downslope.

DYNAMIC CENTRIFUGE MODELLING

Dynamic centrifuge modelling has been used over the past twenty years for the study of soil-structure interaction problems during earthquakes. The technique involves testing scale models in the increased g environment of a geotechnical centrifuge. Utilising the scaling laws derived by Schofield (1980, 81) and summarised in Table 1, allows stresses and strains in model and prototype structures to be identical and hence true prototype behaviour to be observed in the model. Subjecting the models to lateral base shaking in-flight allows the conditions of earthquake loading to be replicated. In the tests described in this paper a scale factor of 50 was used, with 1/50th scale models being tested at 50g. In order to correct the anomaly seen in Table 1 of the difference between the scaling factors for dynamic and seepage time, silicone oil of viscosity 50 times that of water is used as pore fluid. This slows down seepage and thus gives a scale factor for time of 1/n in all cases. This technique has been widely used in dynamic centrifuge modelling and has been shown to have little effect on the behaviour of the soil.

Table 1 : Centrifuge Scaling Laws

Parameter	Ratio of model to prototype
Length	1/n
Area	1/n ²
Volume	1/n ³
Stress	1
Strain	1
Force	1/n ²
Velocity	1
Acceleration	n
Frequency	n
Time (dynamic)	1/n
Time (Consolidation)	1/n ²

EARTHQUAKE LOADING

Lateral shaking of the model container in-flight was achieved using the Stored Angular Momentum (SAM) actuator, Madabhushi et al (1998a). This actuator stores energy in a pair of spinning flywheels, releasing the energy to the package by means of a fast acting clutch. The reciprocating motion from the flywheels is converted to lateral shaking by means of a bell-crank mechanism with a variable lever arm length. Adjustment of this lever arm allows the strength of the earthquake to be selected. This actuator allows earthquake frequency, magnitude and duration to be selected by the user. The experiments were carried out using the Cambridge Equivalent Shear Beam (ESB) container, Madabhushi et al (1998b), which has end walls that simulate the deformations of the soil during the earthquake. This minimises reflection of stress waves from the end walls.

TEST OUTLINES

The models tested comprised slopes of Leighton Buzzard Fraction E sand of relative density 40%, having properties as shown in Table 2.

Table 2 : Properties of Fraction E sand.
(after Tan, 1990)

ϕ_{crit}	32°
D ₁₀	0.095 mm
D ₅₀	0.14 mm
D ₆₀	0.15 mm
e _{min}	0.613
e _{max}	1.014
k at e = 0.72	0.98E-04 m/s
G _s	2.65

Table 3 : Test Properties at prototype scale

Test	Geometry	Angle	Layer Thickness
SKH-5	A	3°	5m
SKH-8	B	6°	3m
SKH-9	B	12°	5m
SKH-10	A	6°	5m
SKH-11	C	6°	5m
SKH-12	C	6°	5m

The slopes tested had angles of between three and twelve degrees and geometries of the forms shown in Figure 4. The models were tested at 50g, giving prototype soil layer thicknesses of between three and five metres. Model properties for each test in the series are shown in Table 3. Models were prepared dry by air pluviation from an overhead hopper in the ESB model container. Models were saturated in-flight with 50cS silicone oil pumped through the model using a pair of peristaltic pumps, until steady-state seepage was achieved. The models were then subjected to earthquake shaking using the SAM actuator. The shaking had a prototype frequency of 1Hz, duration between 25 and 45 seconds and amplitude approximately 25% of g.

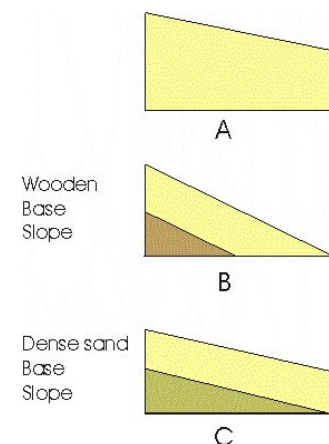


Figure 4: Test geometries

Displacements were measured using marker lines of coloured sand on the surface and at varying depths within the model and, in later tests, using columns of sand to get complete displacement profiles with depth.

Pore pressures and displacements were also measured at various locations within the model using Druck PDCR81 pore pressure transducers and piezo-electric accelerometers manufactured by DJ Birchall.

TEST RESULTS AND DISCUSSION

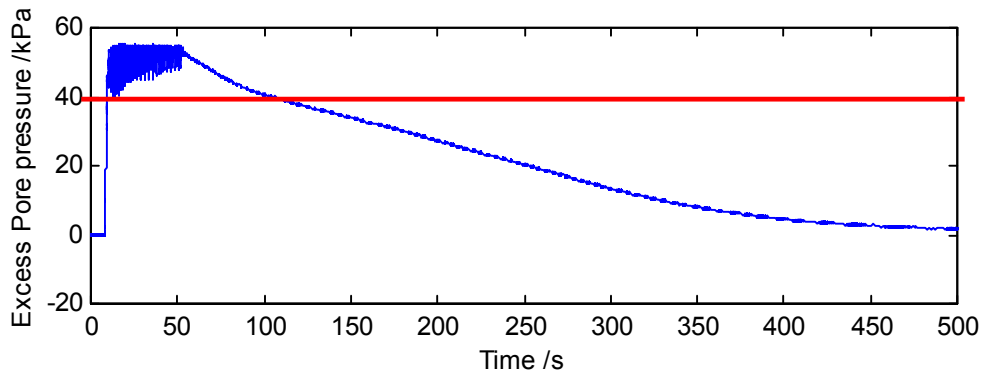


Figure 5 : Build up of excess pore pressure at base of liquefiable layer in test SKH11. Red Line shows maximum pore pressure for static stability.

Excess pore pressures and liquefaction

Examination of the Pore Pressure Transducer (PPT) traces from each of the tests shows a rise in pore pressures throughout the model sufficient to cause full liquefaction of the sand layer. The build-up and dissipation of this pore pressure can be seen in Figure 5, along with the threshold value of pore pressure for static stability of the slope. It can be seen that the slope is statically unstable at the base of the liquefiable layer for a period of 90 seconds (prototype scale), during which lateral spreading occurs. As there is only a drainage boundary at the surface of the layer, the pore pressures dissipate from the base upwards. This results in the sand closer to the surface being unstable for a greater length of time. Isochrones of excess pore pressure at various times during the dissipation can be seen in Figure 6.

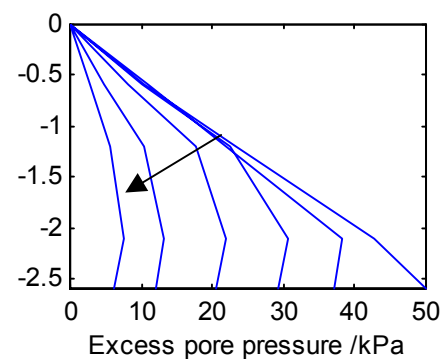


Figure 6 : Isochrones of excess pore pressure with depth at one minute intervals after cessation of shaking for test SKH11.

Marker line movement

Marker lines of coloured sand were placed within the model in order to observe the deformation occurring within the sand layer. On the sand surface lines were placed perpendicular to the slope in order to check the validity of the plane strain condition. Within the model, layers parallel to the surface and vertical columns of coloured sand give a grid in section, allowing the deformation to be visualised. The locations of these markers before and after the earthquake for test SKH-11 with type C slope, (see Figure 4), are illustrated by Figure 7.

Surface marker lines were seen to remain straight, as the glass sides of the ESB box gave a true plane strain condition for the tests. Post-flight excavation of the model revealed the movement of the subsurface marker lines.

It can be seen from Figure 7 that, whilst most previous work has assumed soil displacement due to lateral spreading to be a maximum at the soil surface, in this case there is a significant increase in displacement with depth. This could have a significant effect on the forces exerted on objects such as pile foundations founded within the laterally spreading deposit.

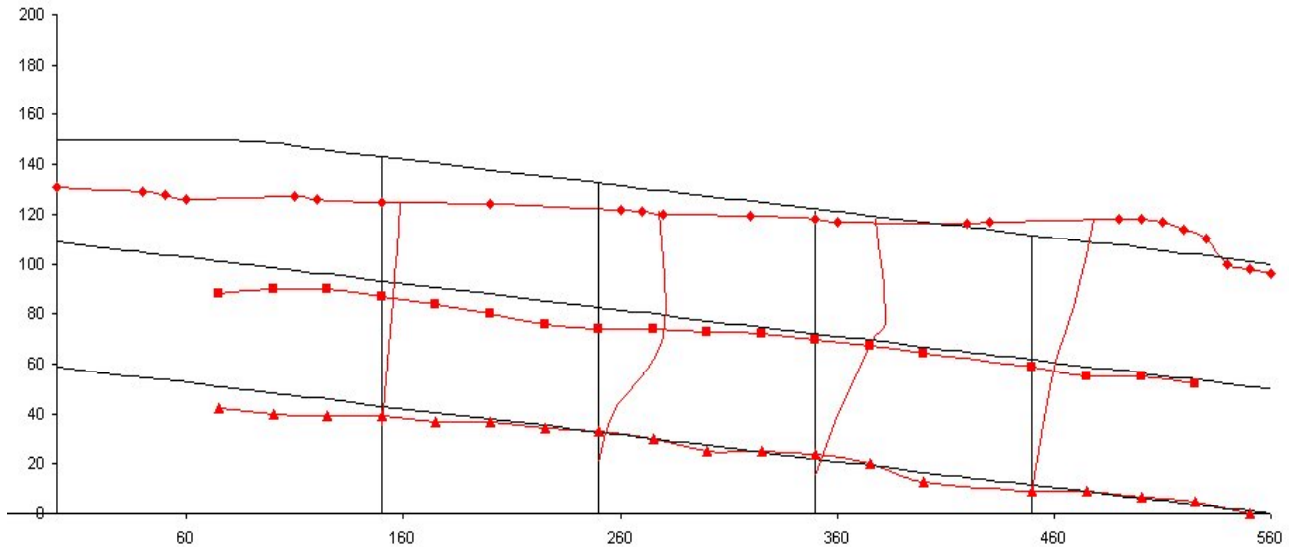


Figure 7 : Test SKH-11 Marker line movements. Scales shown in mm at model scale.
Pre-earthquake in black, post-earthquake in red.

The observed displacements are consistent with rotation of a block of sand close to the surface of the model with slip occurring within a region passing through the points of maximum displacement. This would explain both the increased displacement with depth and the observed toe heave. This block of sand may have gained strength more quickly post-earthquake than the soil below it due to the curvature of the water table in the centrifuge.

This increased movement with depth was also seen in other tests in the series for which sub-surface data is available. The deformations observed at the surface and beneath it are summarised in Table 4.

Table 4 : Observed marker line movements in models, scaled to prototype scale

Test	Geometry*	Slope angle /degrees	Maximum Surface Movement	Maximum Sub-Surface Movement
SKH-5	A	3	1m	n/a
SKH-8	B	6	0.6m	n/a
SKH-9	B	12	0.75m	1.25m
SKH-10	A	6	1m	3m
SKH-11	C	6	1.4m	1.6m

* See Figure 4 for test geometries.

This observation of increased displacement with depth which was a feature of this series of centrifuge experiments has also been observed in some field studies. For example, Hamada (1992) observed that at the Niigata Family Court House there was evidence of increased displacement with depth, due to slippage occurring at the water table, between a lower liquefied layer and a surface crust above it.

CONCLUSIONS

Displacements within laterally spreading layers of liquefiable sands can be important in calculating the forces induced on structures within this soil. Numerical modelling of these situations requires a knowledge or prediction of the magnitude and distribution with depth of the soil flow occurring. Most work carried out in this field has assumed a half-sinusoid or parabolic distribution of displacement with a maximum at the surface, often determined from aerial photogrammetry of field studies.

Dynamic centrifuge modelling has been carried out on models of a variety of geometries to study this phenomenon. Based on the results from these experiments, it can be seen that, at least in cases with the

geometries modelled, the surface displacement of the liquefied soil layer is not necessarily the maximum displacement occurring.

The use of parabolic or half sinusoid distributions of soil flow when numerically modelling the behaviour of piles within spreading deposits is hence not necessarily conservative. Care must thus be taken when designing for this situation to provide adequate pile strength to resist the added forces from rotation of surface sand blocks.

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