Dynamic Response Analysis of Highway Embankments

Yasin S. Toksoy and Ayşe Edinçliler

Abstract As the severity and the occurrence rate of natural disasters, such as earthquakes, increases; highway embankments become more susceptible to related hazards. However, highway embankments are considered to be an important lifeline which must be in continuous operation under any circumstances. In light of the recent advances and latest research, geosynthetics can successfully and effectively be used to reinforce highway embankments against the primary and secondary effects of earthquake induced damages. It is important to estimate the approximate dynamic behaviour of engineering structures via numerical simulations before the experimental studies. This study covers numerical modelling of the dynamic response of full-scale highway embankments using the Mobile Seismic Shaker (MSS) in the field as a dynamic source. This numerical simulation phase has been used to ensure the true structural design and true instrumentation. The numerical simulations have been performed implementing the FEM technique using PLAXIS 2D software and includes the dynamic response analysis of dimensionally identical unreinforced and geogrid reinforced highway embankment models. Revealed numerical results clearly show that, geogrid reinforcement can successfully reduce the total displacements and transmitted accelerations at crest level which are key structural performance indicators.

Keywords Highway embankments · Seismic performance · Geosynthetics · Numerical modelling

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1 Introduction

The consideration of the role of roads and highways to provide required safety and emergency needs in case of a natural disaster such as earthquakes, highlights the importance of dynamic performance of highway embankments especially in earthquake prone areas. Because roads and highways are considered to be very important lifelines and lifelines must be in continuous operation under any circumstances [1–3].

Mitigating earthquake hazards and risks of engineering structures have always attracted researches. However, the dynamic performance of highway embankments is one of the important topics in the literature although these structures 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 [4].

Highway embankments, slopes or dam like structures and their static and dynamic stability and durability must be maintained in early construction stages. The required stability conditions shall be achieved with the implementation of various engineering applications to reinforce this kind of structures. There are a number of improvement techniques by means of static and dynamic performance available in the literature for the reinforcement of highway embankments but this study particularly concentrates on geosynthetic reinforcement.

The integration of geosynthetic materials to the civil, geotechnical and earthquake engineering applications has become an advantageous and cost-effective way to achieve the required stability conditions of related structures. Geosynthetics are synthetic materials that are commonly used to solve civil and geotechnical engineering problems. The use of these materials is not limited to static load conditions. Geosynthetics are capable of absorbing dynamic forces and transmitting less dynamic forces to engineering structures [3–5].

Due to the primary and secondary effects of earthquakes, highway embankments experience minor to major scale of damage all around the world constantly. Due to the additional tensile strength provided and the soil-structure interaction, it is a common practice to use geosynthetics to improve the seismic performance of earth structures like embankments [6]. In the literature, it is possible to find many kinds of different studies on geosynthetic reinforcement of different geotechnical structures [7–12].

Previous studies related with the dynamic performance of highway embankments and slopes are generally based on numerical simulations and shaking table experiments. A few shaking table experiments related to the seismic behavior of reinforced slopes and embankments are also provided in the literature [13]. Provided experimental and numerical studies aim to determine the effect of slope angle on the results. In a research, the effect of frequency on seismic response of reinforced soil slopes was studied. Clayey soil was used for the experiments and reinforced and unreinforced slopes with two different slope inclinations of 45° and 60° were tested in a laminar box. Biaxial geogrids were used for reinforcement of slopes and models were excited dynamically under 0.3 g of acceleration with different frequency values of 2, 5 and 7 Hz. It was concluded that the increase in frequency values leads to an increase in displacement values [14].

In an experimental study, scaled highway embankment models were 1-g shaking table tested under different dynamic motions with different frequency and amplitudes in addition to the real earthquake records. Dimensionally identical unreinforced and geotextile-reinforced highway embankment models were subjected to input dynamic motions (2–14 Hz 40 cycle and scaled Düzce Eqe. record) to determine the effect of the inclusion of geosynthetics on the dynamic response of highway embankment models. Results clearly show the geosynthetic reinforcement successfully reduced the settlements and transmitted accelerations up to 85% and 56%, respectively [15].

In a full-scale shaking table experiment, the dynamic response of highway embankments reinforced with flexible container bags was studied. The method is basically placing the flexible container bags (with different configurations) at the toe of the embankment for earthquake resistance purposes. Instrumented full-scale models were shaking table tested under 5 Hz 40 cycle of harmonic motion. Results of the study suggests that proposed method improves the dynamic response of highway embankment models [16].

Regarding the previous experience and expertise, the aim of this research is to determine the effects of geogrid reinforcement on the seismic performance of highway embankments numerically prior to field scale tests. The study is parametric in a way that the seismic performance of the highway embankments is investigated by performing seismic performance analyses using the same dynamic input which Mobil Seismic Shaker (MSS) is capable of applying in field scale. The MSS is a very special and expensive device which is specifically developed for research purposes. There are only few MSS' around the world and there is only one in Turkey, which is operated by the Earthquake Engineering Department of Boğaziçi University in KOERI.

The native soil parameters were determined by a series of geophysical tests including Pressuremeter tests, Multichannel Analysis of Surface Waves (MASW) tests, Electrical Resistance Tomography (ERT) tests and laboratory tests. By using the tested field data, two different highway embankment models with and without geogrid reinforcement were modelled and obtained results were compared under the same dynamic motion.

2 Numerical Study

Numerical simulations of the proposed field scale seismic performance tests have been performed using the commercially available PLAXIS 2D Connect Edition software with finite element modelling technique. Mobile seismic shaker (MSS) operated by KOERI Earthquake Department is going to be used as a seismic source for the proposed field experiments. So that, a selected input dynamic motion of which MSS is capable of applying is also used in numerical analysis. MSS is capable of applying 27 kN of force between 0–225 Hz both vertically and horizontally. A point load which

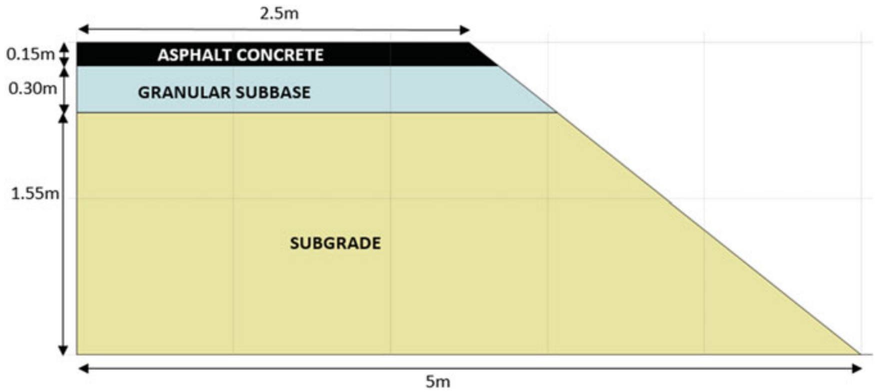

Fig. 1 Unreinforced highway embankment model

is located 1 m away from the toe of the embankment models is used to mimic the MSS as a seismic source. As the embankments models are symmetric, only the right half has been modelled and subjected to dynamic excitations. Dynamic response analysis requires special boundary conditions to avoid reflection of seismic wave which may possibly cause distortions and unrealistic results. Thus, viscous boundaries are defined to the edges of the mesh. The unreinforced embankment model and its dimensioning identical to the field models are represented in Fig. 1. The geogrid reinforcement used in the numerical analysis has an ultimate tensile strength of 40 kN/m^2. However, PLAXIS use axial stiffness (EA) parameter instead of T_{ult} value. Provided from the design charts, the axial stiffness value of the proposed geogrid material under 5% strain level has been calculated as 2000 kN/m and used as an input value. The geogrid reinforced embankment model and its dimensioning is represented in Fig. 2.

The details of all the materials, material models and related properties are given in Table 1. These parameters are compatible with the related studies in the literature.

An input dynamic motion of incremental 0–100 Hz sinusoidal motion with a peak acceleration value of 1.1 g is selected for the numerical analysis. This input is going to be used for the field experiments as well. The acceleration-time history of the record is given in Fig. 3.

3 Results

Numerical results taken from two models are represented by means of total displacements and transmitted acceleration values. The possible sensor locations in field tests were approximated and the similar locations were defined in the software prior to the analysis. Total displacement distributions of unreinforced and Geogrid reinforced highway embankment models are represented in Figs. 4 and 5.

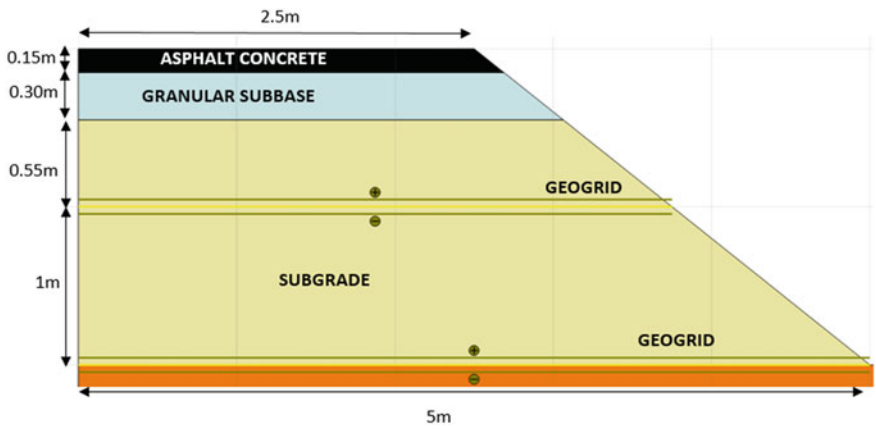

Fig. 2 Geogrid reinforced highway embankment model

Table 1 Material properties used in finite element modelling

	Asphalt concrete	Granular subbase	Subgrade material	Very firm silty clay (Baltalimanı formation)
Material model	Linear Elastic	Mohr–Coulomb	Mohr–Coulomb	Mohr–Coulomb
γ_{unsat} (kN/m^3)	24	22	18	18
E’ (kN/m^2)	2.1 E^6	100 E^3	25 E^3	50 E^3
Poisson ratio	0.4	–	0.34	–
Cohesion (kN/m^2)	–	0.01	40	17
Ø	–	45°	30°	12°

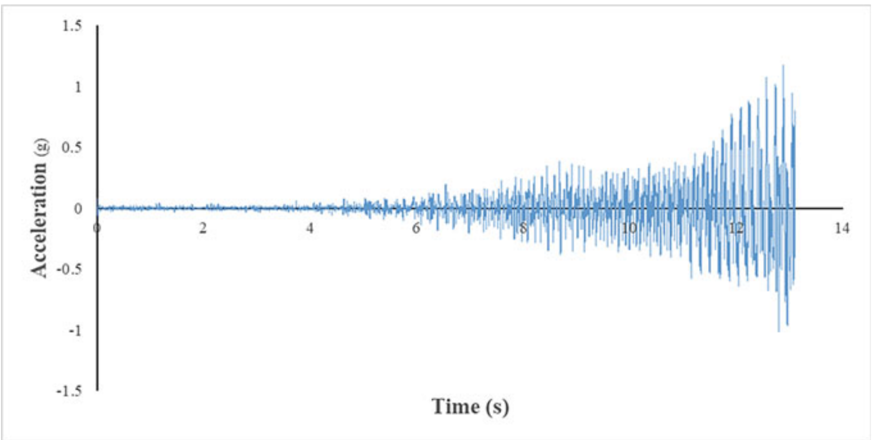

Fig. 3 Input motion of 0–100 Hz harmonic motion

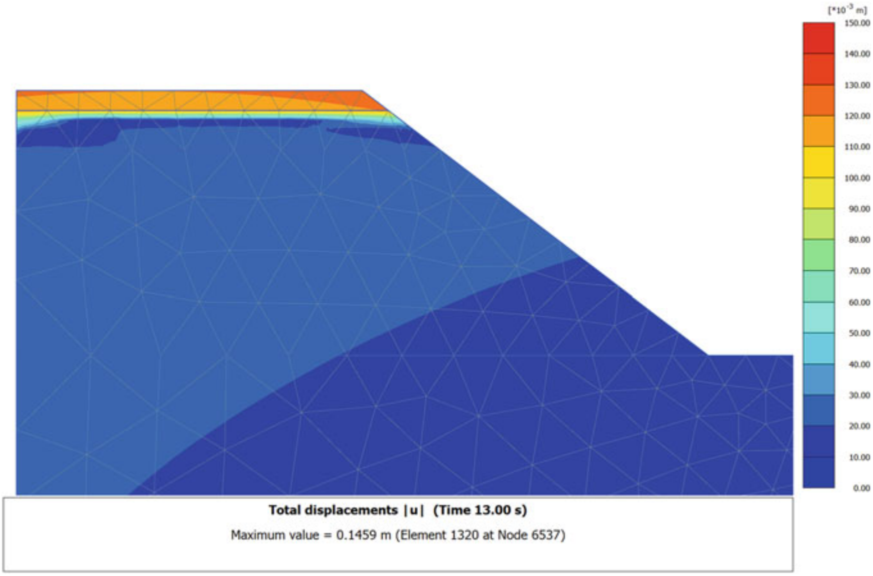

Fig. 4 Total displacement distributions of unreinforced model

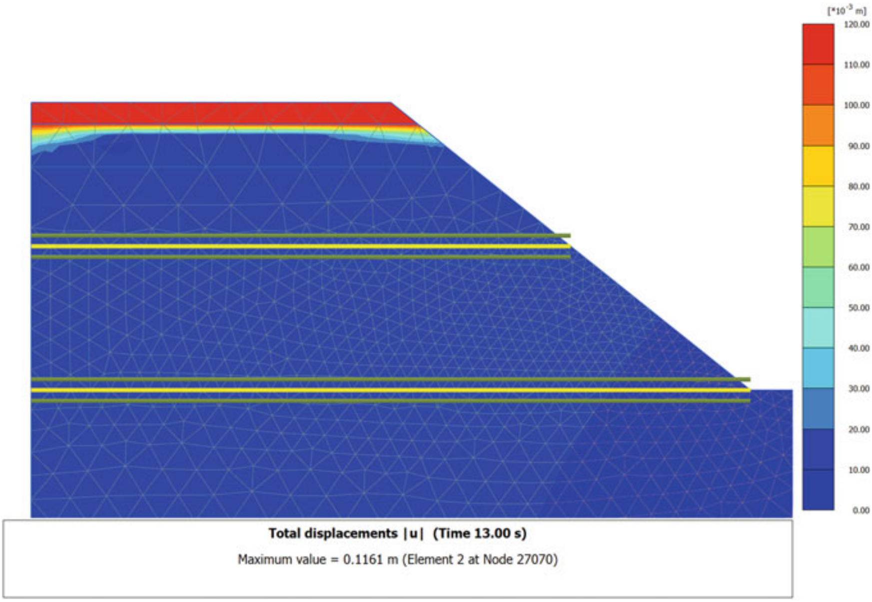

Fig. 5 Total displacement distributions of geogrid reinforced model

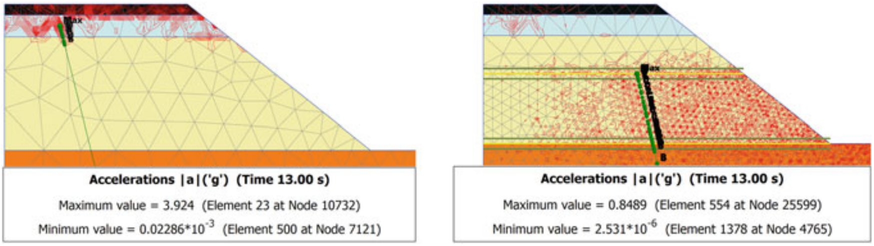

Fig. 6 Total acceleration distributions of unreinforced and geogrid reinforced models

Table 2 Summary of numerical results at the crest

	Total displacements (cm)	Total accelerations (g)
Unreinforced model	15	3.92
Geogrid reinforced model	12	0.85

As can be inferred from the displacement distribution figures, unreinforced model displaces approximately 15 cm. It is seen that the settlement is only concentrated at the crest level. As can be seen in Fig. 5, the geogrid reinforced model displaces approximately 12 cm, which is also observed at crest level. Transmitted acceleration distributions of unreinforced and Geogrid reinforced highway embankment Models are represented in Fig. 6.

It is obvious from the total acceleration distribution figures that the geogrid reinforcement can successfully absorb the dynamic energy and transfer less dynamic motion to the highway embankment model. Observed maximum acceleration value in the unreinforced model is 3.92 g around the crest level. However, the maximum acceleration value observed in geogrid reinforced model is only 0.85 g. Aforementioned results are tabulated in Table 2, for ease of comparison.

4 Conclusions

This paper presents the numerical part of the study which involves the field-scale dynamic response of highway embankment models. Determination of the dynamic response of full-scale highway embankments using the Mobile Seismic Shaker (MSS) in the field as a dynamic source was studied. This numerical study is the simulation of the field-scale testing in which the input parameters are based on previously performed geophysical tests. Obtaining the approximate dynamic behavior of the highway embankment models before the field-scale construction phase is an essential tool to estimate the effectiveness of the geogrid reinforcement on the seismic performance of the embankment model. This numerical simulation phase has also been used to ensure the true structural design and true instrumentation.

Performed dynamic response analysis of the proposed embankment models reveal that the geogrid reinforcement can substantially and successfully reduce the total displacements and transmitted accelerations at crest level, which are key structural performance indicators. Due to the additional tensile strength provided from the geogrid layers, the geogrid reinforced model displaces 20% less than the unreinforced case. Also, peak transmitted acceleration value on the reinforced embankment model is 78% less than the unreinforced model. Presented results highlighted that the geogrid reinforcement is an effective reinforcement element to mitigate the earthquake hazards of the highway embankments.

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References

1. Edinçliler A (2017) Using waste tire–soil mixtures for embankment construction. In: International workshop on scrap tire derived Geomaterials "opportunities and challenges". Kanto Branch Jpn Geotechn Soc, 319–328
2. Edinçliler A, Baykal G, Saygılı A (2010) Influence of different processing techniques on the mechanical properties of used tires in embankment construction. Waste Manage 30:1073–1080
3. Edinçliler A, Toksoy YS (2017) Physical model study of the seismic performance of highway embankments with and without geotextile. J Earthq Tsunami 11(2). https://doi.org/10.1142/S1793431117500038
4. Toksoy YS (2014) Investigation of the seismic performance of reinforced highway embankments. MSc Thesis, Boğaziçi University, Istanbul, Turkey
5. Edinçliler A, Toksoy YS (2018) Effects of improvement techniques on seismic performance of highway embankments. In: 16th European conference on earthquake engineering (16ECEE) proceedings, 18–21 June, Thessaloniki, Greece
6. Koseki J (2012) Use of geosynthetics to improve seismic performance of earth structures. Geotext Geomembr 34:51–68
7. El-Emam ME, Bathurst RJ (2004) Experimental design, instrumentation and interpretation of reinforced soil wall response using a shaking table. Int J Phys Model Geotecnics 4:13–32
8. El-Emam ME, Bathurst RJ (2007) Influence of reinforcement parameters on the seismic response of reduced-scale reinforced soil retaining walls. Geotext Geomembr 25:33–49
9. Yegian MK, Kadakal U, Catan M (1999) Geosynthetics for earthquake hazard mitigation. Indian Fabrics Assoc Int 1:87–100
10. Perez A, Holtz RD (2004) Seismic response of reinforced steep soil slopes: results of shaking table study. In: Geotechnical engineering for transportation projects, ASCE geotechnical special publication (126), pp 1664–1672
11. Lin YL, Leng WM, Yang GL, Li L, Yang JS (2015) Seismic response of embankment slopes with different reinforcing measures in shaking table tests. Nat Hazards 76:791–810
12. Wartman J, Seed RB, Bray JD (2005) Shaking table modeling of seismically induced deformations in slopes. J Geotechn Geoenviron Eng 131(5):610–622
13. Lin ML, Wang KL (2006) Seismic behavior in a large-scale shaking table test. Eng Geol 86:118–133

14. Srilatha N, Latha GM, Puttappa CG (2013) Effect of frequency on seismic response of reinforced soil slopes in shaking table tests. Geotext Geomembr 36:27–32
15. Edinçliler A, Toksoy YS (2017) Shake table tests to measure the dynamic performance of geotextile-reinforced embankment. Periodica Polytechnica Civil Eng 61(4):803–814
16. Nakazawa H, Kawamata Y, Shibuya S, Kato S, Jeong K, Baek J, Lohani TN, Morita A, Takemoto O, Moriguchi Y (2020) Full-scale experiment of earthquake resistant embankment using flexible container bag. J Disaster Res 15(6):765–781