Embankment loading analysis in laboratory conditions

Terraplén análisis de carga bajo condiciones de laboratorio

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ABSTRACT

The embankment model has been developed in laboratory conditions, considering actual embankment characteristics. The forces to which it is subjected in the model have been evaluated using shaking table experimental and analytical methods. Excess pore water pressure is measured through pore pressure sensors in the shaking table experiment and embankment stability has been assessed using analytical methods. The results revealed that the embankment suffered nonlinear collapse during increasing pore water pressure, and shaking table dynamic force on the embankment model was very sensitive but was open to failure mitigation. Embankment seismic simulation using shaking table experiments helped identify model stability. The embankment and subsoil pore water pressure theoretical and experimental analysis concluded that nonlinear liquefaction characteristics played a major role in model behaviour.

Keywords: Embankment, modelling, stability, shaking table, nonlinear liquefaction.

Introducción

Earthquakes are the most catastrophic natural phenomena which cannot be predicted. They are characterised by shaking of the ground in all possible directions, causing hazards of varying intensity to mankind throughout the entire world. However, the effect of earthquakes can be controlled and minimised through some understanding and findings.

Some observations for simulating seismic loading have been made to date (Van Laak et al, 1994; Kanatani et al., 1995; Jafarzadeh and Yanagisawa, 1995; Yoshida and Finn, 2000). Pore water pressure increases in a saturated sand deposit when it is subject to seismic loading and settlement occurs during and after an earthquake due to rearrangement of grains and redistribution of voids within soils. Large settlements can occur, especially when there is liquefaction in the sand deposit. Because of their excessive damaging effect for foundations, utilities and lifelines (Hwang et al., 2003), a method has been proposed for evaluating sand deposit settlement according to the factor of safety against liquefaction (when maximum shear strain reaches 3.5%), relative density (D_r) and maximum induced cyclic shear strain. Although some field observations have been used for comparisons, all developments have mainly been based on the results of laboratory experiments regarding small sand specimens in conditions quite different to those concerning *in situ* soil deposits in the field. These experiments cannot truly simulate actual sand deposits' behaviour, especially when there is liquefaction (Ishihara and Yoshimine, 1992). Many researchers' investigations have reported using shaking table tests, such as analysing radial and rotational shear strain components by using multi-directional horizontal shaking (Chang, 2011). Sand specimen settlement has been measured and evaluated during and after each shaking test (Ueng, et al., 2010). The numerical simulation of three full-scale geosynthetic-reinforced soil walls seismically loaded onto a shaking table have been studied (Lee et al., 2010). Shaking table tests have been used for four full-scale single-story structures to investigate the out-of-plane behaviour of unreinforced masonry

(URM) panels in RC frames (Tu et al., 2010). Shaking table tests have been used for scaled utility tunnel models, with and without construction joints, in non-uniform input earthquake wave excitation (Chen et al., 2010). Gradational characteristics regarding reliquefaction mechanisms using 1 g shaking table tests and five sands having differing gradation characteristics have been determined (Ha et al., 2011). The Hilbert-Huang transform data-processing technique has been used for characterising the seismic responses of soil–quay wall systems for measuring data in a series of geotechnical centrifuge shaking-table tests (Wei et al., 2010). Many other investigations have been designed for obtaining a better understanding, classification and prediction of all types of liquefaction behaviour (Heidari and Andrus, 2010; Chang et al., 2011; Samui et al., 2011; Shahir y Pak, 2010; Lee et al., 2010; Wang et al., 2011). This paper deals with understanding pore water pressure behaviour by changing soil foundation density in different layers when a dynamic seismic force was applied to a shaking table model, and using an analytical method for understanding embankment dynamic behaviour.

Methodology and experiments

The experimental procedure followed the steps given below:

– Filter plates were fixed and sealed on top of baffle walls inside an acrylic box on the shaking table;

– The aluminium channels were fixed with gummed tape inside the shaking table's acrylic box;

– The pore pressure sensors (Figure 1) were kept and tied to the string at required location inside the shaking table's acrylic box;

– Signal conditioners for pore pressure sensors were switched on;

– The prepared sand was laid for constructing the model;

- Coloured sand was laid horizontally and vertically every 10 cm;

- Water was slowly allowed through baffle walls for saturating the model;

- Pore pressure sensor readings were set to zero in the corresponding signal conditioner to ascertain excess pore water pressure generated during shaking;

- Shaking was carried out uniformly for a specified duration (~ 12 seconds); and

- The results recorded in a computer were saved soon after completion of the experiment (Namdar, 2009).
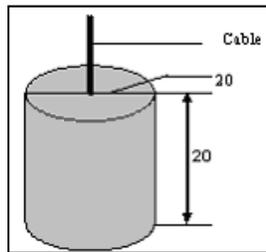
Figure 1. Pore pressure sensor.
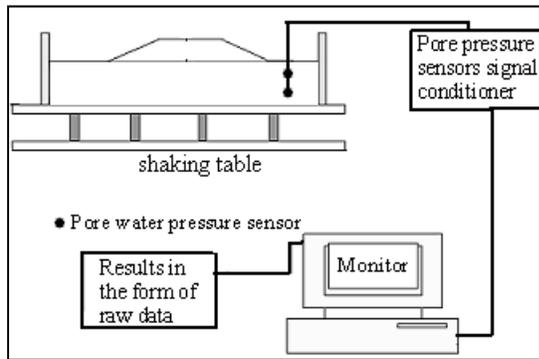
Figure 2. Schematic diagram of shaking table with model embankment
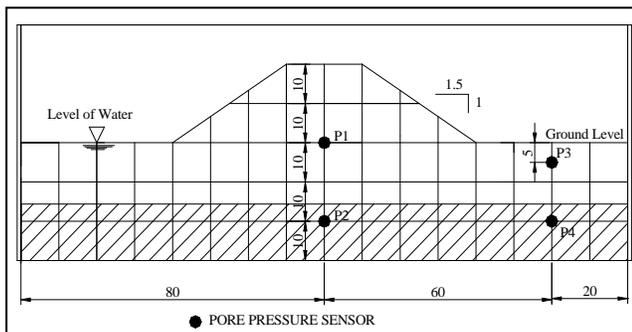
Figure 3. Position of transducer during the shaking table test (Namdar, 2009)

An embankment experimental model was considered and Figure 2 gives a schematic diagram of the shaking table with a model embankment whilst Figure 3 gives a ground level cross-section with sand, water level and pore pressure sensor positions for the embankment model.

Results and discussion

Shaking table experimental and analytical methods have been used in this practical and theoretical research work for embankment model stability analysis. Tables 1-2 and Figures 4-6 give the shaking table test results and analytical calculation results are given in Table 3. The shaking table dynamic force quickly collapsed the system; it was difficult to clearly observe slope failure shape. The pore pressure sensors helped to recognise nonlinear liquefaction.

Table 1. Characteristics of shaking table embankment model

Weight of dry sand	Embankment		0.65	kN
	Subsoil		3.19	kN
Quantity of water used for saturation			88	Litres
Duration of saturation			190	Minutes
Duration of shaking			12	Seconds
Duration of data collection			60	Seconds
Maximum displacement recorded during shaking			16	mm
Water level	After complete saturation		304	mm
	After shaking		340	mm
Average model density	Before saturation	Embankment	12.01	kN/m³
		Subsoil	12.44	kN/m³
	After saturation	Embankment	12.6	kN/m³
		Subsoil	13.8	kN/m³

The analytical methods used for calculating safety factor involved three methods: Bishop, ordinary and Janbu in constant mass and volume (Table 3). These results indicated that minimum and maximum safety factors appeared in ordinary and Bishop methods, respectively.

Table. 2. Detail of pore pressure characteristics during shaking table test

Features	P1	P2	P3	P4
Maximum pore water pressure (kPa)	1.0	3.25	2.7	3.95
Minimum pore water pressure (kPa	0.0	1.95	1.3	1.45
Average pore water pressure (kPa)	0.5	2.60	1.5	2.70

Table. 3. Analytical result of slopes

SI No.	Method of calculation	Factor of Safety	Total volume (M³)	Total Mass (Kg)
1	Bishop	1.396	344.74	4,504.1
2	Ordinary	1.018	344.74	4,504.1
3	Janbu	1.127	344.74	4,504.1

Figures 4-6 indicate that pore water pressure variation at different parts of the system led to creating nonlinear stress-strain and nonlinear liquefaction. Unit weight in each part of model had to be considered. Figure 6 shows nonlinear liquefied sand approximate tolerance which has direct correlation with the model's safety and stability factors. The indirect simulation technique clearly indicated that stress-strain, deformation and site stability could be precisely modelled and earth structures could be designed or redesigned based on that for optimising safety factors and maximum stability and minimum project cost.
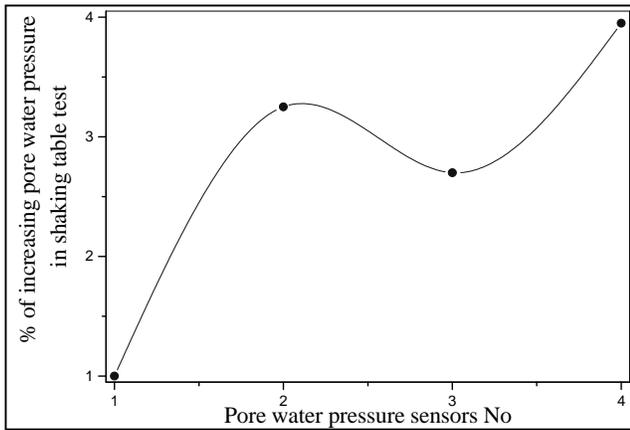
Figure 4. Detail of pore pressure characteristics
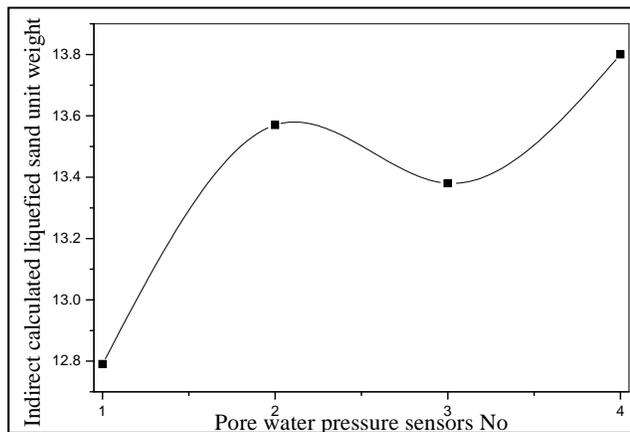
Figure 5. Pore water pressure sensors No Vs. indirect calculated lique-
fied sand unit weight
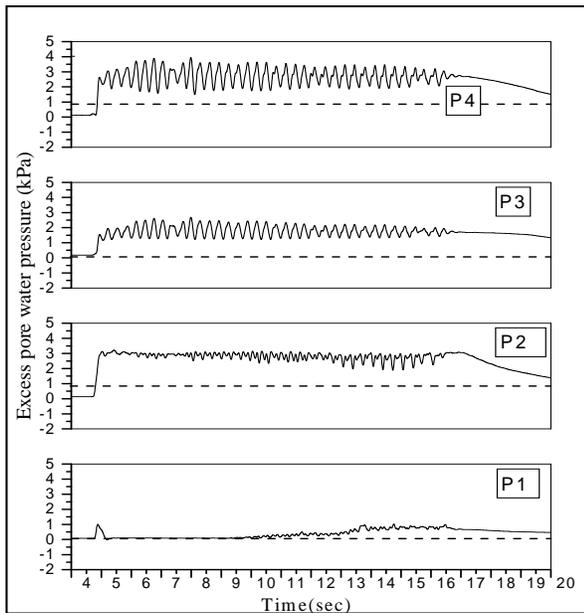
Figure 6. Time histories of excess pore water pressure of test in shaking
table test, (Namdar, 2009)

Conclusion

– The behaviour of the embankment model subjected to dy-
namic force has been studied and theoretical and experimen-
tal embankment seismic mitigation and pore water pressure
functions evaluated;

– The pore water pressure result indicated nonlinear liquefac-
tion governing system stability and the dense layer reducing
nonlinear liquefaction and pore water pressure;

– The indirect simulation technique clearly indicated that stabil-
ity and deformation could be precisely modelled and that
earthen structures could be designed or redesigned based on
that for optimising safety factors and achieving maximum
stability and minimum project cost; and

– Theoretical and experimental embankment and subsoil pore
water pressure analysis concluded that nonlinear liquefaction
characteristics play a major role in the model's behaviour.

Acknowledgements

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