Indian Geotechnical Journal, 36(4), 2006, 321-333

Shaking Table Studies on Reinforced Soil Retaining Walls

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Introduction

Reinforced soil retaining walls offer improved performance in addition to the advantages in ease and cost of construction over conventional retaining wall systems. Recent earthquake experiences, all over the world, evidenced the effective performance of retaining walls constructed using reinforced soil during earthquakes, in the absence of foundation liquefaction, lateral spreading or sliding (Tatsuoka et al. 1997). Studying the performance of reinforced retaining walls under cyclic ground shaking conditions helps to understand better how these walls actually behave during earthquakes and to establish precise design procedures. In that aspect several analytical, numerical (Cai and Bathurst 1995; Bathurst and Hatami 1998) and some experimental studies (Ling et al. 2005; Ramakrishnan et al. 1998; Matsuo et al. 1998) were reported in the literature.

Juran and Christopher (1989) described the results of a laboratory model study on the performance, behaviour and failure mechanisms of reinforced soil-retaining walls using different reinforcing materials, namely: woven polyester geotextile strips, plastic grids, and non-woven geotextile strips. Palmeira and Gomes (1996) presented comparisons of predicted stability results with observed results of model reinforced soil walls. Richardson et al. (1977) pioneered small scale and full-scale shaking table tests on reinforced soil walls of metallic reinforcement. Sakaguchi (1996) carried out shaking table tests on a model of 1.5 high reinforced wall. The facing of the wall was constructed with lightweight blocks and five layers of geogrid reinforcement. Koseki et al. (1998) performed a series of shaking table tests on relatively small-scale models of geosynthetic reinforced soil retaining walls (GRS-RW) with full height rigid facing and conventional type (gravity, leaning and cantilever types) retaining walls. Ling et al. (2005) presented experimental study of the earthquake performance of modular block-reinforced soil retaining walls. Mandal (1987) presented information about the development and use of geotextiles in India. In spite of tremendous increase in construction of reinforced soil retaining walls in the last few years, the studies available on seismic vulnerability of these permanent important structures are limited. This paper studies some of the important behavioural aspects of reinforced soil retaining walls under dynamic conditions through shaking table tests.

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A computer controlled hydraulically driven single degree of freedom (horizontal) shake table with loading platform of 1 m × 1 m size and payload capacity of 1 ton is used in the experiments. Models of retaining walls have been constructed in a laminar box with geotextile reinforcement using the wrap around technique with dry sand backfill. The test wall is constructed to a size of 750 × 500 mm in plan and 600 mm deep. The model retaining wall is constructed in lifts, each lift being reinforced with a layer of geotextile and wrapped at the facing for a length of 10 cm. The model is instrumented with accelerometers and soil pressure sensors at different locations. Horizontal displacements of the facing are measured during shaking. The response of the reinforced retaining walls with the variation in acceleration and frequency of base shaking and surcharge loading has been monitored. In all the tests the height of the wall and the length of reinforcement are kept as 600 mm and 450 mm respectively.

Equipment and Materials Used in the Experiments

Shaking Table

A computer controlled servo hydraulic single degree of freedom (horizontal) shaking table facility has been used in simulating horizontal shaking action, associated with seismic and other vibration conditions. The table can test models weighing up to 1000 kg with a footprint of up to 1 m × 1 m. Shaking action is provided by a digitally controlled servo-hydraulic actuator with ±200 mm stroke and of 30 kN force rating. A dedicated control room housing the control system including a host computer is provided to facilitate testing under both constant amplitude as well as pseudo-random conditions. The shake table can be operated within the acceleration range of 0.05g to 2g and frequency range of 0.05 Hz to 50 Hz with the amplitude of ± 200 mm. Maximum velocities that can be allowed is 0.3 m/sec.

Laminar box

The major problems associated with laboratory model studies are scaling and the boundary effects, especially in studies related to earthquake engineering. This problem can be reduced to some extent by using a laminar box. A laminar box is a large sized shear box consisting of several frictionless horizontal layers. The laminar box used for the tests is rectangular in cross section with inside dimensions of 500 mm × 1000 mm and 800 mm deep with fifteen rectangular hollow aluminum layers, machined such that the friction between the layers is minimum. The gap between the successive layers is 2 mm and the bottom most layer is rigidly connected to the solid aluminum base plate of size 800mm × 1200 mm in plan and thickness of 15 mm. The layers are separated by linear roller bearings arranged to permit relative movement between the layers in the long direction with minimum friction. Figure 1 shows the laminar box mounted on the shake table.

Backfill Material

Locally available dry sand is used as the backfill material. Figure 2 shows the grain size distribution of the sand used in the tests. The sand is classified as poorly graded sand with letter symbol SP as per the Indian Soil Classification System (IS: 1498-1970). The sand has achieved the maximum dry unit weight of 18 kN/m^3 in vibration test and the minimum dry unit weight observed in loosest state is 15 kN/m^3. Other index properties are determined as per IS: 2720 (Part 14) – 1983 and are given in Table 1.

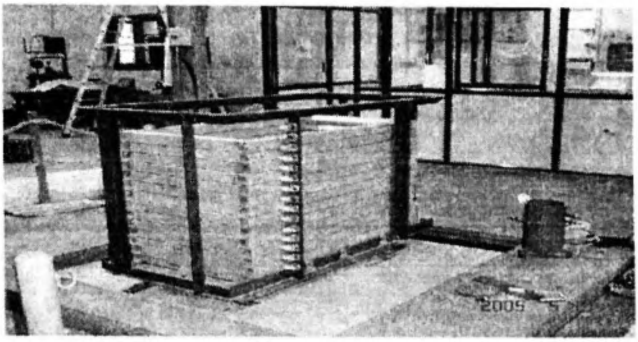

Fig. 1 Laminar Box Mounted on Shake Table

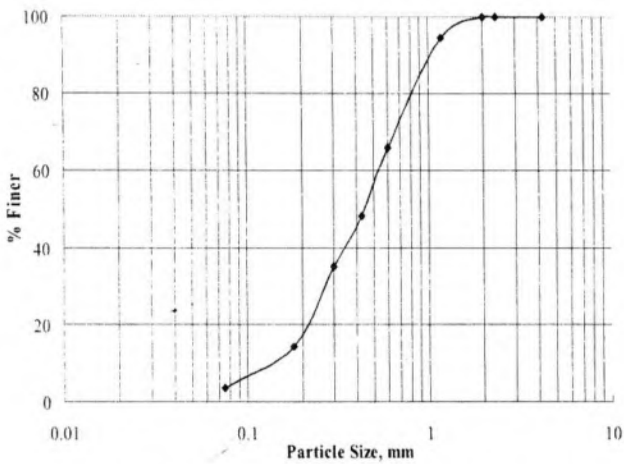

Fig. 2 Grain Size Distribution of the Test Sand

TABLE 1: Index Properties of the Test Sand

Specific Gravity	2.64
e_{max}	0.76
e_{min}	0.437
D-10, mm	0.145
D-30, mm	0.27
D-60, mm	0.53
Coefficient of curvature (C_c)	0.949
Uniformity coefficient (C_u)	3.65

Reinforcement

The material used for reinforcing the sand in the tests is woven geotextile. This is a polypropylene multifilament woven fabric. The individual multifilaments are woven together in such a manner as to provide dimensional stability relative to each other. The properties of geotextile are given in Table 2.

Tensile strength of the geotextile was determined by the wide-width strip method as per the ASTM D-4595 (2001) and it's value is equal to 55.16 kN/m. The results of the wide width tensile strength test conducted in warp direction are presented in Figure 3.

TABLE 2: Properties of Geotextile

Breaking strength	warp	55.5 kN/m
	weft	46.0 kN/m
Elongation at break	warp	38%
	weft	21.3%
Thickness		1 mm
Mass per unit area		230 gm/m^2

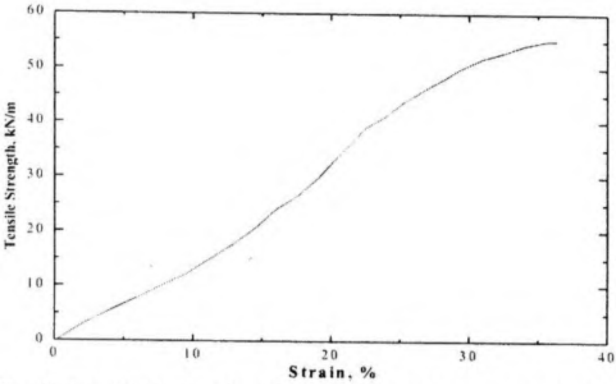

Fig. 3 Wide Width Tensile Strength Test Results for Geotextile

Instrumentation

The model is instrumented with accelerometers and soil pressure sensors at different locations within the retaining wall. Four accelerometers and three pressure sensors are used in each model tests. Accelerometers are of analog voltage output type with a full-scale acceleration range of ± 2g in both the X- and Y- axes, within the bandwidth of 1Hz - 2 kHz. Pressure sensors are of strain-gauge type with a measuring capacity of up to 100 kPa. Horizontal displacement of the facing is obtained using three LVDTs placed at different elevations.

Model Preparation and Testing Procedure

Model retaining walls are constructed in laminar box to a size of 750 mm × 500 mm in plan and 600 mm deep. The model is constructed in lifts of equal height while reinforcing each lift with a layer of woven geotextile. Each geotextile layer is wrapped at the facing for a length of 150 mm. To achieve uniform density, sand was placed in the laminar box using pluviation (raining) technique. The height of fall to achieve the desired relative density was determined by performing a series of trials with different heights of fall. However, the actual relative densities achieved in each test were monitored by collecting samples in small cups of known volume placed at different locations and levels during the model retaining wall preparation. The average unit weight and relative density achieved were within the range of 16 – 16.1 kN/m^3 and 34 – 37% respectively for the same height of fall. The retaining wall is constructed using wooden plank – formwork for each lift. After the completion of all lifts up to full height of the wall (600 mm), a nominal surcharge of 0.5 kPa (in the form of concrete slabs) is applied to give an anchorage to the wrapped textile at the top. After that, the supported formwork is carefully withdrawn lift wise sequentially from bottom to top. Model configuration along with layout of the instrumentation is shown in Figure 4. Accelerometers (A) and pressure sensors (P) were embedded in the soil while filling sand at different levels as shown in the figure. One accelerometer, A0, is fixed to the shake table to record the base acceleration and the other three accelerometers A1, A2 and A3 are placed at elevations 150, 300 and 600 mm respectively from the base at a constant distance of 10 cm from the facing. Three pressure sensors, P1, P2 and P3 are placed inside the wall, in contact with facing at elevations 80, 220 and 380 mm respectively from the base to observe horizontal pressures on the facing. To measure horizontal displacement, three LVDTs, L1, L2 and L3 are positioned at elevations 200, 350 and 500 mm respectively along the facing.

Testing program is devised to observe the dynamic response of reinforced soil retaining wall models with the variations in acceleration and frequency of the sinusoidal base shaking and surcharge loading in terms of acceleration and horizontal pressure response at different elevations and the displacement at facing. For the present study, all the models are constructed using sand in four lifts, each of 150 mm height to get total wall height (H) of 600 mm. Length of geotextile reinforcement at the interface of sand layers is kept as 450 mm. The parameters varied in model test are base acceleration, frequency and the surcharge pressure on the crest. Base acceleration was kept as 0.1g, 0.15g and 0.2g in different tests. Frequency is varied from 1 Hz to 3 Hz. The surcharge pressure on the retaining wall is kept nominal (0.5 kPa) in some tests, where as it is increased to 1 kPa and 2 kPa in other tests. The parameters varied in different model tests are given in Table 3.

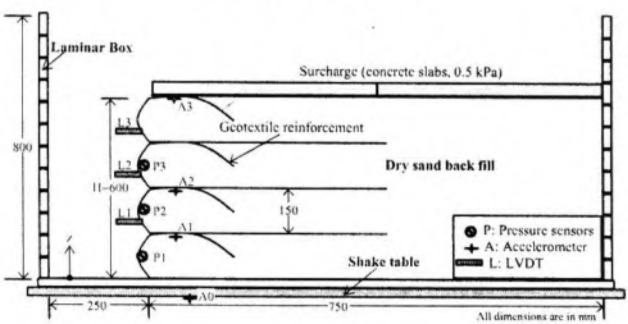

Fig. 4 Test Wall Configuration and Instrumentation

Results and Discussion

Acceleration – time histories of the model test T1 (with 0.5 kPa surcharge at 0.1 g base acceleration and 1 Hz frequency) at different elevations are shown in Figure 5. It is observed that the acceleration recorded by A3 (at 600 mm elevation) is on an average about 1.3 times of the base acceleration (A0), where as accelerations at other two locations (A1 and A2) are almost equal to the base acceleration. Figure 6 shows the acceleration time histories at different elevations for base acceleration of 0.2g with 2Hz frequency (T7 test). It is observed from this figure that the acceleration recorded at A3 is 1.7 times the base acceleration at A0. Accelerations at A1 and A2 are slightly amplified to about 1.07 and 1.15 times the base acceleration respectively.

TABLE 3: Test Parameters for Different Tests

Test No.	Base Acceleration, g	Frequency, Hz	Surcharge, kPa
T1	0.10	1	0.5
T2	0.10	1	1.0
T3	0.10	1	2.0
T4	0.10	2	0.5
T5	0.10	3	0.5
T6	0.15	2	0.5
T7	0.20	2	0.5

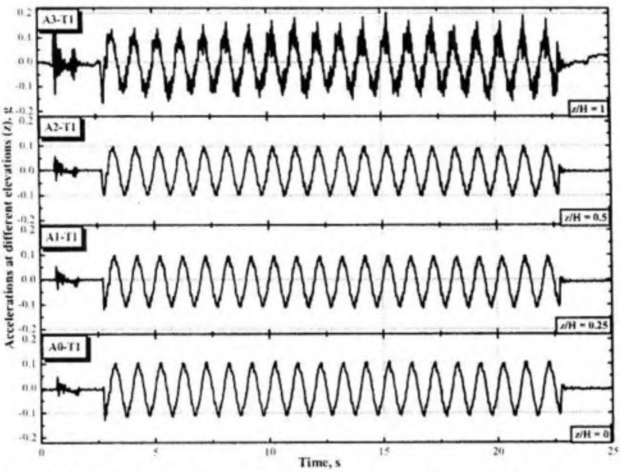

Fig. 5 Acceleration Histories at Different Elevations for Test T1

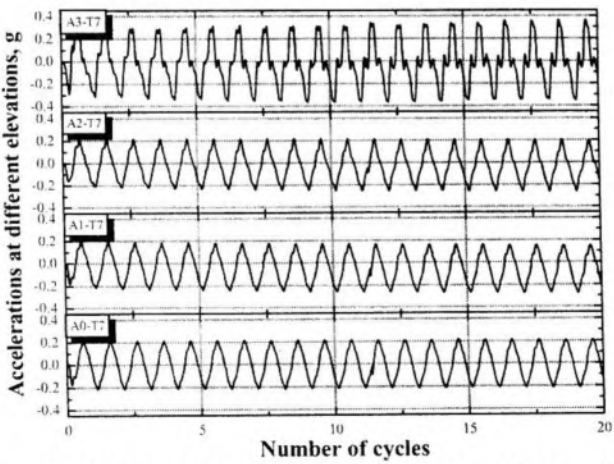

Fig. 6 Acceleration Histories at Different Elevations for Test T7

Acceleration response at A3 for tests with different surcharge pressures is compared in Figure 7 for model tests T1, T2 and T3 with 0.5, 1.0 and 1.5 kPa surcharge pressure respectively. Slight attenuation in acceleration with increase in surcharge is observed. Figure 8 shows accelerations histories at A3 for tests T1, T4 and T5, with 1, 2 and 3 Hz frequency respectively for the base acceleration of 0.1g, representing the frequency effect on dynamic response of model walls. Increase in the peak-to-peak acceleration values with the increase in frequency, for the same base acceleration, is observed from the figure.

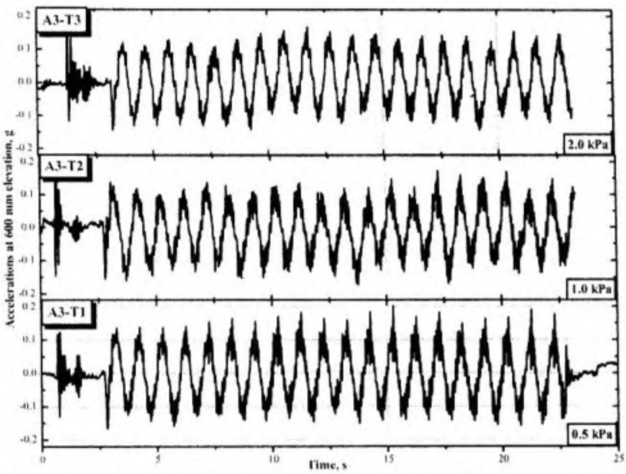

Fig 7 Accelerations at A3 for Different Surcharges (T1, T2 and T3 Tests)

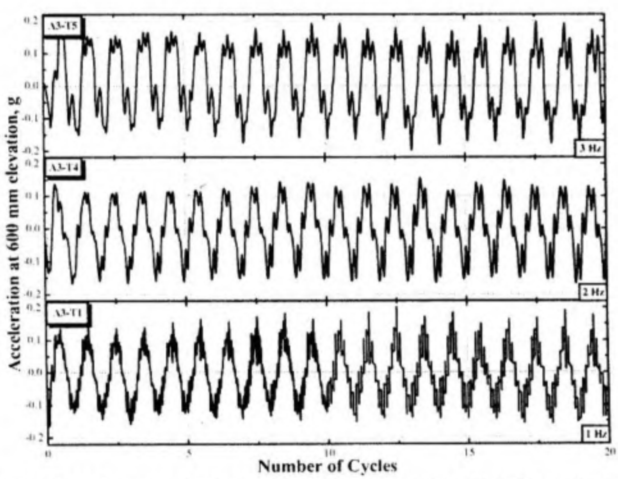

Fig. 8 Accelerations at A3 for Different Frequencies (T1, T4 and T5 tests)

Figure 9 shows the displacement variations at different elevations along wrapped facing of model retaining wall for test T1. A sudden rise in displacement in the first cycle and then gradual increase with number of cycles is observed. Figure 10 depicts the displacement profile for model tests T1, T2 and T3, after 20 cycles of base motion, providing an insight into the effect of different surcharge loadings. In this figure, displacements are presented in nondimensional form after normalizing the elevation (z), and horizontal displacement (δh), with total height of the wall (H). Displacements at all elevations decreased with the increase in surcharge pressure. Also, from the figure it can be observed that the maximum deformation of the wall is 3.6 mm ($\delta h/H = 0.6\%$) at a surcharge pressure of 0.5 kPa, whereas it is decreased to 1.6 mm ($\delta h/H = 0.27\%$) at a surcharge pressure of 2 kPa.

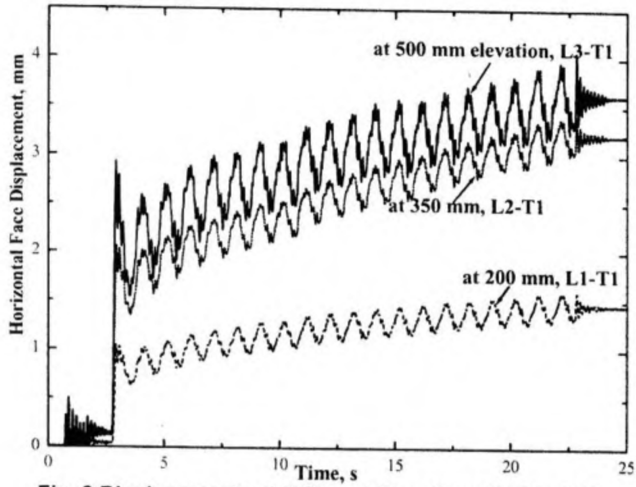

Fig. 9 Displacements at Different Elevations for Test T1

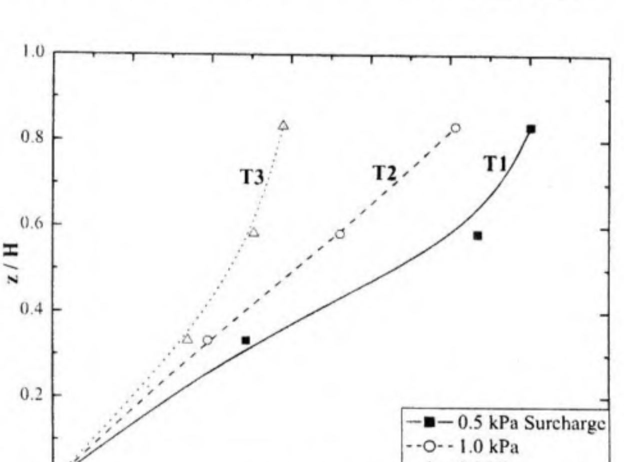

Fig. 10 Normalized Displacements after 20 Cycles for T1, T2 and T3 Tests

Variation of horizontal displacements at different elevations along the facing for the test T4 with increase in number of base shaking cycles is presented in Figure 11. It is observed form the figure that increase in displacement is stepping up with the elevation.

Figure 12 presents the variation of horizontal face displacements with number of cycles at 350 mm elevation (L2) for the tests T1, T4 and T5 with frequency of 1, 2 and 3 Hz respectively. Parallel trend of increase in displacement is observed for all the three frequencies. However, displacements along the facing decreased with increase in frequency. Figure 13 shows the normalized form of the displacement profile of facing after 20 cycles against different frequencies for tests T1, T4 and T5, depicting the diminishing trend of displacements with increase in frequency. Figure 14 shows the normalized form of the displacement profile of facing after 20 cycles against different base accelerations (Tests T4, T6 and T7). More flattening of the displacement profile was observed for higher base accelerations resulting in maximum horizontal displacement of 2.2 % of the total height of the wall, H, for 0.2 g as against 0.57 % for 0.1 g base acceleration.

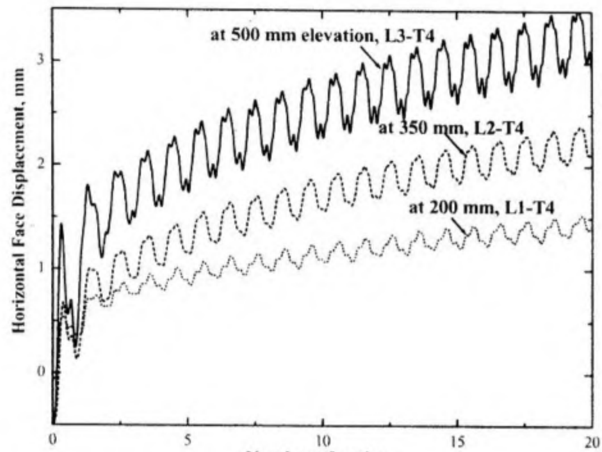

Fig. 11 Displacements at Different Elevations for Test T4

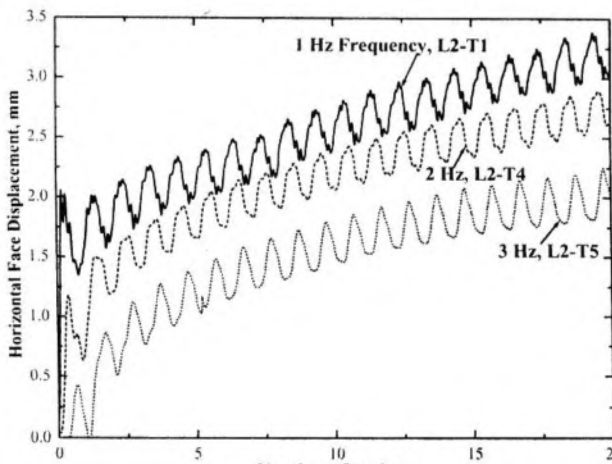

Fig. 12 Horizontal Displacements at L2 Location for Tests T1, T4 and T5

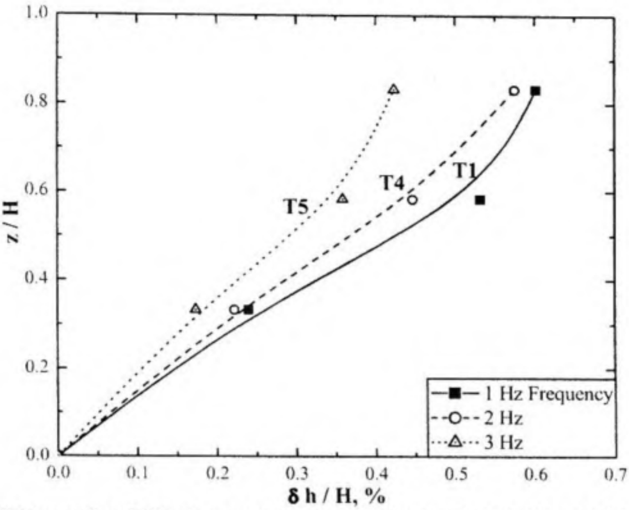

Fig. 13 Normalized Displacements after 20 Cycles for T1, T4 and T5 Tests

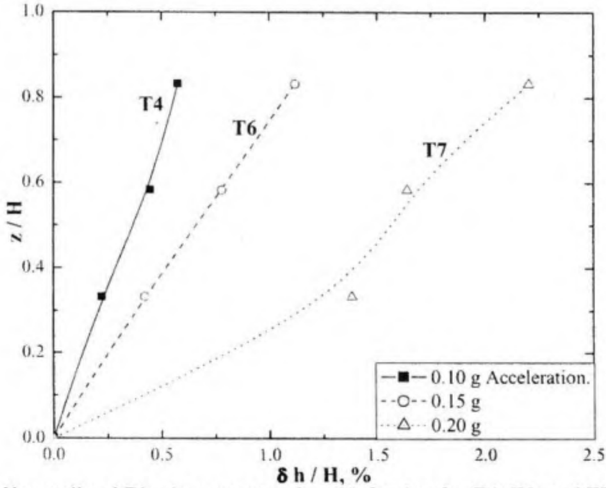

Fig. 14 Normalized Displacements after 20 Cycles for T4, T6 and T7 Tests

The time-histories of horizontal pressures, normalized with the corresponding initial pressures, on the facing at 80 mm elevation for T1, T4 and T5 tests are presented in Figure 15. At higher frequencies, the horizontal pressures recorded are higher at same location and sharp increase in horizontal pressures is observed as the shaking progressed. At lower frequencies, pressure variations with shaking are not significant. Variation of incremental horizontal pressure with increase in number of cycles at P1 and P3 locations for the test T4 is shown in Figure 16. Absolute incremental pressures and peak-to-peak change in incremental pressures are low at higher elevations, as expected. The effect of base acceleration on the incremental horizontal pressures near facing at P1 is shown in Figure 17. From the figure it can be observed that the peak-to-peak variation in the incremental pressure is increasing with the increase in base acceleration. Average peak-to-peak change in the pressure for 0.2g base acceleration is 0.65 kPa and for 0.1g base acceleration is 0.15 kPa, clearly indicating the relatively quick mounting up of incremental pressures in the model at higher base accelerations.

The results presented in this paper are based on the laboratory model tests with all limitations of small-scale tests. Hence the results cannot be directly extrapolated to the prototype reinforced earth walls. However they have thrown a sufficient insight on the relative performance of reinforced retaining walls subjected to base shaking, providing important information regarding the effects of frequency, acceleration and surcharge pressure with clear implications for design.

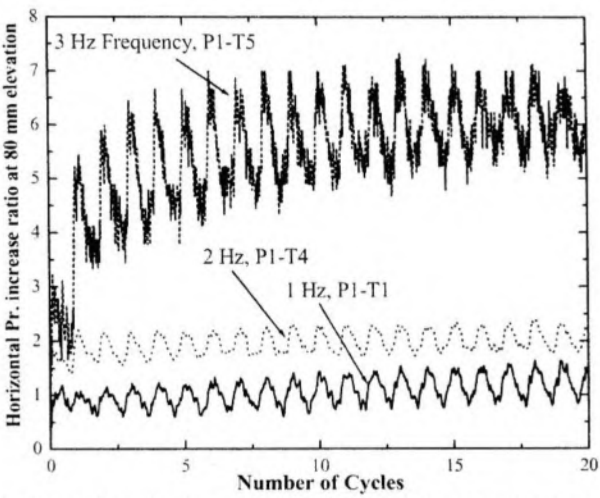

Fig. 15 Normalized Horizontal Pressures at P1 for T1, T4 and T5 Tests

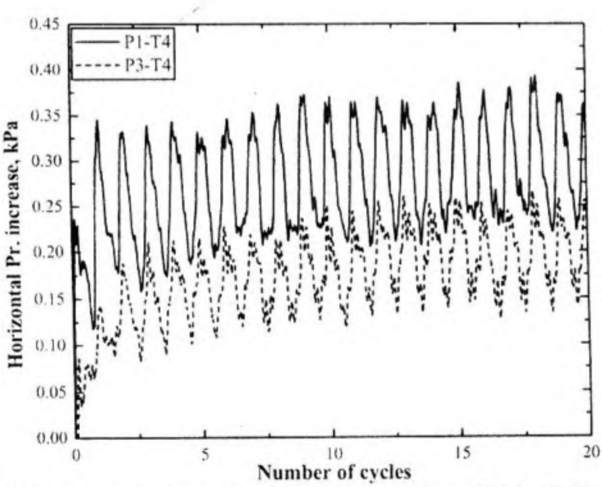

Fig 16 Incremental Horizontal Pressures at P1 and P3 for T4 Tests

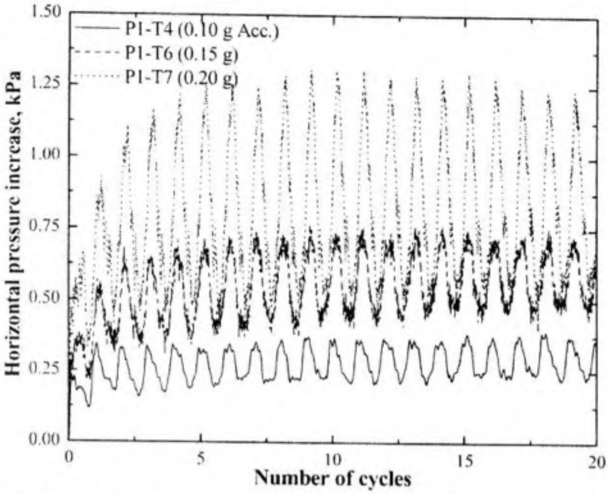

Fig. 17 Incremental Horizontal Pressures at P1 for T4, T6 and T7 Tests

Conclusions

Shaking table studies are carried out on wrap-faced reinforced soil retaining walls to gain insight into their behaviour under dynamic loads. Model retaining walls are tested with variations in the acceleration and frequency of base sinusoidal shaking and surcharge loading. It is observed that the response of wrap-faced geotextile reinforced model soil retaining walls is significantly affected by the changes in frequency, surcharge and acceleration of base shaking. Acceleration response gets attenuated with increase in surcharge pressure, the difference being more at higher elevations. Increase in surcharge loading or frequency of shaking results in decrease in deformations along the facing. Displacement profile for the facing of the retaining walls is observed to flatten for higher base accelerations. Horizontal pressures inside the retaining wall are sensitive to frequency of shaking as well as base accelerations. In spite of the limitations associated with small-scale tests, the results from this study provide useful guidelines regarding the relative performance of reinforced soil retaining walls under various test conditions with clear implications for design.

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