Investigation of seismic performance of geotextile reinforced embankments by shake table tests and numerical modelling

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ABSTRACT: Highways are one of the main lifelines that should be in continuous operation during and after natural disasters. Geosynthetic reinforcement can successfully mitigate the earthquake hazards on highway embankments. It is one of the most superior reinforcement techniques due to their unique characteristics. This study represents the numerical simulation of the shake table tests on the seismic behavior of the geotextile-reinforced embankment. Scaled shake table tests of unreinforced and geotextile reinforced highway embankment models, which had been modeled with respect to the prototype, have been subjected to a scaled real earthquake record in laboratory conditions. Dynamic performance analyses have been performed with the finite element modeling technique using the PLAXIS 2D software. Numerical results were compared with the experimental results prior to the evaluation of the results according to the selected performance criteria. Comparison of the shake table tests with the numerical studies has an important role on the estimation of the seismic behavior of the engineering structures. The aim of this paper is to verify the results obtained from numerical results to that of the results from shake table tests. The results of the verification study indicate that the numerical study reasonably represents the dynamic behavior of the geotextile reinforced embankment. Outcomes present remarkable conclusions about the effect of geosynthetic reinforcement and scaling effects. More importantly, it was determined that a numerical model could provide reasonable results based on the shake table tests.

Keywords: Highway embankments; Geosynthetics; Seismic performance; Shake table tests; Numerical modelling.

1 INTRODUCTION

Recent major earthquakes have caused many landslides and severe damage to highway structures in Turkey (Omer and Resat, 2002; Bakir and Akis, 2005) and in China (Xu et al., 2014). In the literature, it is possible to find the different studies on geosynthetic reinforcement of different geotechnical structures (El-Emam and Bathurst, 2004, 2007; Yegian et al.,1999; Perez and Holtz, 2004; Lin et al., 2015).

Various studies in the literature focus on mitigating earthquake hazards of engineering structures. Highway embankments are one of the least studied structures even though highway embankments and roads are clearly vulnerable to earthquake induced damages. It is very important to improve the seismic performance of highways as well as to mitigate earthquake related hazard to provide continuous operation of such lifeline structures (Toksoy, 2014). The stability of highways are a serious problem that should be considered under static and dynamic loads because highways are very important lifelines which should be continuously in service even after disastrous events to provide required safety and emergency needs (Edinçliler and Toksoy, 2017).

Physical modelling represent the behavior of a model structure which is considered as a representative of a prototype. Full-scale modeling is used when all the properties of the prototype structure are replicated with 1:1 scale in the laboratory. In the small scale models, a reduced scale model of a full size structure, prototype, is created. The scaled model is instrumented and tested to investigate the behavior of the prototype structure. However, scaling comes with great advantages and disadvantages at all times as small scale modelling is inexpensive, easy and efficient; whereas there is an ongoing argument among researchers about how accurately reduced scale models can satisfy the requirements of the similitude. In the literature, a few shake table experiments related to the seismic behavior of reinforced slopes and embankments were performed by Wartman et al. (2005), Lin and Wang (2006) and Toksoy, 2014). Srilatha et al. (2013) studied the effect of frequency on seismic response of reinforced soil slopes. It was concluded that the increase in frequency values leads to an increase in displacement values.

It is reported that the typical scale factors of shake table experiments for modeling of the dams up to 1:75 scaling factor for strength models and 1:400 scaling factor for elastic models are given (Harris and Sabnis, 1999). Related to the given statements, various studies with a scaling ratio of 1:50 or even smaller experimental models are given in the literature which successfully reflect the typical behavior of the prototype geotechnical structure.

Dynamic performance of highway embankments especially in earthquake prone areas should attract more attention due to the fact that highways are essential lifelines that should be in continuous operation. This extensive study consists of two simulations by experimental and numerical modelling. In the experimental part, 1:50 scaled unreinforced and two layers of geotextile reinforced highway embankment models with respect to the similitude laws have been subjected to shake table tests using the time scaled record of the Düzce Earthquake. In this study, the similitude requirements for 1g tests (Iai, 1989; Iai, 1997; Iai and Sugano, 1999) were adopted for the embankment models. For numerical studies, the PLAXIS software was used. Full scale dynamic performance analyses of the same models have been performed with the same earthquake record which has not been subjected to any scaling laws. Defined performance indicators as transmitted accelerations and displacements were evaluated and compared.

2 EXPERIMENTAL STUDY

In this study, 1g shake table tests were carried out on reduced scale models. Highway embankment models for shake table experiments were designed using a rigid soil box with dimensions of 90×40×50 cm. The box is made of plexiglas with 15mm thickness. During the study, two different embankment models are studied. These are dimensionally identical unreinforced and geotextile reinforced embankment models. Preliminary seismic performance tests indicate that two layers of geotextile reinforcement inclusion are enough to provide the required stability conditions. Geotextile reinforcements are placed at the bottom and right in the middle height of the embankment model. The prototype geotextile has ultimate tensile strength of T_{ult}:175 kN/m, however the scaled geotextile's ultimate strength (T_{ult}) is 0.07 kN/m, which is 2500 times weaker according to the scaling laws. All embankment models are designed with respect to the regulations and the recommendations of FHWA-NHI-09-083. The prototype highway embankment is considered as a wide, four-lane structure and the model embankment is designed as a 1:50 scale of the prototype. Embankments were placed over the same foundation soil layer with density of 16.5 kN/m^3 and the relative density of Dr: 60%. The crest of the embankment modes was constructed with 40 cm width. Because of the symmetry, the crest of the embankment is taken as 20 cm wide. The scaled embankment has 20 cm height with an inclination of 45°. Shake table tests are performed at BU-KOERI laboratory. A total of nine accelerometers (A1-A9) and four displacement sensors (D1-D4) were used for the experiments. Test set-up is represented in Figure 1 and instrumentation plan is given in Figure 2. Time scaled real record of the Düzce Earthquake (PGA=0.35g) was used for the shake table experiments as shown in Figure 3.

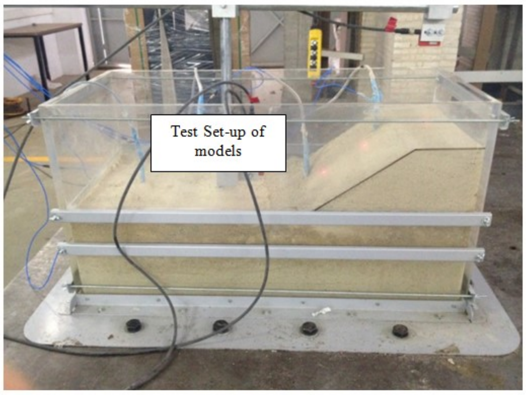


Figure 1. Test set-up of the embankment models.

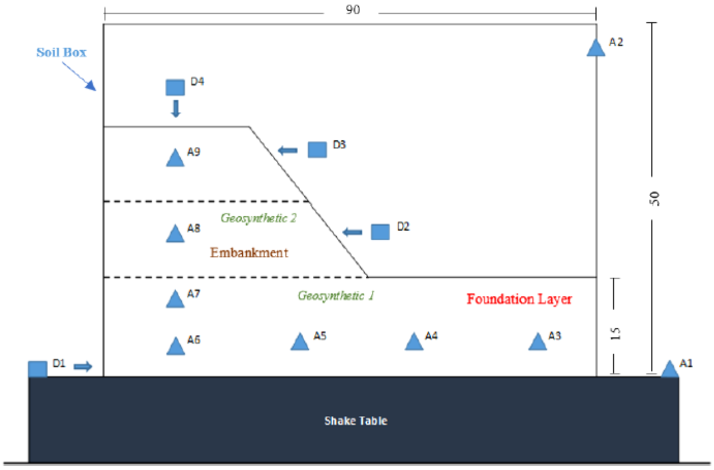


Figure 2. Instrumentation plan.

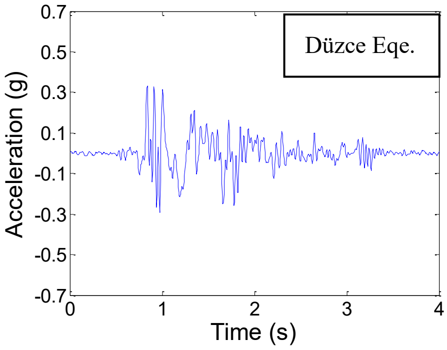


Figure 3. Scaled input dynamic motion (KOERI).

3 NUMERICAL STUDY

A series of numerical analyses are performed to investigate the dynamic behavior of unreinforced and geotextile reinforced highway embankment models by using the PLAXIS 2D. Two dimensionally identical FEM's are designed, modelled and considered for the dynamic response analyses. The considered embankment model for the analyses is a highway embankment with 45° inclination, height of 5m and 20m width at crest. Since the model is symmetric, only right-half of the highway embankment is modelled just as it is in experimental study. All soil models are modelled using hardening soil model, which is an advanced soil model for simulating the behavior of different types of soil. Two layers of geotextiles are used for the reinforced model; one layer is placed at the bottom of the embankment whereas the second one is layered right in the middle height of the embankment. The tensile strength of reinforcement layers is 175kN/m. The same dynamic excitation in the experimental part was subjected to the models. To avoid the spurious reflections and refractions in model boundaries, the model mesh is introduced as large as possible in the software and absorbent boundary is defined only to the right edge of the mesh as left edge is the axis of symmetry. The dynamic motions are applied to numerical models by introducing a prescribed displacement in x-axis direction. Input parameters for the numerical modeling are given in Table 1 and embankment models subjected to dynamic analysis are represented in Figure 4.

Table 1. Input parameters of materials for hardening soil model.

	Foundation Soil	Embankment Soil
γ_{unsat}	17kN/m^3	16kN/m^3
Ø	33°	30°
E_{50}^{ref}	35000kN/m^2	25000kN/m^2
E_{oed}^{ref}	35000kN/m^2	25000kN/m^2
E_{ur}^{ref}	105000kN/m^2	75000kN/m^2

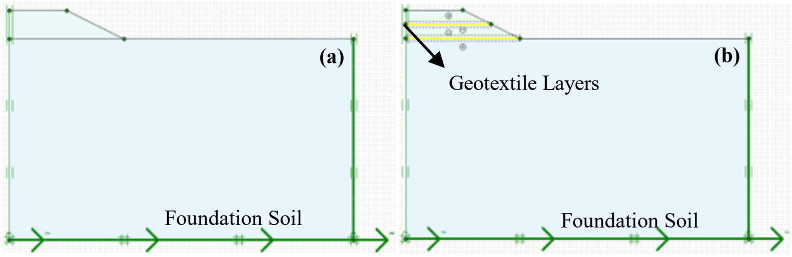


Figure 4. Embankment models subjected to dynamic analysis, a) Unreinforced Model; b) Reinforced Model.

4 RESULTS

Obtained experimental and numerical results by means of transmitted accelerations and displacements are presented in the following parts.

4.1 *Experimental results*

Transmitted acceleration values obtained from shake table tests are tabulated in Table 2. Experimental results by means of transmitted accelerations reveal that the effect of reinforcement is partial under the scaled Düzce Earthquake record. The transmitted accelerations in A9 decrease from 0.39g to 0.34g, which equals to a reduction of 13%. The A2-A6 measurements are not affected by the inclusion of geosynthetics and A7 measured 0.34g and 0.32g similarly, A8 measured 0.35g and 0.31g in the unreinforced and reinforced embankment models, respectively. Amplification Factor (AF) decreases from 1.11 to 0.97 at the crest of the model after reinforcement, which indicates a state of deamplification. The acceleration-time history of A9 is represented in Figure 5. Displacement values are given in Table 3.

Table 2. Transmitted acceleration values under Düzce Earthquake excitations.

Acc. No.	Unreinforced Model (PGA)	Reinforced Model (PGA)
A1	0.35	0.35
A2	0.31	0.30
A3	0.24	0.24
A4	0.31	0.30
A5	0.30	0.30
A6	0.31	0.30
A7	0.34	0.32
A8	0.35	0.31
A9	0.39	0.34

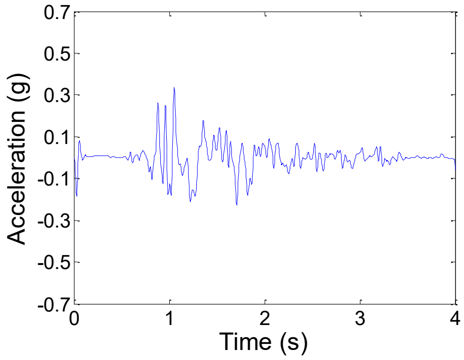


Figure 5. Acceleration-time history (A9).

Table 3. Maximum displacement values under scaled Düzce Earthquake.

Displacement sensors	Unreinforced Model (cm)	Reinforced Model (cm)
D1	0.98	0.98
D2	0.75	0.88
D3	0.97	0.90
D4	0.49	0.20

The effect of geotextile reinforcement by means of displacement values is clear in Table 3. Under the scaled Düzce Earthquake record, even though the measurement of D2 increases slightly, the measurement of D3 decreases from 0.97cm to 0.90cm and the settlement values decrease from 0.49cm to 0.20cm, which equals to a significant reduction of 59%.

4.2 *Numerical results*

Numerical simulations of the shake table tests of embankment models have been performed with the help of the FEM technique using PLAXIS 2D software. The sensor locations in physical tests were approximated and the same locations were defined in the software prior to the analyses. The same abbreviations in shake table tests were used in numerical study for ease of comparison. Seismic data were obtained from those predefined locations and used to compare with the physical ones (Figure 6).

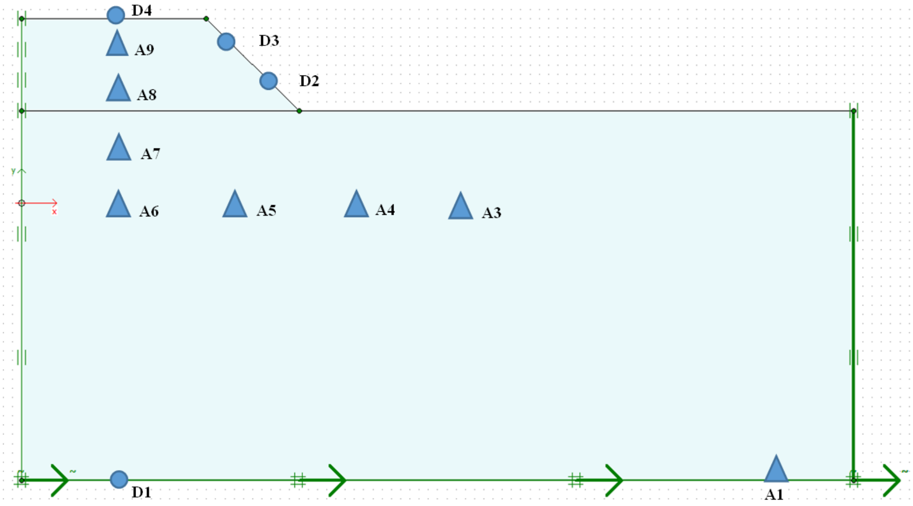


Figure 6. Pre-defined data measurement locations in numerical analyses.

Obtained numerical results from dynamic FEM analyses by means of transmitted accelerations and displacements are shown in Table 4 and Table 5, respectively.

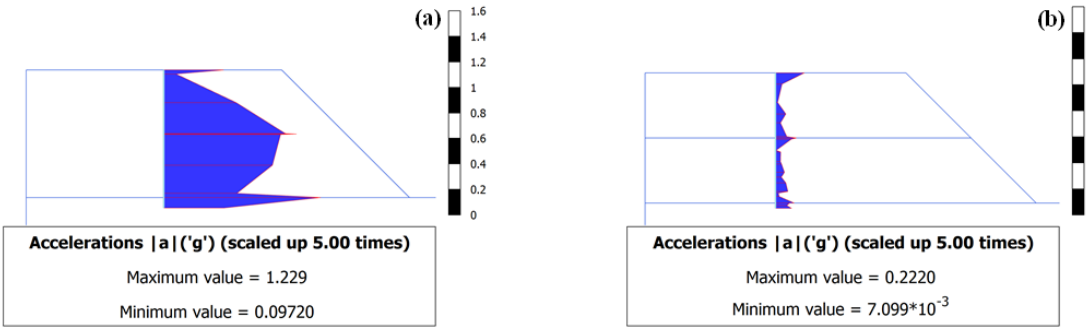
Table 4. Transmitted PGA values under Düzce Earthquake excitations.

Acc.No.	Unreinforced Model (PGA)	Reinforced Model (PGA)
A1	0.35	0.35
A3	0.49	0.38
A4	0.47	0.35
A5	0.40	0.32
A6	0.38	0.28
A7	0.45	0.24
A8	0.88	0.19
A9	0.55	0.20

Table 5. Maximum displacement values under Düzce Earthquake.

Displacement No.	Unreinforced Model (cm)	Reinforced Model (cm)
D1	25.2	25.2
D2	67.5	19.8
D3	114.2	14.4
D4	9.9	4.1

Results of the numerical analyses reveal that the inclusion of geotextile layers into the embankment model affects the dynamic performance significantly. As seen from Table 4, dynamic excitations of Düzce Earthquake amplify accelerations travelling through the soil deposit and the unreinforced embankment itself. As visualized in Figure 7a, A6 and A7, which are located right beneath the embankment model, were subjected to 0.38g and 0.45g of acceleration in the unreinforced case, respectively. Transmitted accelerations reach maximum value at A8 with the measurement of 0.88g near the base of the embankment and in the upper side of the unreinforced model, 0.55g is observed around the location of A9. On the other hand, deamplification occurs within the reinforced embankment model with the inclusion of the seismic energy absorbing geosynthetic layers. The effect of the first geotextile layer can be observed around A6 and A7 with 0.28g and 0.24g, respectively. Transmitted acceleration values around A8 and A9 are observed as 0.19g and 0.20g, respectively. As seen in Table 4 and Figure 7b, seismic waves travelling through the geotextile layers are deamplified. In comparison with the unreinforced case, transmitted accelerations are up to 78.4% less in the reinforced embankment model.



(a) **(b)**

Figure 7. Transmitted accelerations, a) Unreinforced model, b) Reinforced model.

Unreinforced model experiences shallow surface sliding under the Düzce Earthquake excitations (Figure 8a). As seen in Table 5, the majority of the total displacements in unreinforced model occur around D2 (67.5cm) and D3 (114.2cm). The maximum vertical displacement is observed as 9.9cm (D4). Displacement values are much lower in the reinforced case (Table 5). Because of the additional tensile strength, total displacements are successfully reduced to 19.8cm in D2 and 14.4cm in D3 (Figure 8b). Settlement at the crest is observed to be 4.1cm (D4). By means of displacements, obtained results are up to 87.4% less with the inclusion of geosynthetic layers.

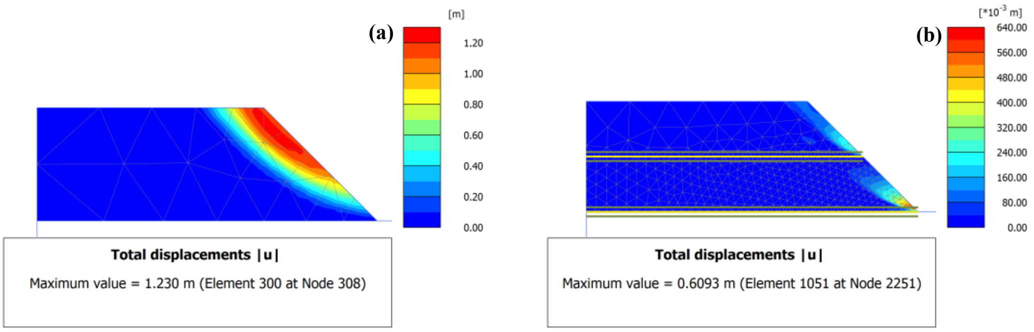


Figure 8. Total displacements, a) Unreinforced model, b) Reinforced model.

5 EVALUATION OF EXPERIMENTAL AND NUMERICAL MODELS

This extensive study presents the comparison and verification of the data obtained from scaled shake table tests and FEM analyses. The main aim is to determine how accurately the results obtained from physical scaled shake table tests and the results obtained from numerical full-scale analyses represent each other. Dynamic performance analyses were performed using the 1999 Düzce Earthquake record and similitude laws were applied for the shake table tests. All comments and reviews are based on the data readings from the predefined acceleration (A1-A9) and displacement (D1-D4) points, which are located at crucial locations for the dynamic performance of highway embankments.

Shake table tests have been performed on a 1:50 scaled embankment model with the instrumentation of nine accelerometers and four displacement transducers. Transmitted acceleration data reveal that deamplification occurs in the foundation soil for both models. In the unreinforced model, input ground motion amplifies towards the crest and reaches to a value of 0.39g. The effect of geotextile reinforcement is observed from the measurements A6-A9. Due to the reinforcement effects by means of dynamic performance, the measurement of A6 in the reinforced case is 3.2% less than the unreinforced case. In addition, the transmitted acceleration measurements of A7, A8 and A9 in the reinforced case are 5.9%, 11.4% and 12.8% less than the unreinforced one. It should also be highlighted that all transmitted acceleration measurements inside the reinforced embankment are less than the input acceleration, which refers to deamplification due to the presence of geosynthetic reinforcement. By means of displacements, the inclusion of geosynthetics lessens the amount of displacements both horizontally and vertically. Despite the minor increase of displacement around the toe (D2), the horizontal displacements at D3 decreases by 7.2% and moreover, settlements at the crest successfully decreases by 59% (D4).

Evaluation of the numerical results gives a clue about how the numerical and experimental data represent each other. Unlike the experimental data, deamplification does not occur in the foundation soil in unreinforced case. Instead, it occurs more prominently around the embankment in the reinforced case. The reinforcement effect can be first realized at A6, where the transmitted accelerations are only 26.3% less than the unreinforced case. Also, the obtained results in the reinforced case by means of transmitted accelerations are 46.7%, 78.4% and 63.6% less in A7, A8 and A9, respectively. Total displacements are substantially affected by the geosynthetic reinforcement. The measurements taken at D2 and D3 are 70.7% and 87.4% less in the reinforced case and the amount of settlement is reduced by 58.9% in D4.

Overall comparison of experimental and numerical results highlights the concerns of how accurately a small scale shake table test or FEM models represent the dynamic behavior of an engineering structure. It is appropriate to tell that the dynamic behavior of embankment models by means of transmitted accelerations and displacements follow a similar trend based on the observations both experimentally and numerically. However, it is clear that the reinforcement effect is more apparent in numerical analyses. In other words, the reduction ratios of predefined performance indicators are much higher in the numerical results than the experimental results.

6 CONCLUSIONS

This extensive study consists of two different parts which are experimental and numerical simulations of seismic performance of unreinforced and reinforced embankment models. In the experimental part, 1:50 scaled unreinforced and two layers of geotextile reinforced highway embankment models with respect to the similitude laws were subjected to shake table tests using the time scaled record of the Düzce Earthquake. Using the FEM technique, full-scale dynamic performance analyses of the same models have been performed with the same earthquake record and obtained results have been carefully evaluated and compared with respect to the predefined performance indicators of transmitted accelerations and displacements.

Comparison of the experimental and numerical modelling studies reveals that both simulations can successfully identify the type and severity of the damage under the same strong ground motion. The influence of the inclusion of the geosynthetic layers on the dynamic performance of embankments can also be observed successfully in both techniques. However, it is seen that the reduction ratios in the reinforced model (transmitted accelerations and displacements) are much higher in numerical results than experimental ones. It can be said that the effect of geosynthetic reinforcement can be observed more clearly in the numerical analyses. The main reason may be the effect of scaling in experimental studies or overestimation of the results in the numerical models, As a result, more research should be performed regarding this subject. It should be noted that obtained results are valid for the dynamic motion used in this study and it is possible to achieve different outcomes with different dynamic loads.

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