Dynamic Centrifuge Modelling of the Destruction of Sodom and Gomorrah

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ABSTRACT: It has suggested that the destruction of Sodom and Gomorrah, as described in Genesis, might be attributed to earthquake-induced lateral spreading. This paper describes a pair of centrifuge tests carried out to test this theory, modelling the behaviour of buildings on slopes consisting of alternate layers of liquefiable sand and silt. Investigation of measured pore-pressures show the retention of pore-pressure for sufficiently long that large lateral spreads might be expected to occur.

1 INTRODUCTION

The Biblical story of the destruction of Sodom and Gomorrah in the book of Genesis tells of how these cities were destroyed by God for their wickedness such that nothing remained. Harris & Beardow (1995) suggested that this destruction might have been due to liquefaction-induced lateral spreading of deposits around the Dead Sea owing to an earthquake, with the remains of the cities ending up beneath the water.

Whilst the bible does not specifically mention an earthquake in its account of the destruction of these cities, mentioning instead rains of fire and brimstone, it does claim that the cities disappeared such that nothing was left. This lack of ruins suggests damage that could only be caused by the disappearance of the very land upon which the cities were founded, a situation consistent with lateral spreading of the land into the Dead Sea.

The "fire and brimstone" reference was explained by Harris & Beardow with reference to the presence of hydrocarbon deposits in the area. It is known that there was a trade in bitumen from the region in the biblical period and to the present day, releases of natural gas from the ground have been observed. It is quite conceivable that an earthquake might result in the release of these hydrocarbons from the ground which might be ignited in cities, causing the aforementioned rains of "fire and brimstone".

The proposed mechanism for the destruction of these cities is that, following an earthquake, the land on which these cities were founded, next to the edge of the Dead Sea, liquefied and laterally spread into the sea. Lateral spreading occurs when the shear stresses necessary to maintain stability of sloping ground exceed the shear strength sustainable by the soil. This may occur due to liquefaction under dynamic loading. Liquefaction occurs owing to the propensity of loose soil matrices to contract to Critical State. Under undrained loading, this contractile behaviour may be exhibited as increases in pore-pressure and hence falling effective stress, strength and stiffness.

In order to test this theory, several elements need to fall into place:

1 The Dead Sea region must be shown to be a seismic zone.
2 The soils of the region must be shown to be liquefiable
3 There must be a mechanism by which very large scale lateral spreading can occur.

The first two points will be discussed briefly here, but this paper will concentrate on the third point, which was investigated using a pair of dynamic centrifuge tests.

These centrifuge tests consisted of sloping instrumented beds of soil consisting of alternating layers of liquefiable sand and relatively impermeable silt to simulate the stratified deposits that are found near to the Dead Sea.

2 REGIONAL GEOLOGY

2.1 *Structure*

The Dead Sea lies on the border between the Arabian plate and the Sinai sub-plate, a left-lateral strike-slip fault known as the Dead Sea Fault. This fault is known to be capable of producing significant earthquakes, with six earthquakes of magnitude 6 having been experienced in the last century. Archaeological and biblical evidence points to significant events having occurred during the possible timescale for the destruction of Sodom and Gomorrah, (approximately 2000 BC).

2.2 *Stratigraphy*

Examination of the soil deposits close to the present edge of the Dead Sea shows that the soil is intensely stratified. During the rainy season, floodwaters deposit loose sandy deposits, whereas during the dry season, fine silts and clays are deposited. This results in a regular stratified deposit consisting of liquefiable sand layers separated by relatively impermeable silt layers.

3 CENTRIFUGE TESTING

In order to investigate the behaviour of these layered deposits, two centrifuge tests were carried out, the first consisting of a liquefiable layer overlain by a relatively impermeable silt layer, and the second with two impermeable silt layers separated by another liquefiable layer. The geometries of these models are shown in Figure 1. The models both had slope angles of 3˚ (1 in 20) and a base liquefiable layer of 5m thickness at the centre of the model. On top of this were placed alternate layers of rock flour and liquefiable sand of 0.5m thickness at prototype scale.

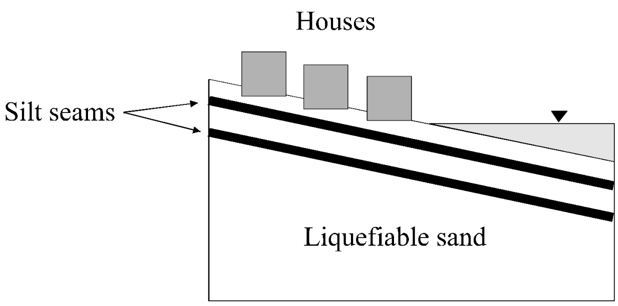

Figure 1. Schematic of centrifuge model with two silt layers

Model buildings were placed on the surface of these soil layers, designed to exert bearing pressures of 50, 100 and 150 kPa. The behaviour of these buildings will be discussed as well as the behaviour of the slope itself. These buildings were constructed from Perspex in order that the soil deformation inside could be observed. Realistic bearing pressures were obtained by constructing the roofs from brass. These buildings had no floor slab and hence bear onto the soil only through the walls, representative of the construction of historic buildings in the Middle East. A view of these buildings in place on the model slope can be seen in Figure 2.

Figure 2. Buildings in place on model slope

3.1 *Model Preparation*

The models were constructed within an ESB, (Equivalent Shear Beam) model container, whose stiffness is matched to that of the enclosed soil column in order to minimize stress-wave reflection from the end walls. The design and performance of this box is discussed by Zeng & Schofield (1996). This box has internal dimensions of 560mm x 235mm x 220mm, thus simulating a soil bed 28m x 11.75m in plan and 11m deep at 50g.

The liquefiable soil layers were prepared by air pluviation of Fraction E silica sand, whose properties are shown in Table 1.

Instrumentation in the form of accelerometers and pore-pressure transducers was placed at the required locations in the model during pouring. These layers were then subjected to vacuum and saturated from the base with silicone oil with a viscosity 50 times that of water in order to correct dynamic scaling laws for velocity, as discussed by Ellis et al. (1998). The impermeable silt layer was then placed as a slurry on the surface and left to consolidate under self-weight before further layers of sand were added.

Table 1. Properties of fraction E silica sand

Property	Value
D10 grain size	0.095 mm
D50 grain size	0.14 mm
D90 grain size	0.15 mm
Specific gravity Gs	2.65
Minimum voids ratio emin	0.613
Maximum voids ratio emax	1.014
Permability at e=0.72	0.98e-4 ms-1
Critical state friction angle ϕcrit	32º

3.2 *Test Procedure*

After model preparation the ESB box was loaded onto the SAM (Stored Angular Momentum, earthquake actuator), whose design and performance is described by Madabhushi et al (1998), and then the combined unit was loaded onto the Cambridge 10m beam centrifuge.

The centrifuge was then accelerated to 50g. Once 50g was achieved, the SAM motor was started and the package was subjected to an earthquake with fundamental frequency 50Hz, magnitude 20 %g and duration 0.5s (at model scale). Data was acquired using the CDAQS system that consists of an on-board A/D converter and memory, interfaced with by a serial link. This allowed data to be acquired at 1kHz for 20 seconds and then at 10 Hz for a further minute. At prototype scale this gives pore-pressure data for approximately one hour after the earthquake.

4 TEST RESULTS & ANALYSIS

The test results and analysis described here will be split into 4 sections, the variation of acceleration through the soil layers, the generation and dissipation of pore-pressure, the predicted lateral movement of the slope and the dynamic response of the model buildings. In this section all quantities will be discussed at prototype scale.

4.1 *Dynamic Response of Soil Bed*

The dynamic response of the soil bed can be studied by comparing the time histories and Fast Fourier Transforms (FFT's) of accelerations measured at different parts of the soil bed to those of the input motion.

It can be seen from Figures 3 and 4 that as time progresses, the acceleration experienced at the surface of the slope is attenuated relative to the input. It can also be seen that this effect is most pronounced for the fundamental and first harmonic of the earthquake motion, little effect being seen at higher harmonics. By the end of the earthquake, the acceleration is attenuated by approximately 70%.

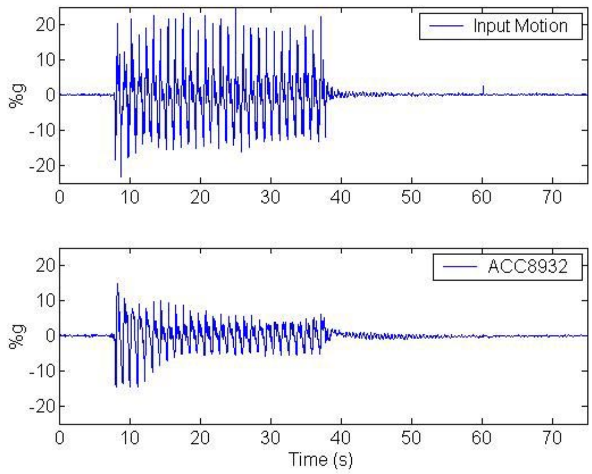

Figure 3. Time histories of acceleration at base and surface of model in Test 2

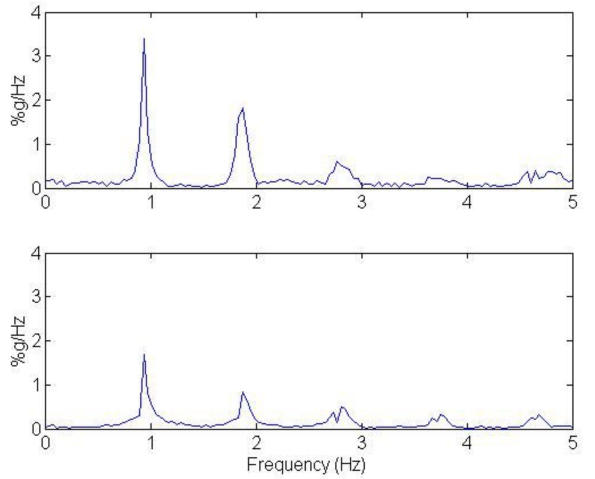

Figure 4. FFT's of accelerations measured at base and surface of model in Test 2

4.2 *Generation and dissipation of pore pressure*

PPT's were present in the soil bed in order to measure the pore-pressures generated during the earthquake and their dissipation with time. Figure 5 shows time histories of pore pressure for a column of PPT's close to the centre of the model.

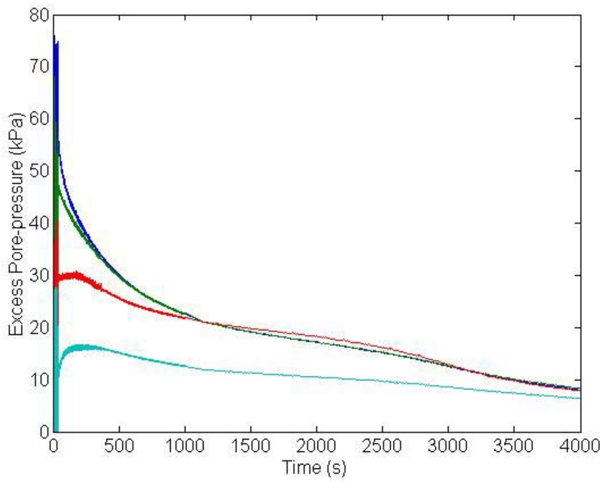

Figure 5. Pore-pressure time histories

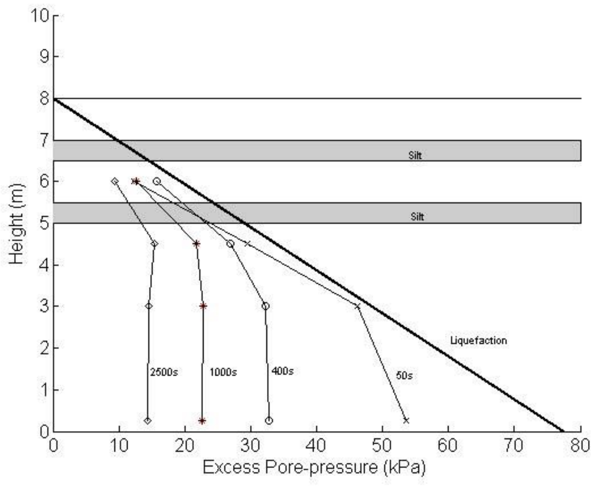

Figure 6. Isochrones of pore-pressure

It can be seen that after 1000s, the pore-pressures in the lower sand layer, (highest 3 traces), have equalized at approximately 20kPa of excess pore-pressure whereas the excess pore-pressure in the upper liquefiable layer is almost constant at 15kPa. This gives a localization of pore-pressure gradient across the silt layer owing to its lower permeability. Isochrones of pore-pressure at various times are shown in Figure 6.

It can be seen from these isochrones that the upper liquefiable layer will remain liquefied for approximately 1000s, as only after this time is the pressure at the top of the upper liquefiable layer less than that required for full liquefaction at the top of that layer.

It is reasonable to assume that the excess pore-pressure through this layer is constant with space, as the permeability of this layer is much higher than that of the silt layer.

We can thus conclude from these results that the layers will drain successively from the base upwards, with upper layers remaining liquefied for long periods of time, (over fifteen minutes in this experiment.)

When soil layers remain in a liquefied state for a prolonged period after earthquake shaking has stopped, the particles tend to settle, leaving a water-film above the top surface of the particles, below the impermeable layer. This will create a very weak sliding surface, allowing large displacements to accrue. This phenomenon has been seen experimentally by Kokusho (1999) and was also used to explain large ground deformations observed during the Niigata earthquake (Kokusho & Fujita 2001).

4.3 *Predicted displacements*

Centrifuge modelling does not lend itself well to modelling the large displacements that might be expected to occur on the field infinite slope, as the presence of a model container invariably limits the maximum movement that can be observed. In this experiment, post-earthquake the slope was seen to settle to an arc of the same radius as the centrifuge. Once the surface has reached this profile there is no more driving force for lateral displacement, as this is a minimum energy condition. The measured lateral displacements were approximately 2.5m at prototype scale.

Studying the pore pressures observed in the upper liquefiable layer allows an estimate to be made of the possible field displacements that might be accrued. As was mentioned in Section 4.2, full liquefaction was observed in this upper layer for 1000 seconds after the earthquake. If we consider that for this period of time the surficial soil will accelerate downslope, we can estimate the distance for which this soil might travel. In this case, assuming that the liquefied soil has no residual strength, which would be a reasonable assumption if a water film is formed, the predicted displacement is 250 km. Whilst this is clearly an upper-bound on displacement, it shows that the displacements of hundreds of metres necessary for the cities of Sodom and Gomorrah to have disappeared are feasible with layered soil profiles.

4.4 *Building behaviour*

Two model buildings were instrumented with accelerometers to monitor their dynamic behaviour. One of these buildings was a single-storied building 2.5m square and 3m high exerting a bearing pressure of 50kPa, whereas the second was a two-storied building 3.75m square and 6m high. This second building had accelerometers at the top and base in order to measure both translational and rocking modes of vibration.

Figure 7 shows the time histories of acceleration of the ground surface and at the top and bottom of the tall building.

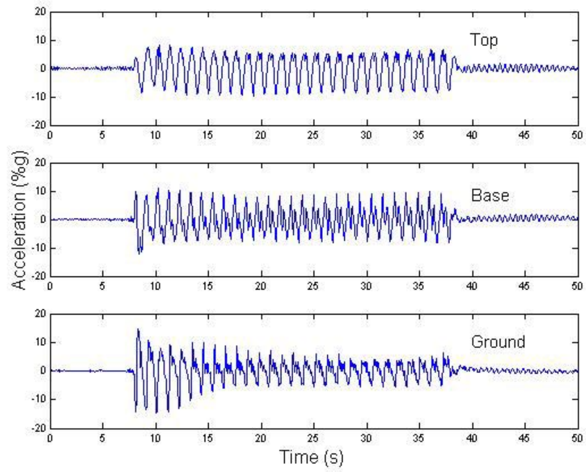

Figure 7. Time histories of acceleration of the tall building

It can be seen that whereas the ground acceleration is significantly attenuated with time, the acceleration of the buildings remains approximately constant. It can also be seen that the frequency content of the accelerations is markedly different. The top of the building has a frequency of approximately 1Hz, (the fundamental frequency of the earthquake), whereas at the base of the building there is a significant 2Hz component that increases with time. This shows that there is significant rocking taking place at 1Hz that is masking the 2Hz component present in the earthquake motion at the top of the building.

The single-storied building, conversely, shows amplification of the 1Hz component and attenuation of the 2Hz component. Only one accelerometer was present on this building, so it is impossible to separate out rocking and translational modes of vibration.

The frequency components of the various accelerations are shown by the FFT's in figure 8.

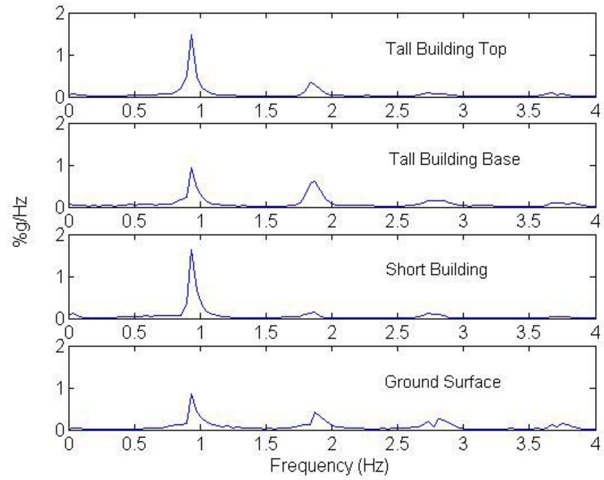

Figure 8. FFT's of accelerations measured on buildings

5 CONCLUSIONS

It has been shown that layered deposits of liquefiable sand and relatively impermeable silt, as found around the Dead Sea, are susceptible to liquefaction. It has also been shown that the presence of the impermeable layers slow the dissipation of excess pore-pressures and may hence greatly increase the magnitude of lateral spreading that would result owing to the formation of extremely low shear strength water films at the boundaries between layers.

It is thus shown that liquefaction-induced lateral spreading after an earthquake of these layered deposits is a plausible explanation for the disappearance of the cities of Sodom and Gomorrah, with displacements of hundreds of metres or even kilometres being possible even on fairly gentle slopes.

It is not possible to state categorically whether this is what actually happened, as insufficient evidence is available at this time, approximately 4,000 years after the event is supposed to have taken place. In order to show this, archaeological evidence would need to be collected by searching for remains beneath the Dead Sea. This is not however in the scope of this paper.

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REFERENCES

Ellis, E.A., Soga, K., Bransby, M.F. & Sato, M. 1998. Effect of pore fluid viscosity on the cyclic behaviour of sands. In Kimura, Kusakabe & Takemura (eds.), *Proc. Int. conf. Centrifuge '98, Tokyo, 23-25 September 1998*. Rotterdam: Balkema.

Harris, G.M. & Beardow A.P. 1995. The destruction of Sodom and Gomorrah: a geotechnical perspective, *Quarterly Journal of Engineering Geology*, 28(4):349-362.

Kokusho, T. 1999. Water film in liquefied sand and its effect on lateral spread, *ASCE Journal of Geotechnical and Geoenvironmental Engineering,* 125(10):817-826.

Kokusho, T. & Fujita, K. 2001. Water films involved in post-liquefaction flow failure in Niigata city during the 1964 Niiigata earthquake. In Prakash (ed.), *Proc 4th Int. Conf. Rec. Adv. Geotechnical Earthquake Engineering and Soil Dynamics, San Diego, 26-31 March 2001.*

Madabhushi, S.P.G., Schofield, A.N. & Lesley, S. 1998. A new stored angular momentum (SAM) based earthquake actuator. In Kimura, Kusakabe & Takemura (eds.), *Proc. Int. conf. Centrifuge '98, Tokyo, 23-25 September 1998*. Rotterdam: Balkema.

Zeng, X. & Schofield, A.N. 1996. design and performance of an equivalent shear beam container for earthquake centrifuge modelling, *Géotechnique* 46(1):83-102