Indian Geotechnical Conference – 2010, GEO*trendz*
December 16–18, 2010
IGS Mumbai Chapter & IIT Bombay

Performance of Small Scale Model Slopes in Shaking Table Tests

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ABSTRACT

The shaking table tests are conducted on small scale embankment slopes to study their behavior under dynamic conditions. Medium grained local sand with a water content of 3% is used in the study. The slope angle for the model slope is kept at 35^0 with three slope heights of 0.15, 0.18 and 0.21 m. All the three slope models are tested under the peak ground acceleration of 0.1 g. The acceleration and deformation at the base and the crest of model slopes are monitored to find the responses of embankments under dynamic condition. The failure surfaces developed during the induced motion are fairly shallow and confined within the slope surfaces. The increase in amplitude of acceleration toward the outward slope direction was observed in shaking table tests. The crest displacement history as observed in the laboratory test is well compared with numerical analysis.

1. INTRODUCTION

The recent earthquakes in India, like, Bhuj Earthquake (2001), Chamoli Earthquake (1999), Jabalpur Earthquake (1997) and Latur Earthquake (1993) have pointed out how vulnerable our existing infrastructures are to ground motions and that more research is required to properly understand the behavior of these infrastructures under seismic condition. During the Bhuj Earthquake several road embankments and embankment dams failed or suffered severe distress (EERI, 2001). The model test on the shaking table is one of the ways to study the behavior of embankment slopes under dynamic condition in the laboratory. Clough and Pirtz (1956) performed the first well-documented shaking table study of slopes. Seed and Clough (1963) also used shaking table tests to study the earthquake resistance of sloping core dams. Wartman et al. (2003, 2001) conducted a small scale shaking table test to simulate slope behavior under a 1g gravity field. Lin and Wang (2006) used a large-scale shaking table test model on sandy slope to study the dynamic behavior under earthquake conditions. This paper presents the results of the tests performed to study the dynamic behavior of the embankment slopes. The surface displacements, settlement of the crest and the accelerations at the base and the crest of the slopes have been measured during the tests. The observed test has also simulated numerically using a finite element program called FLAC (Itasca Consulting Group, Inc., 2005). The results of the numerical analyses are then compared with those obtained from the shaking table tests.

2. SHAKING TABLE TEST

The shaking table has a maximum stroke length of 150 mm and a peak frequency of 50 Hz. Experimental setup is shown in Figure 1. Model slopes are prepared inside a test box.

The 1.0 m x 0.90 m x 0.48 m (length x width x height) rectangular test box is made up of 10 mm thick Perspex glass sheets to enable observation of deformations of the slopes from the side

Fig. 1: Experimental Setup

The sides of the box are fixed rigidly with steel angles to prevent any movement. The model box is fixed to the base plate of the shaking table with bolts. This base plate is fitted with very smooth wheels which slide in horizontal direction on two parallel rails. The three sides of the box are covered with 10 mm thick thermocol sheets to minimize the boundary effects. Sand particles are glued to the bottom surface of the model box to generate surface roughness, so that there is no slippage along the bottom surface during shaking. Acceleration responses during shaking are measured by using Delta Tron Accelerometers (B & K Type 4507). Two accelerometers are mounted on the base plate of the shake table to measure the horizontal and vertical vibrations. One accelerometer is placed at the base of the slope and another one is placed at the crest of the model slope. The Bruel & Kjaer (B&K) Pulse 6.1 system (Type 3560c) sound and vibration meter is used for the data acquisitions.

A system calibration has been done to check the performance of the experimental setup before starting the experimental work. The objective of the calibration is to verify that the amplification produced by the system is negligible. The loading sequence used for the system calibration consists of a 10-sec of horizontal sinusoidal motions with peak acceleration of 0.1g at 4.65 Hz frequency and is shown in Figure 2.

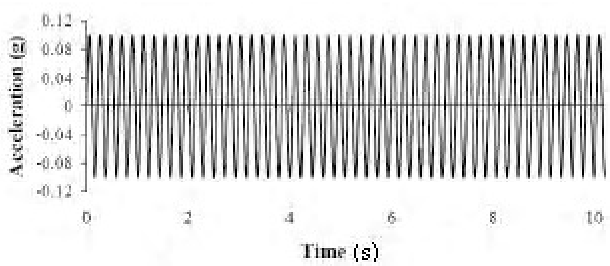

Fig. 2: Input Loading Sequence

Acceleration response of the two accelerometers fixed to the model box is shown in Figure 3.

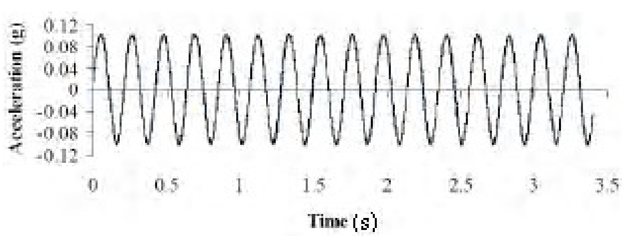

Fig. 3: Responses of Acceleration Fixed to Model Box

It observed that no significant amplification of the system is registered during the loading and the system appears to behave linearly throughout the loading history. The responses of the accelerometers are found to be sinusoidal with predominant frequency of 4.65 Hz. The vertical vibration of the shaking base plate and the model box is also measured. The magnitude of the vertical vibration (0.0075g) of the base plate is very less as compared to the horizontal input motion and can not significantly affect the test results. Another important aspect is to ensure that the predominant frequency of the input motion is different from the natural frequency of the model to prevent a resonance condition from developing, which may lead to premature failure. The natural frequency of the base plate along with the test container and the soil slope is determined experimentally by subjecting the whole test setup to a motion and then allowed it to shake freely until it stops by its own. As may be seen from the Figure 4, the natural frequency of the whole test setup is much higher than the predominant frequency of the system as shown in Figure 2.

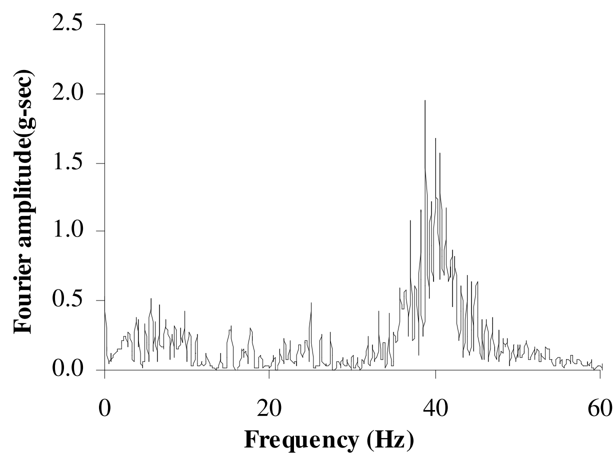

Fig. 4: Frequency Content of the Whole Test Setup with Soil Slope

3. SPECIMEN PREPARATION AND MATERIAL PROPERTIES

The soil used in this study is a local uniform medium sand (Kasai River sand). It is classified as poorly graded sand (SP), according to the Unified Soil Classification System. The specific gravity of the sand is 2.7. The maximum dry unit weight $\gamma_{d\,max}$ is 16.7 kN/m^3, and the minimum dry unit weight $\gamma_{d\,min}$ is 14.03 kN/m^3. The uniformity coefficient (c_u) and coefficient of curvature (c_c) of the sand are found to be 2.84 and 0.87, respectively. In all the model tests, the bulk unit weight of the sand is maintained at 15.02 kN/m^3 and a relative density D_r of 60 %. The drained triaxial shear test is performed on the soil sample to find shear strength parameters. The cohesion and angle of friction are obtained from triaxial (drained) test as 0 kPa and 35^0, respectively. Before the construction of the model slopes, 3% water is added to the sand and it is allowed to cure for 24 hours in an airtight polythene bag. The slope models are constructed in the test box by compacting the cured sand up to the desired height by controlled-volume method.

4. RESPONSE OF THE SLOPES

The development of the sliding surface and the crest settlement are monitored with the progress of the tests.

The sliding surface and the crest settlement at the end of each test are shown in Figure 5.

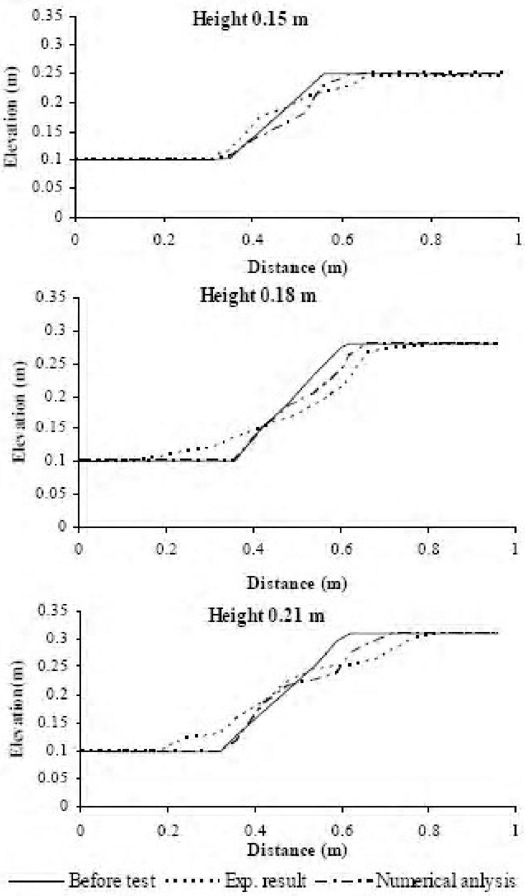

Fig. 5: Side Profile of Failed Model Slopes

The results in general indicate that the development of the sliding surface and separation of the soil body near the crest is more prominent. The failure surface is shallower for the cases of 15 cm slope height. The failure surface is developed near the mid width for all cases and appeared to be deeper for steep slopes, which is consistent with the field observations of earthquake induced landslides (Khazai and Sitar, 2004).

The failure surface close to the crest is more or less circular. Some hairline tension cracks at the crest are also prominent. These cracks are more prominent and more in numbers for the models with 15 cm slope height. Less number of cracks is developed when the slope height is more. This may be due to the fact that the slope becomes more unstable with the increase in slope height and the sliding (failure) surface is shallower as the slope fails with less number of loading cycles.

Four accelerometers are used to obtain acceleration responses during the tests. Two accelerometers are attached to the shaking table base platform to get horizontal and vertical input acceleration parameters, respectively. Another two accelerometers are placed at the centre of base and crest length of the model slopes, respectively. The applied horizontal motions are same for all the cases and also same as recorded by the accelerometer located at the base of the slope. The crest acceleration histories of all the slopes is shown in Figure 6

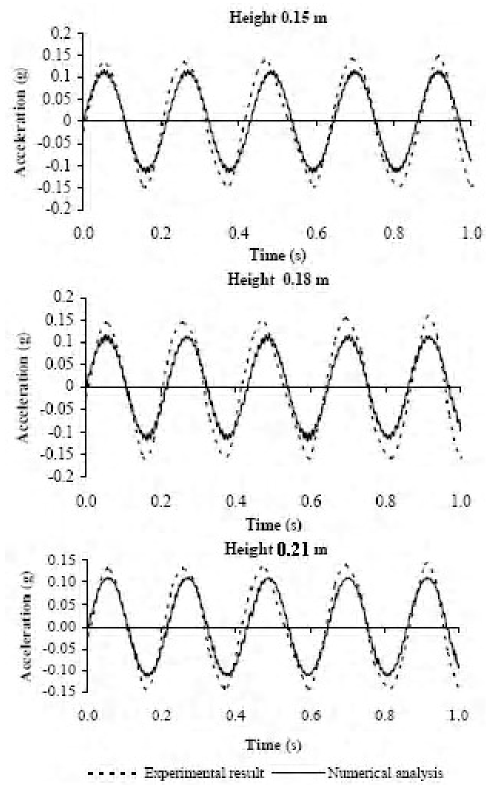

Fig. 6: Crest Acceleration Histories of Model Slopes

The Table 1 summarizes the magnification of the acceleration through the slopes and the maximum crest settlement for each test.

Table 1: Crest Settlements and Crest Amplification from Shaking Table Experiments and FLAC Analyses

Height of Slope (m)	*Experimental Results*	
	Maximum Crest Settlement (mm)	*Amplification at the Crest*
0.15	34	1.290
0.18	55	1.365
0.21	48	1.283
Height of Slope (m)	*Numerical Results*	
	Maximum Crest Settlement (mm)	*Amplification at the Crest*
0.15	23	1.149
0.18	52	1.322
0.21	52	1.168

5. CONCLUSIONS

Based on the investigations reported in this study, the following conclusions are drawn:

The failure surfaces observed in the shaking table tests and numerical analyses for all the slope cases are shallow and of rotational type. Deformations of the slopes measured during the tests are more or less uniform across the lateral width of the slope models suggesting that side wall friction is generally not significant. Several hairline tension cracks at the crest of the slopes were prominent in all the shaking table tests. These cracks are more prominent and more in numbers for the models with 0.15 m slope height. The acceleration histories recorded at the crest of the slopes during shaking table tests are similar in nature. The amplitude of acceleration toward the outward slope direction is found to be larger than that toward the inward slope direction, for all the cases. This implied development of a sliding surface and separation of the soil body near the crest. In the shaking table tests, amplification in acceleration response is observed with the increase in height of model slopes. The numerical analysis by FLAC, in general, modeled the crest settlements reasonably well but does not predict the heaving and outward movement of soil observed at the toe of the slopes in all the shaking table tests. The numerical analyses depict rotational/ translational type of movement along the slopes as observed in the laboratory tests but do not exhibit any localized shear failure surface.

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