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ORIGINAL ARTICLE

Seismic Response of Soil Slopes in Shaking Table Tests: Effect of Type and Quantity of Reinforcement

N. Srilatha[1] · G. Madhavi Latha[2] · C. G. Puttappa[3]

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Abstract To study the effect of reinforcement type and quantity on the response of model slopes in this study, a series of shaking table tests were carried out on model slopes reinforced with different quantities of geotextile and geogrid. Model slopes were constructed to an angle of 45° using poorly graded sand. Acceleration of base shaking and shaking frequency were varied in different tests. The response of model soil slopes is compared in terms of the acceleration amplifications and horizontal displacements of the slope measured at different elevations. Results from these model tests revealed that the acceleration amplifications were slightly lesser in case of geogrid reinforced slopes because of higher interfacial friction of cohesionless soil with the geogrid. Acceleration amplifications were not affected by varying the quantity of reinforcement. However, horizontal displacements reduced drastically with the inclusion of reinforcement. Though the difference was not substantial, geotextile reinforced slopes were more effective in reducing the deformations compared to geogrid reinforced slopes. With the increase in the quantity of reinforcement, deformations decreased linearly, until reinforcement saturation occurred, beyond which the rate of decrease of deformations was less.

✉ G. Madhavi Latha
madhavi@civil.iisc.ernet.in

N. Srilatha
srilatha@civil.iisc.ernet.in

C. G. Puttappa
puttappacg@gmail.com

[1] Indian Institute of Science, Bangalore 560012, India

[2] Department of Civil Engineering, Indian Institute of Science, Bangalore 560012, India

[3] Department of Civil Engineering, MSRIT, Bangalore 560054, India

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Introduction

Response of reinforced soil slopes to seismic loading conditions is governed by the properties of soil, properties of reinforcement and geometry of the slope apart from the ground motion parameters of the seismic event. Studies specific to seismic response of reinforced soil slopes mainly focused on the investigation of failure mechanisms, understanding the effect of reinforcement parameters and ground motion parameters on the seismic stability of the slopes. Researchers used experimental, field investigation and numerical techniques to understand the response of reinforced soil slopes under seismic loading conditions. Physical modelling using reduced scale models is often preferred by the researchers because of several advantages like reasonably large size models, facility to embed instrumentation and ability to carry out tests under controlled conditions. Researchers have successfully used shaking table tests [1–4] and centrifuge tests [5, 6] to understand the influence of various parameters on the seismic performance of reinforced soil slopes or walls. The test results generally showed that the permanent displacements increased with increasing input motion amplitude and decreased with increasing reinforcement stiffness, density, and decreasing slope angle.

Through shaking table studies on 1:2 reduced scale models of geotextile-reinforced soil retaining walls of 1.9 m height subjected to E1 Centro earthquake and sinusoidal harmonic motion, Guler and Enunlu [7] demonstrated that geosynthetic reinforced retaining structures behave very successfully under earthquake loading conditions. Lin and Wang [8] performed large scale shaking table tests to study the dynamic response of sand slopes under earthquake conditions. It was observed that the response of the soil converted from linear to nonlinear at the acceleration amplitude of 0.5 g. The failure surface appeared to be fairly shallow and confined to the slope surface, which was consistent with the field observations of earthquake-induced landslides. Huang et al. [9] performed a series of full-scale shaking table tests on reinforced soil slopes subjected to stepwise intensified sinusoidal pulse loads with various frequencies and reported that accelerations and displacements of the slopes showed frequency dependent behaviour. Transition from the state of amplification towards the state of deamplification at the crest of the slope consistently preceded the critical collapse state of the slopes. Wang et al. [10] investigated the earthquake triggered failure modes, failure mechanisms and failure surfaces of slopes by means of field investigations, large scale shaking table tests and numerical analysis. Large scale shaking table tests could reproduce the process of deformation and failure of slopes in field. Tension cracks emerged at the top and upper part of the model, while the bottom of the model remained intact, which was consistent with the field observations. Through shaking table tests on model slopes with different combinations of reinforcement length, strength/stiffness and vertical spacing, Perez [11] showed that the failure surface gets flatter with the increase in quantity of reinforcement. Lo Grasso et al. [12, 13] carried out shaking table tests on geogrid reinforced soil slopes and demonstrated that reducing the spacing of reinforcement near the top of the slope is beneficial for the stability of slopes. Shaking table model tests carried out by Sugimoto et al. [14] on geogrid reinforced soil slopes with sand bag facing showed that the slopes undergo large ductile deformations without any distinct failure surface under sinusoidal as well as scaled earthquake shaking. Lin et al. [15] performed large scale shaking table tests on three reinforced embankment slope models with Wenchuan earthquake motions. These studies showed a decreasing trend in horizontal acceleration response with the increase in peak input horizontal acceleration. Huang et al. [16] applied sinusoidal waves and actual seismic waves measured from the Wenchuan earthquake to the slope models in shaking table tests under 37 different loading configurations. The location of sliding plane in the model was consistent with the location of the maximum horizontal acceleration. The present study is focused towards understanding the difference in the seismic response of soil slope with geotextile and geogrid reinforcement and to study the effect of reinforcement quantity on the performance under different ground shaking conditions.

Equipment and Materials Used in the Experiments

Shaking Table

A computer controlled servo hydraulic uniaxial (horizontal) shaking table facility has been used in simulating horizontal seismic action, associated with seismic or any other vibration conditions. The shaking table has a loading platform of 1 m $\times$ 1 m size and the payload capacity is 1 ton. The shaking table can be operated within the acceleration range of 0.05 g to 2 g and frequency range of 0.05 Hz to 50 Hz with the amplitude of $\pm$200 mm. The major problems associated with laboratory model studies are scaling and the boundary effects, especially in studies related to earthquake engineering. Models of soil slopes have been built in a laminar box to reduce the boundary effect to some extent. The laminar box used for the tests is rectangular in cross section with inside dimensions of 500 mm $\times$ 1000 mm and 800 mm deep with fifteen rectangular hollow aluminum layers. These layers are separated by linear roller bearings arranged to permit relative movement between the layers with minimum friction. Details of the shaking table setup and laminar box were presented by Srilatha et al. [17].

Soil

Locally available sand was used to prepare the model slopes. The soil was classified as poorly graded sand (SP) according to the Unified soil classification system. Particle size distribution curve of the test soil is shown in Fig. 1. Properties of the soil are listed in Table 1.

Reinforcement

A biaxial geogrid and a geotextile were used in the present study to reinforce the model soil slopes. Figure 2 shows the dimensional details of the geogrid used in experiments. The ultimate tensile strength of the geogrid was determined from standard multi-rib tension tests as per ASTM: D 6637. The ultimate tensile strength of the geotextile was determined from the wide-width tensile strength test conducted as per ASTM D-4595. Results of the tensile strength tests on the geosynthetics are given in Fig. 3. Properties of the geotextile and geogrid are listed in Table 2.

Instrumentation

Accelerometers and ultrosonic non-contact displacement transducers (USDT) were used to measure the response of the model slope during seismic shaking. Accelerometers are of analog voltage output type with a full-scale acceleration

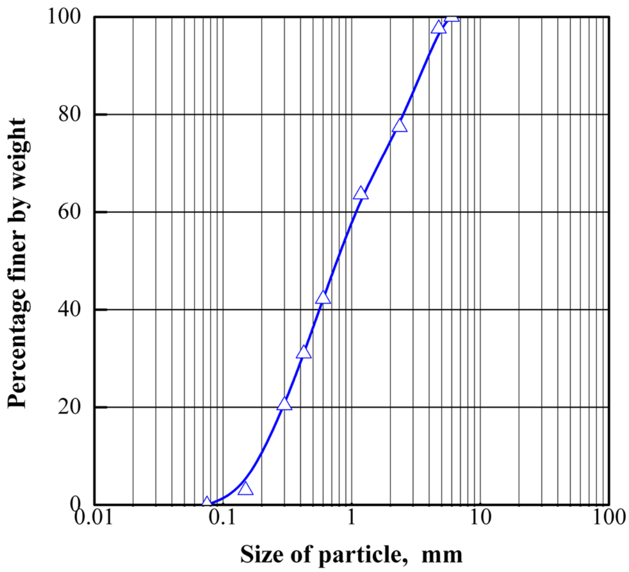

Fig. 1 Grain size distribution of the soil

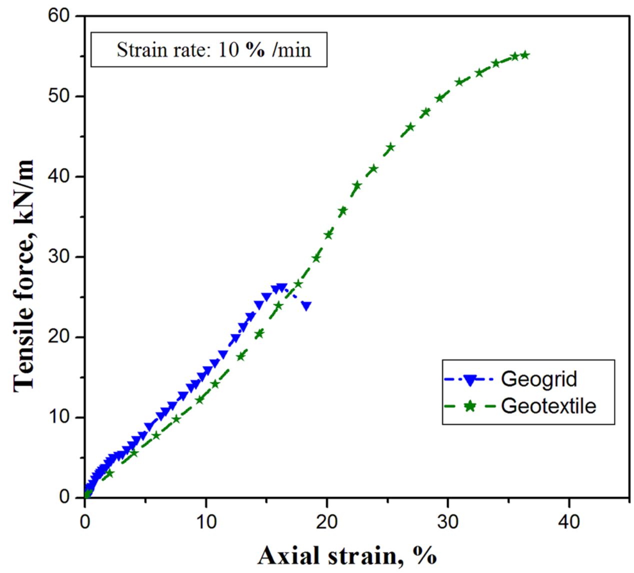

Fig. 3 Load-elongation response of geosynthetics from tension tests

Table 1 Properties of the soil

Parameter	Value
Specific gravity	2.65
Percentage of gravel-size fraction	2.5
Percentage of sand-size fraction	97
Percentage of (silt + clay) size fraction	0.5
D_{10}, mm	0.22
D_{30}, mm	0.425
D_{60}, mm	1.1
Coefficient of curvature (Cc)	0.74
Coefficient of uniformity (Cu)	5
Soil classification	Poorly graded sand (SP)

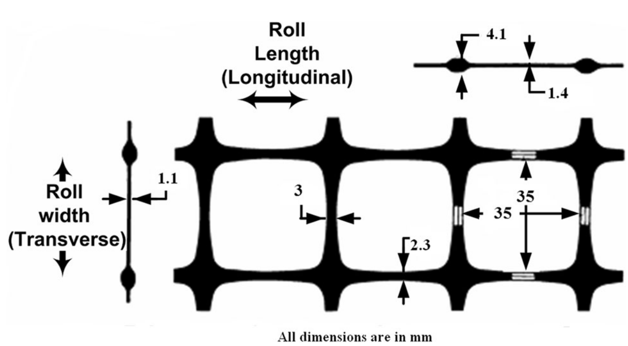

Fig. 2 Dimensional details of the geogrid

range of ±2 g along both the x and y axes, with sensitivity of 0.001 g and these accelerometers were connected to the shaking table controller through a junction box for data acquisition [17]. Non-contact type ultrasonic displacement transducers were used to measure the horizontal displacements at different elevations. These sensors work on ultrasonic energy multiple pulses, which travel through the air at the same speed of sound. The sensing range of these sensors is 30 to 300 mm with short dead zone of 30 mm and output response time is 30 ms.

Model Construction and Testing Methodology

To cover the gap between the each rectangular panel, polyethylene sheet was used inside of the laminar box and also to minimize the friction between the model and the laminar box. For compaction, a mass of 5 kg was dropped from a height of 450 mm on 150 mm × 150 mm square steel base plate with fixed guide rod at the centre of the base plate to achieve the desired unit weight for each layer. Three layered compaction was adopted for unreinforced and two layer reinforced slopes and four layered compaction was used for one layer and three layer reinforced slopes. Total number of blows used was 180 in all cases, 60 on each layer in case of three layered compaction and 45 on each layer in case of four layered compaction. This method ensured uniform unit weight of soil in all models, as verified from many trials. Schematic diagrams of typical reinforced single, two layer and three layer slopes with instrumentation are shown in Fig. 4. Construction sequence of typical geotextile reinforced soil slope is shown in Fig. 5. Reinforcement was placed at the interface of the compacted soil layers. Each model was constructed using poorly graded sand in three equal lifts, each of 200 mm, to get a total slope height (H) of 600 mm with a base width of 850 mm. The remaining space in the laminar box

Table 2 Properties of the geosynthetics

Parameter	Geogrid	Geotextile
Ultimate tensile strength (kN/m)	26	55.5
Yield point strain (%)	16.50	38
Aperture size (mm)	35 × 35	–
Aperture shape	square	–
Thickness (mm)	Variable (refer Fig. 2)	1
Secant modulus at 2 % strain (kN/m)	219	152
Secant modulus at 5 % strain (kN/m)	169	138
Mass per unit area (kg/m^2)	0.22	0.23

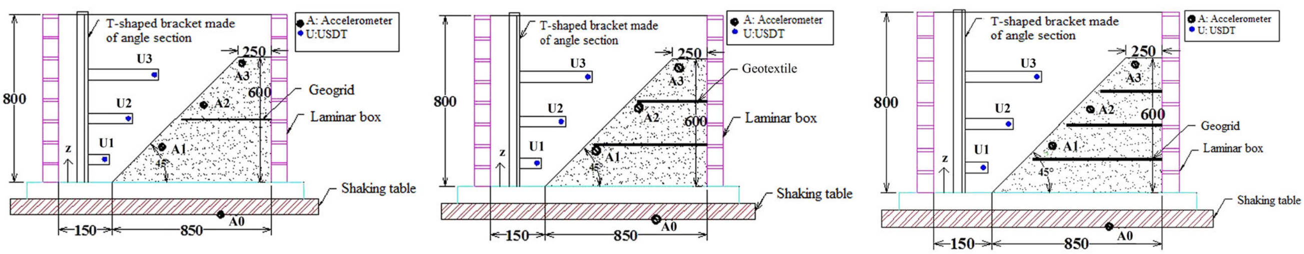

Fig. 4 Schematic diagrams of reinforced model soil slopes: **a** single layer, **b** two layers, **c** three layers

(150 mm × 500 mm in plan) was kept empty for mounting the displacement transducers and that space was packed with concrete cubes enclosed in plywood panels during compaction. The unit weight and water content of the model slopes were in the range of 17–17.1 kN/m^3 and 10–10.1 % respectively in all these model tests. The geogrid and geotextile reinforcement was provided at the interface of the compacted layers and was kept at a distance of 50 mm from the face of the slope to the full width of the slope for all the reinforced model slopes. Then the slope of required angle is marked and the compacted soil was trimmed to the required slope geometry using a trowel. After finishing the model preparation the plywood and concrete cubes were removed one by one. During the

Fig. 5 Sequence of model slope construction: **a** marking slope geometry, **b** soil compaction in layers, **c** placing reinforcement between layers, **d** finished model slope

process of compaction the accelerometers, A1, A2 and A3 were embedded in soil at elevations 170, 370 and 570 mm from the base of the slope, where one accelerometer, A0, was fixed rigidly to the bottom of the shaking table to measure base acceleration. Three displacement transducers, U1, U2 and U3 were positioned along the face of the slope at elevations 200, 350 and 500 mm from the base of the slope to measure the horizontal face displacements. The transducers are fitted in wooden planks which were bolted horizontally to the T-shape steel bracket which is in turn fitted to the steel frame. The response of the slope was recorded in terms of acceleration at different elevations and the displacement of the facing.

Shaking table tests in this study are 1-g model studies carried out on reduced scale models. The stresses and deformations measured in the experiments do not truly represent the stresses and deformations in field because of low confining pressures and boundary effects in model studies. Hence it is essential to apply proper similitude rules for the experiments in order to apply the results to actual field conditions. Many shaking table model studies on slopes in literature have used much smaller slope models in experiments. For example, Lo Grasso et al. [12] and Lin and Wang [8] used slopes of 0.5 m height and Huang et al. [9] used model slopes of 0.48 m height. Though scale effects cannot be completely eliminated in 1-g model studies, similitude laws to correlate the model and prototype scaling and response are effectively used by several researchers. In the present study, similitude relations derived by Iai [18] and later used by Meymand [19] and Lin and Wang [8] were used. A geometric scale factor, λ_L, was defined as the proportionality constant between the model and prototype. The geometric scaling factor λ_L used in the present study is 10. The slope height of 0.6 m used in the study in order to simulate a 6 m high prototype slope in the field. Accordingly the scaling parameters between prototype and model slope were derived are listed in Table 3. Scaling of reinforcement tensile strength is not attempted in this study. Hence the geogrid used in the study simulate very strong prototype geogrid.

Sixteen different shaking table tests on unreinforced and reinforced soil slope models were performed in this study. These tests are devised to understand the effect of reinforcement parameters on acceleration, frequency of base shaking and reinforcement on the response of the slope during seismic excitation. The test parameters varied in different tests are given in Table 4. The base acceleration was varied from 0.1 to 0.3 g and frequency was varied from 1 to 7 Hz in different tests. Test code for each test gives the reinforcement type, number of reinforcing layers, base acceleration and shaking frequency in sequence. Unreinforced, geogrid reinforced and geotextile reinforced model tests are represented with letter symbols U, G and T respectively. In case of tests on geotextile reinforced models, the number of geotextile layers used in the model follows the letter T. Base accelerations used were 0.1, 0.2 and 0.3 g in different tests, which are represented as A1, A2 and A3 respectively. Various shaking frequencies used in the tests were 1, 2, 5 and 7 Hz, which were represented by F1, F2, F5 and F7 respectively in the test code. For example, T3A3F2 represents the model test, where the slope is reinforced with 3 layers of geotextile, subjected to base shaking at an acceleration of 0.3 g and frequency of 2 Hz. The resonant frequencies of the slopes change significantly with the height of the slope.

Resonant frequency of the unreinforced model slope was calculated from its shear wave velocity by using the following equation given by Hardin and Richart [20].

$$V_S = (13.788 - (6.488 \times e)) \times (\sigma_o')^{\frac{1}{4}} \quad (1)$$

where V_S is the shear wave velocity of the model in m/s, e is the void ratio of soil in model slope and σ_o' is the mean effective confining pressure in Pa. The void ratio of the compacted model slope was 0.68 and the mean effective confining stress at the bottom of the model slope was 10.2 kPa. Shear wave velocity of the model was calculated as 94 m/s as per Eq. (1). Kramer [21] gave an expression to calculate the natural frequency of the model from its shear wave velocity.

$$f_n = \frac{V_S}{4H} \quad (2)$$

where f_n is the natural frequency of the compacted model slope in Hz and H is the depth of compacted model slope in meters. According to Eq. (2), the natural frequency of the compacted model slope of height 600 mm and shear wave velocity of 94 m/s is calculated as 40 Hz. The frequency range used in the present study is much less than the natural frequency and hence the models are not subjected to resonance. Each model slope is subjected to 40 cycles of base shaking with the corresponding frequency.

Effect of Reinforcement Type on the Response of Model Slopes

Response at Base Shaking of 0.3 g and 2 Hz

Response of geotextile and geogrid reinforced soil slopes constructed with single, two and three layers of reinforcement and subjected to the same base shaking of 0.3 g acceleration and 2 Hz frequency for 40 cycles is compared. To simplify the presentation of acceleration response at different elevations of the slope, Root mean square acceleration amplification factor (RMSA) is used. RMSA amplification factor is the ratio of response acceleration

Table 3 Law of similitude of the prototype and model [18]

Parameter	Model parameter	Equation for scaling factor = (prototype/model)	Scaling factor	Prototype parameter
Acceleration (g)	0.1, 0.2, 0.3	1	1	0.1, 0.2, 0.3
Dimensions of the slope (L × B × H) m	0.85 × 0.5 × 0.6	λ_L	10	8.5 × 5 × 6
Unit weight of soil (kN/m^3)	17	1	1	17
Frequency (Hz)	2	$1/(\lambda_L)^{3/4}$	0.17	0.35
Stress	σ_m	λ_L	10	$10 \times \sigma_m$
Time	t_m	$\lambda_L^{3/4}$	5.62	$5.62 \times t_m$
Displacement (m)	d_m	λ_L	10	$10 \times d_m$
Length of reinforcement (m)	L_R	λ_L	10	$10 \times L_R$

Table 4 Test parameters varied in the present study

S. no.	Test code	Type of reinforcement	No. of reinforcing layers	Acceleration (g)	Frequency (Hz)
1	UA3F1	None	None	0.3	1
2	UA3F2	None	None	0.3	2
3	UA3F5	None	None	0.3	5
4	UA3F7	None	None	0.3	7
5	G1A3F2	Geogrid	1	0.3	2
6	G2A3F2	Geogrid	2	0.3	2
7	G3A3F2	Geogrid	3	0.3	2
8	T1A3F2	Geotextile	1	0.3	2
9	T2A3F2	Geotextile	2	0.3	2
10	T3A3F2	Geotextile	3	0.3	2
11	T3A3F5	Geotextile	3	0.3	5
12	G3A3F7	Geogrid	3	0.3	7
13	T3A3F7	Geotextile	3	0.3	7
14	T3A3F1	Geotextile	3	0.3	1
15	T3A1F2	Geotextile	3	0.1	2
16	T3A2F2	Geotextile	3	0.2	2

value in the soil to that of corresponding value of the base motion [21]. Acceleration amplification is observed to be the most at the top of the slope in all the tests.

Figure 6 presents the effect of reinforcement type on acceleration response of soil slopes subjected to base shaking of 0.3 g acceleration and 2 Hz frequency. The elevation is normalized with respect to the height of the slope in all the plots. Comparison of RMSA amplification factors with elevation for single, two and three layer reinforced slopes with different types of reinforcement are shown in Fig. 6a, b and c respectively. Acceleration amplification factors were close to unity at all the elevations along the height of the slopes, indicating that the reinforcement type has no effect on the acceleration amplifications at the specific base shaking conditions. The computed maximum RMSA amplification factor at a normalized height of 0.95 for unreinforced model slope was 1.074, whereas it was 1.046 for single layer geogrid reinforced slope and 1.064 for single layer geotextile reinforced slope. For two layer and three layer reinforced slopes, geogrid reinforcement has slightly reduced the acceleration amplifications at higher elevations, whereas the response of geotextile reinforced slopes was closely matching with the response of unreinforced slope. At lower elevations of the slope, there was no effect of reinforcement on the acceleration amplifications. Slight reduction in acceleration amplifications was observed in case of geogrid reinforced soil slopes. However, the difference in behaviour is not significant and hence it is evident from the model test results that the type of reinforcement has no significant influence on the acceleration response of the slopes at low frequencies.

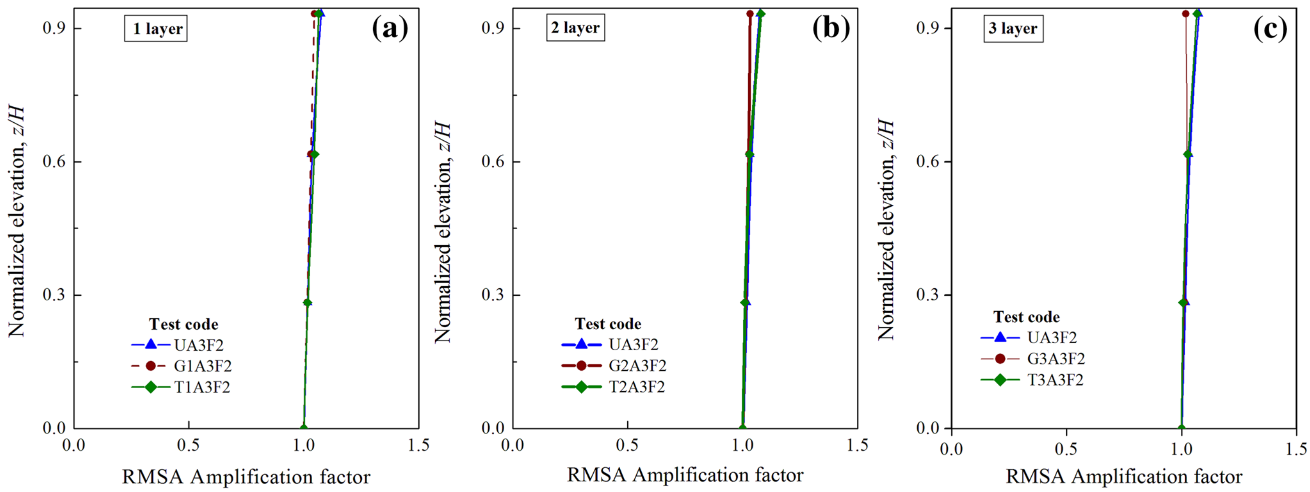

Fig. 6 Effect of reinforcement type on acceleration response of soil slopes at a base shaking of 0.3 g and 2 Hz: **a** single layer reinforcement, **b** two layer reinforcement, **c** three layer reinforcement

Figure 7 presents the effect of reinforcement type on the horizontal displacement response of soil slopes subjected to base shaking of 0.3 g acceleration and 2 Hz. Comparison of horizontal displacements with elevation for single, two and three layer reinforced slopes with different types of reinforcement are shown in Fig. 7a, b and c respectively. The measured horizontal displacement at a normalized height of 0.84 was 146.35 mm for unreinforced model slope and it reduced to 88.81 mm with a single layer geogrid reinforcement and 71.33 mm with a single layer geotextile reinforcement, as shown in Fig. 7a. Similar behaviour was observed in case of two and three layers of reinforcement, as shown in Fig. 7b and c. For a three layer reinforced slope, maximum displacement was 16.33 and 11.65 mm with geogrid and geotextile reinforcement respectively. Geotextile reinforcement was proved to be better than the geogrid reinforcement in reducing deformations for this case. Several earlier researchers demonstrated the decrease in deformations of reinforced soil structures with the increase in reinforcement stiffness [22].

Tensile strength of the geotextile used in this study was 55.5 kN/m and that of the geogrid was 26 kN/m. However, tensile stiffness of geotextile and geogrid are almost the same at low strain levels, which represent the model test conditions. The reason for better displacement control with geotextile reinforcement is better mobilization of friction at the interface due to large area of contact between fine sand and geotextile compared to geogrid. Figure 8 shows the photographs of model slope of soil before shaking (Fig. 8a), unreinforced soil slope after shaking (Fig. 8b), two layer geogrid soil slope (Fig. 8c) and two layer geotextile soil slope (Fig. 8d), respectively subjected to a base shaking frequency of 2 Hz at the end of 40 cycles of base motion. As observed from the figures, unreinforced slope

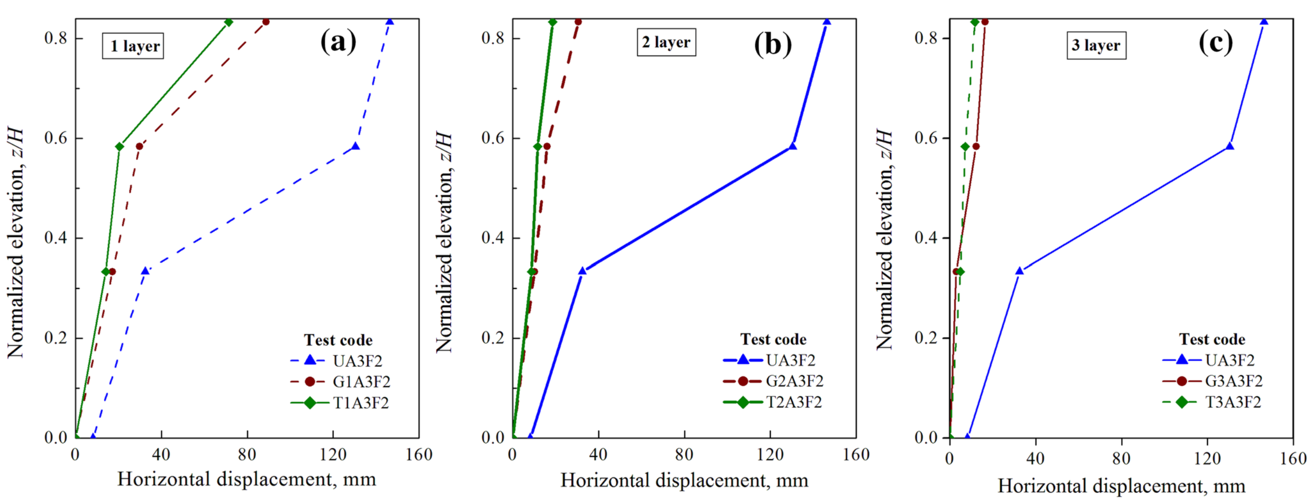

Fig. 7 Effect of reinforcement type on displacement response of soil slopes at a base shaking of 0.3 g and 2 Hz: **a** single layer reinforcement, **b** two layer reinforcement, **c** three layer reinforcement

(Fig. 8b) has shown extensive cracking at the end of the test. Reinforced soil slopes has not shown any cracks during and at the end of the tests, showing high benefit of reinforcement by the inclusion of two layer geogrid and geotextile reinforcement (Fig. 8c, d).

Response at Different Frequencies

To study the effect of reinforcement type on acceleration and horizontal displacement response of reinforced soil slopes subjected to different frequencies, model soil slopes reinforced with three layers of geogrid/geotextile were tested at 0.3 g base acceleration and different frequencies. Geogrid reinforced model slopes were tested at frequencies of 2, 5 and 7 Hz, while geotextile reinforced model slopes were tested at 1, 2, 5 and 7 Hz frequencies. Figure 9 presents the effect of reinforcement type on acceleration response of soil slopes subjected to two different frequencies 2 and 7 Hz. When the three layer reinforced slope was subjected to base shaking of 2 Hz, a slight deamplification was observed at higher elevations. At frequency of 7 Hz, accelerations were amplified considerably for both the types of reinforcement. Compared to unreinforced soil slope, amplifications were less in reinforced slopes, the effect is more prominent at higher frequencies. Horizontal displacement response of these slopes at two different frequencies is plotted in Fig. 10, which shows that both geogrid and geotextile were equally effective in reducing deformations to a large extent.

Figure 11 presents the summary of effect of reinforcement type on the acceleration and displacement response of model slopes subjected to base shaking of different frequencies. Geogrid reinforced slope displayed lesser accelerations compared to geotextile reinforced slope, especially at higher frequencies because of higher interfacial friction, as shown in Fig. 9a. Difference in displacement behaviour of slopes with different types of reinforcement is not substantial at all the frequencies (Fig. 10).

Response at Different Accelerations

The model slopes were subjected to different base accelerations with shaking frequency of 2 Hz. Since the geotextile reinforcement was performed well in reducing displacements from the earlier study, to understand the effect of reinforcement at different base accelerations, tests were carried out on model slopes reinforced with geotextile subjected to 0.1, 0.2 and 0.3 g base accelerations at 2 Hz shaking frequency. Acceleration and horizontal displacement response from these model tests are presented in Figs. 12 and 13 respectively along with results from unreinforced model tests subjected to similar ground motion. Figure 12 clearly shows that the geotextile reinforcement does not have significant influence on the acceleration amplifications at all three base accelerations investigated. The measured horizontal displacement at a normalized height of 0.84 was 3.34, 4.66 and 146.35 mm at 0.1, 0.2 and 0.3 g accelerations, whereas the corresponding

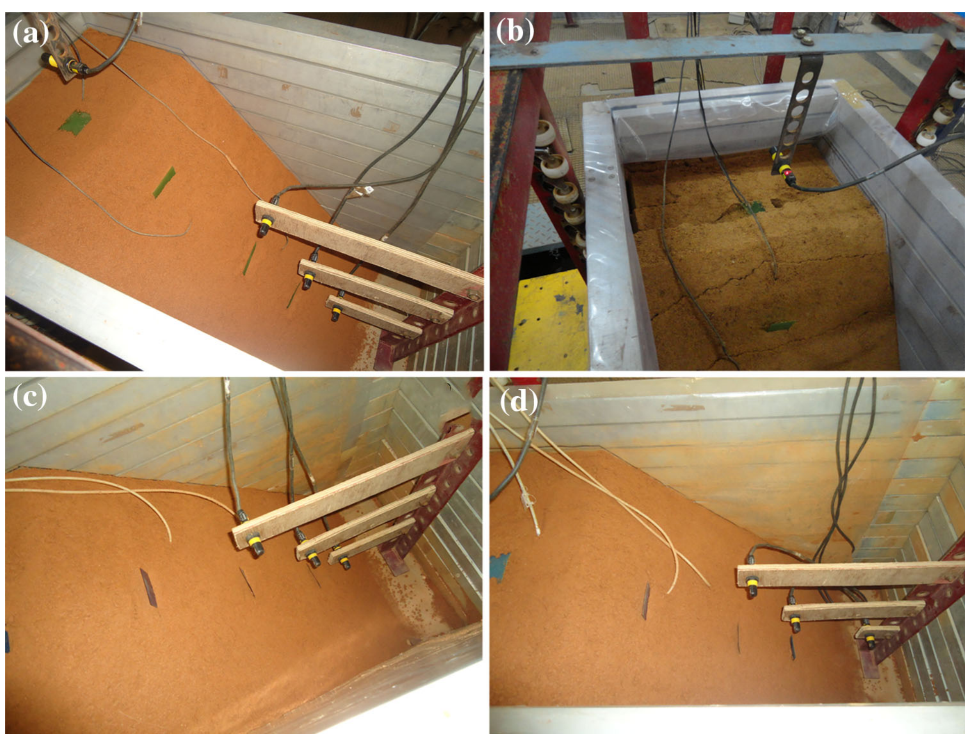

Fig. 8 Photographs of the model slopes: **a** slope before the test, **b** unreinforced slope after the test at a frequency of 2 Hz, **c** Geogrid reinforced slope after the test at a frequency of 2 Hz, **d** geotextile reinforced slope after the test at a frequency of 2 Hz

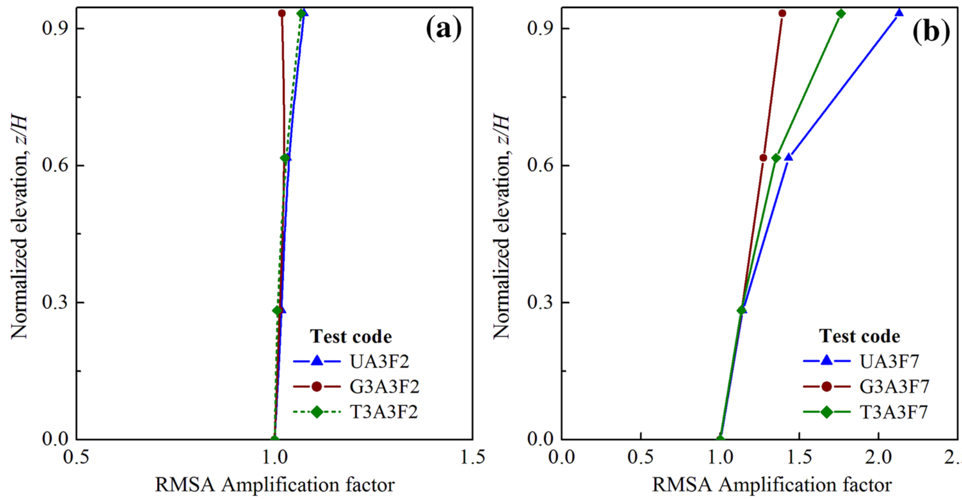

Fig. 9 Effect of type of reinforcement on acceleration response of soil slopes at different frequencies: **a** 2 Hz frequency, **b** 7 Hz frequency

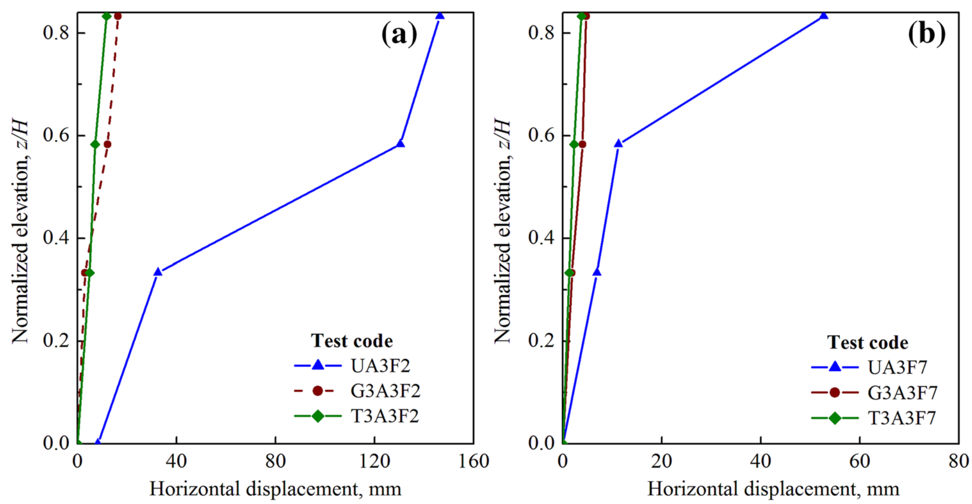

Fig. 10 Effect of type of reinforcement on displacement response of soil slopes at different frequencies: **a** 2 Hz frequency, **b** 7 Hz frequency

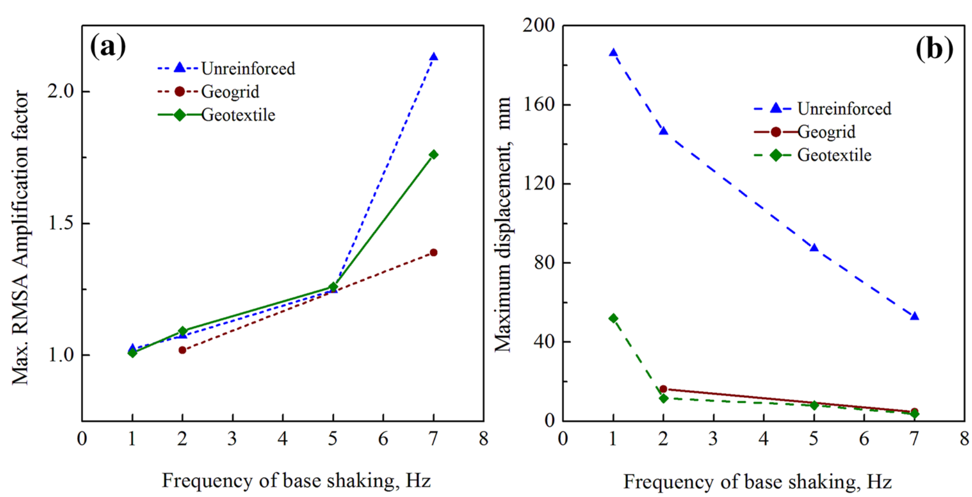

Fig. 11 Effect of reinforcement type on the response of model slopes at different frequencies: **a** maximum RMSA amplification factors, **b** maximum horizontal displacements

displacement in case of 3 layer geotextile reinforced slope reduced to 1.03, 3.01 and 11.65 mm respectively. The catastrophic flowslide type of failure occurring in case of unreinforced soil slope at 0.3 g acceleration and 2 Hz frequency (Fig. 8b) was arrested when the slope was reinforced with 3 layers of geotextile and the deformations were reduced by about 92 % for that case. The efficiency of geosynthetics on the prevention of slope instabilities and

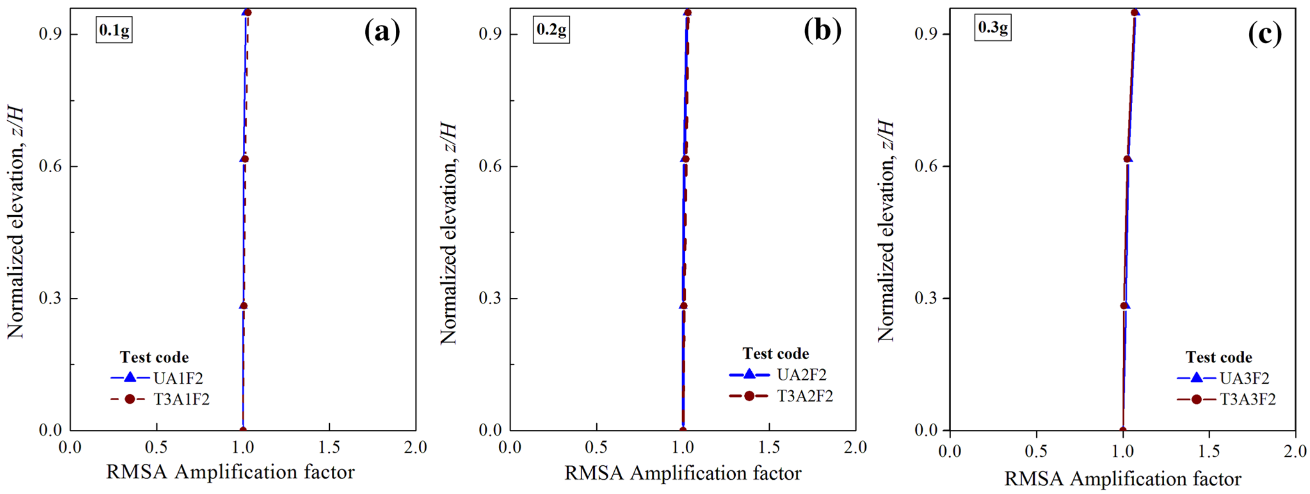

Fig. 12 Acceleration response of unreinforced and 3 layer geotextile reinforced model slopes at different accelerations of shaking: **a** 0.1 g, **b** 0.2 g, **c** 0.3 g

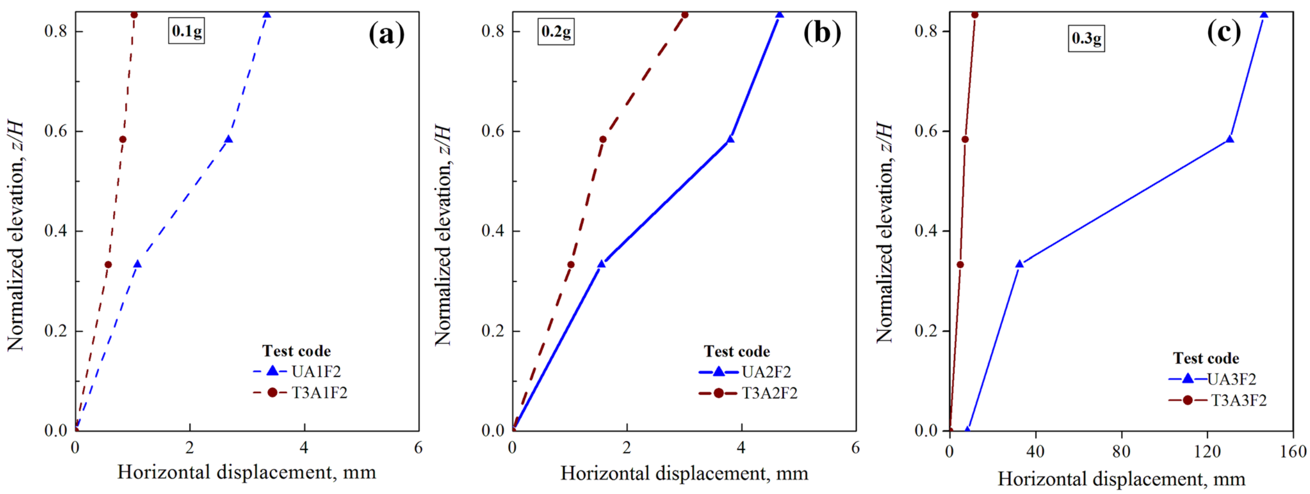

Fig. 13 Displacement response of unreinforced and 3 layer geotextile reinforced model slopes at different accelerations of shaking: **a** 0.1 g, **b** 0.2 g, **c** 0.3 g

the reduction of the anticipated stress levels on the geostructures was highlighted by Tsompanakis [23].

Figure 14 presents the maximum acceleration amplification factors and horizontal displacements of unreinforced and 3 layer geotextile reinforced soil slopes with variation in base shaking acceleration. Reinforcement was effective in reducing horizontal deformations at all accelerations, the benefit being substantial at higher accelerations.

Effect of Quantity of Reinforcement

Effect of quantity of reinforcement on the seismic response of soil slopes was investigated through model tests on soil slopes reinforced with single, two and three layers of geogrid/geotextile. Figure 15 presents the effect of quantity of reinforcement on the acceleration amplification response of both geogrid and geotextile reinforced slopes along with the unreinforced slope subjected to a base shaking of 0.3 g acceleration and 2 Hz frequency. As seen from Fig. 15, acceleration amplifications were not influenced significantly with the inclusion of reinforcement.

Figure 16 shows the effect of quantity of reinforcement on horizontal displacement response of geogrid and geotextile reinforced model slopes along with the response of unreinforced slope. It can be observed that displacements decreased with the increase in the reinforcement quantity. Figure 17 presents the effect of quantity of reinforcement on the response of both geogrid and geotextile slopes subjected to base shaking of 0.3 g acceleration and 2 Hz frequency. The quantity of reinforcement is represented by normalized vertical spacing (S_v/H) in this plot, S_v

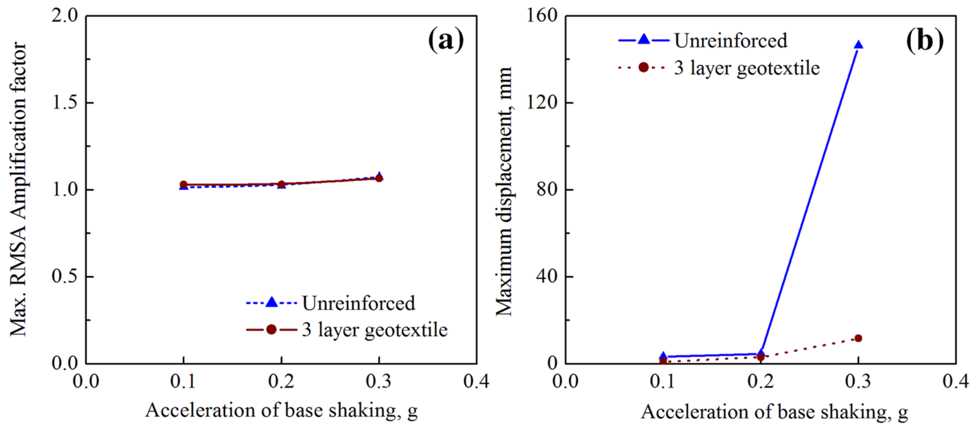

Fig. 14 Response of unreinforced and 3 layer geotextile reinforced soil slopes with change in acceleration of base shaking: **a** maximum RMSA amplification factors, **b** maximum horizontal displacements

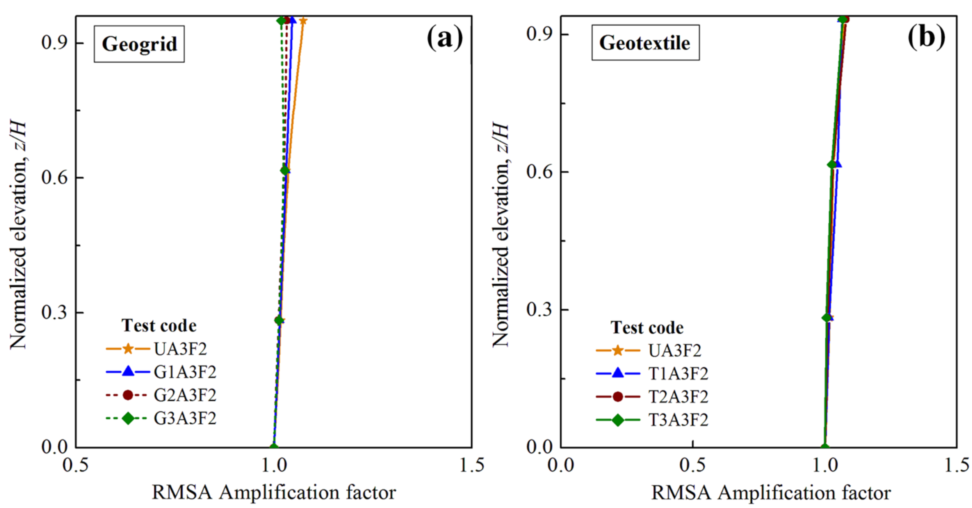

Fig. 15 Effect of quantity of reinforcement on acceleration response of soil slopes: **a** geogrid reinforced slope, **b** geotextile reinforced slope

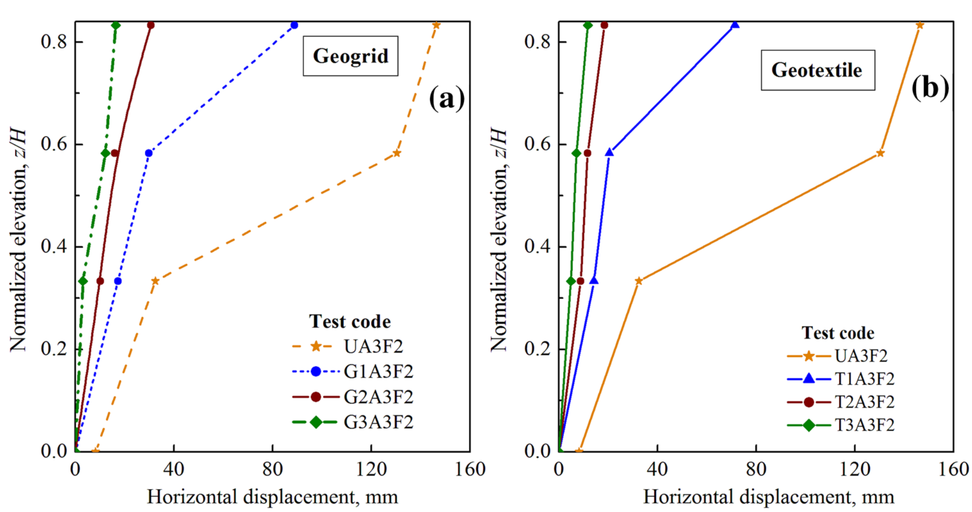

Fig. 16 Effect of quantity of reinforcement on displacement response of soil slopes: **a** geogrid reinforced slope, **b** geotextile reinforced slope

representing the vertical spacing between the reinforcing layers. As observed from figure, quantity of reinforcement does not have considerable influence on the acceleration amplifications. With the increase in number of reinforcing layers or decrease in normalized vertical spacing of reinforcement layers, slight reduction in amplification factors is observed. The acceleration amplification factors are between 1.0 and 1.5, similar to the amplification factors reported by El-Emam and Bathurst [22] for model walls of 1 m height tested at 0.3 g acceleration. Drastic reduction in

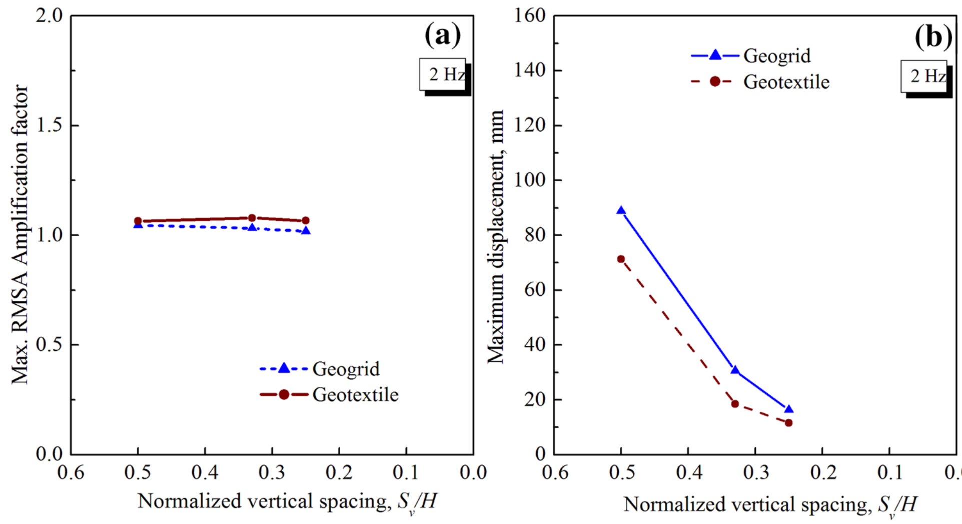

Fig. 17 Effect of spacing of reinforcement on the response of reinforced soil slopes: **a** maximum RMSA amplification factors, **b** maximum horizontal displacements

horizontal displacements with the increase in the quantity of reinforcement was observed for both geogrid and geotextile reinforced soil slopes. The reduction in displacement was substantial with the inclusion of single and two layers of reinforcement, showing linear decrease in deformations with the increase in the number of reinforcing layers and further increase in the quantity of reinforcement could reduce the deformations only to a certain extent, indicating reinforcement saturation. The reduction in lateral deformations with 50 % reduction in vertical spacing (which means doubling the number of reinforcing layers) is about 67 % in case of geogrid and 74 % in case of geotextile. Sakaguchi et al. [24] reported a 40 % reduction and Bathurst and Hatami [25] reported a 32 % reduction in lateral displacements of reinforced vertical walls tested at 0.3 g acceleration with doubling up the number of reinforcement layers. The reductions in lateral deformations observed in the present study for 45° model slopes are much higher than these values.

It should be noted that the present study uses only one type of poorly graded sand and the results may not be equally applicable to other types of soils. Also, extrapolation of results from model tests to the field slopes using similitude laws has certain limitations because of boundary effects in model studies and the difficulties in scaling reinforcement properties.

Conclusions

The following major conclusions are drawn from this study.

- Inclusion of reinforcement did not have significant influence on the acceleration amplifications, but the displacements were drastically reduced by reinforcing the slopes.
- Geotextile reinforcement was slightly better in decreasing the horizontal deformations, though the tensile stiffness of both these materials is almost same, because of better mobilization of friction at the interface in case of geotextile due to its large area of contact.
- The catastrophic flowslide type of failure occurring in case of unreinforced soil slope at 0.3 g acceleration and 2 Hz frequency was arrested when the slope was reinforced even with a single layer of geotextile or geogrid, indicating the importance of soil reinforcement in mitigating seismic hazards.
- Reinforcement was effective in reducing lateral deformations at all accelerations, the benefit being substantial at higher accelerations.
- Acceleration amplifications were not significantly affected by the quantity of reinforcement.
- Rate of decrease in deformations with increase in the quantity of reinforcement was drastic up to certain extend (2 layers in this study) and further increase in the quantity of reinforcement could reduce the deformations only to a certain extent, indicating reinforcement saturation.

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