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Seismic response of geosynthetic reinforced earth dams

Réponse sismique des barrages en terre armée géosynthétiques

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ABSTRACT: Dams located over active fault zones are quite susceptible to earthquake induced damages. Dynamic analysis is recommended for important dams and embankments, failure of which may lead to high levels of risk. Dynamic analysis essentially involves estimation of the deformation behavior of an earth dam or an embankment using the finite element or finite difference method. Under severe ground motions, Major contributors to earth dam failure are overtopping, piping, and structural failure. Variants of using geosynthetics for reinforcing soils in dam construction are possible. Reinforcing the soil with geosynthetics has proven to steepen the slopes, thereby considerably reducing the earthen material used for the dam construction. Reinforced earth dams also provide the advantages of structural flexibility, increase in factor of safety of the slopes, displacement and stress level reduction. In this study, the effects of reinforcing the slopes with geosynthetics on seismic response of the earth dams were evaluated. Unreinforced and reinforced earth dam models were subjected to different destructive ground motions by using the two dimensional finite element code. Numerical results were evaluated and represented with respect to the selected performance indicators of the study.

RÉSUMÉ: Les barrages situés au-dessus de zones de faille actives sont très sensibles aux dommages causés par les séismes. L'analyse dynamique est recommandée pour les barrages et les remblais importants, dont la défaillance peut entraîner des niveaux de risque élevés. L'analyse dynamique consiste essentiellement à estimer le comportement en déformation d'un barrage en terre ou d'un remblai en utilisant la méthode des éléments finis ou des différences finies. Sous d'importants mouvements du sol, les principaux contributeurs à la défaillance d'un barrage en terre sont les débordements, les canalisations et les défaillances structurelles. Des variantes d'utilisation de géosynthétiques pour renforcer les sols dans la construction de barrages sont possibles. Renforcer le sol avec des géosynthétiques s'est avéré raidir les pentes, réduisant ainsi considérablement les matériaux en terre utilisés pour la construction du barrage. Les barrages en terre armée offrent également les avantages de la flexibilité structurelle, de l'augmentation du facteur de sécurité des pentes, du déplacement et de la réduction du niveau de contrainte. Dans cette étude, les effets du renforcement des pentes avec des géosynthétiques sur la réponse sismique des barrages en terre ont été évalués. Les modèles de barrages de terre non renforcés et renforcés ont été soumis à différents mouvements destructifs du sol en utilisant le code à deux éléments finis. Les résultats numériques ont été évalués et représentés par rapport aux indicateurs de performance sélectionnés de l'étude.

Keywords: Earth dams, Geosynthetics, Seismic Performance, Finite Element Modelling.

1 INTRODUCTION

Earth dams and embankments should be ideally located away from any potentially active faults. Failure of an embankment dam due to ground rupture is possible when the dam is built over an active fault .

Major contributors to earth dam failure are overtopping, piping, and structural failure. The evaluation of the seismic safety of embankment dams often depends on determining the severity of expected deformations.

Overtopping of the embankment and external/internal cracking are the most common observed failure types for embankment type dams. If the embankment crest falls below the elevation of the reservoir surface, erosion from overtopping can cause the dam to fail. The magnitude of deformations depends on the strengths of the materials. In case of an earthquake, permanent deformations may take place because the dynamic stresses exceed the available strength. In addition, liquefaction or cyclic mobility phenomenon, total collapse of the embankment dam in fault-crossing regions and large seiche waves occurred in the reservoir may lead to dam failure situations (FEMA, 2005).

Seismic performance of dams and their stability issue during and after seismic events is an important concern in dam engineering. Safety requirements for dam structures subject to dynamic loading should involve evaluation of the overall stability of the structure such as verifying its ability to resist induced lateral forces and moments and preventing excessive cracking of the body (Jansen, 1988).

Concrete and embankment type dams are the most commonly preferred techniques in dam engineering. Concrete dams are stable and earthquake resistant even in highly seismic zones with no reported major damage in case of a strong ground motion. However, construction and maintenance costs of concrete dams are high. Embankment dam is a cost effective alternative to concrete type. Different materials can be used as a fill material in embankment dams such as rock, earth or sand-gravel mixtures. Rock fill is commonly preferred as it is relatively easier to implement. With the development in design engineering, the use of sand-gravel fill in embankment dams has a wide spread as it is cost-effective, safe and provides high quality natural construction material (Haselsteiner and Ersoy, 2011).

Earth fill dam structures are huge and complex engineering structures with different design and construction stages than other geotechnical structures. Earth fill dams stores a very large amount of water and subject to high water pressures which makes their prediction of stability and evaluation of deformation complex (Athani et al., 2015).

In the study of Seed et al. (1977), the damage states of a number of dams subjected to major earthquakes in US, Japan, South America and Russia are represented. It is stated that Hydraulic fill dams have been found to be vulnerable to failures however, they can survive moderately strong shaking, up to about 0.2g from Magnitude 6.5 to 7 earthquakes with no harmful effects. It is also stated that dams constructed of clay soils on clay or rock foundations have withstood extremely strong shaking ranging from 0.35 to 0.8g from a magnitude 8-1/4 earthquake with no apparent damage. It was determined that rock fill dams experienced no significant damage. However, for dams constructed of saturated cohesionless soils located in earthquake prone areas, the primary cause of damage or failure is the build-up of pore water pressures in the embankment (Seed et al., 1979).

The successful 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. The use of geosynthetics is common on static load conditions but not limited to. Geosynthetics are capable of absorbing dynamic forces and transmitting less dynamic forces to engineering structures. The use of geosynthetics under foundations, beneath embankments or dam structures can absorb seismic energy and mitigate dynamic excitations that transmit to upper layers of soils and foundation of overlying structures. Tensile strength of the geosynthetic material and the soil-structure interaction between soil and geosynthetic material increases the shear resistance of soil under dynamic conditions. Other important parameters that play an important role in bearing capacity under static and dynamic conditions include the depth to the first layer of reinforcement, vertical spacing of reinforcement layers, and number of reinforcement layers and the properties of the reinforcement (Edinçliler and Toksoy, 2017). Many researches have focused on understanding the dynamic interface shear properties of geosynthetic materials and geosynthetic reinforced soils for the past few decades (Yegian et al.,1995a;b). Energy dissipation along structures and geosynthetic interfaces is also commonly studied by Yegian and Lahlaf (1992), and Zimmie et al. (1994). Variants of using geosynthetics for reinforcing soils in dam construction are possible. The aim of the this study is to evaluate the effects of reinforcing the slope of the embankment dam with geosynthetics on seismic response of the earth dams.

2 NUMERICAL STUDY

This study has been carried out by performing a series of numerical analyses to investigate the dynamic behavior of geosynthetic reinforced embankment dam structures. Finite Element Method has been preferred for the analyses and the software of chose is PLAXIS 2D 2018. Two different FEM's are designed, modelled and considered for the dynamic response analyses. Model 1 represents the embankment dam model with no reinforcement inclusions. whereas Model 2, exemplifies the dam structure model with geogrid reinforcement.

2.1 Materials and methods

The numerical models considered for the analyses are dimensionally identical embankment type dam structures with H:20m, B:10m and L:100m. The water level behind the dam model is 15m. Two different soil properties have been used for the proposed analyses. 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 different models are considered for this study. Model 1 represents the dam structure model with no reinforcement. Model 2 is selected to be a geogrid-reinforced embankment model. Multilevel reinforcements are used when constructing of dam slope. Ten layers of geogrids are used for the proposed model, each of which is placed with 5m spacing. The geogrid material is a uniaxial type with a rigidity value of EA:10000kN/m. In order to avoid the spurious reflections and refractions in model boundaries, which may lead to incorrect results, model mesh is introduced as large as possible in the software and viscous boundaries are defined to the edges of the mesh. The earthquake excitation is applied to models by introducing a prescribed displacement in x-axis direction. Models are given in Figure 1. Soil parameters for Hardening Soil Model are given in Table 1.

Table 1. Input parameters of materials for hardening soil model

	Foundation Soil	**Dam Fill**
γ_{unsat}	17kN/m^3	16kN/m^3
Ø	35°	31°
E_{50}^{ref}	50000kN/m^2	35000kN/m^2
E_{oed}^{ref}	50000kN/m^2	35000kN/m^2
E_{ur}^{ref}	150000kN/m^2	105000kN/m^2

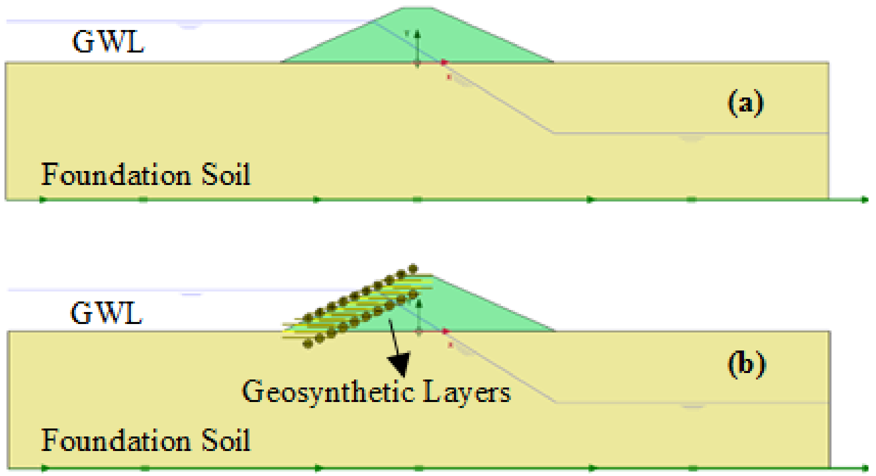

Figure 1. Dam models subjected to dynamic analysis, a) Model 1; b) Model 2

2.2 *Dynamic Motions*

A real earthquake records obtained from BU-KOERI have been used for the dynamic response analysis, which are 1999 Kocaeli Earthquake (Yarımca Station) with a PGA of 0.32g and pre-dominant frequency of 0.29Hz (M_w:7.6) in addition to the 2014 Gökçeada Earthquake (Meteoroloji Station) with a PGA value of 0.18g and 2.49Hz of pre-dominant frequency(M_w:6.5). Related accelerogram can be seen in Figure 1 and 2.

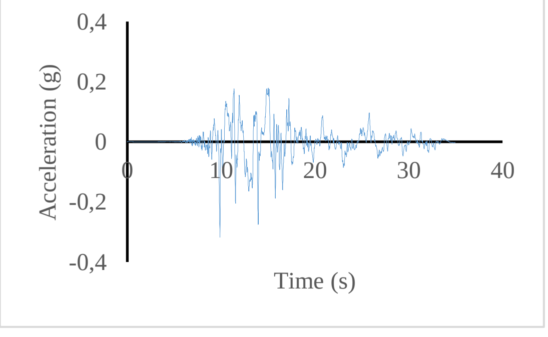

Figure 2. Kocaeli Earthquake Accelerogram (Yarımca Station)

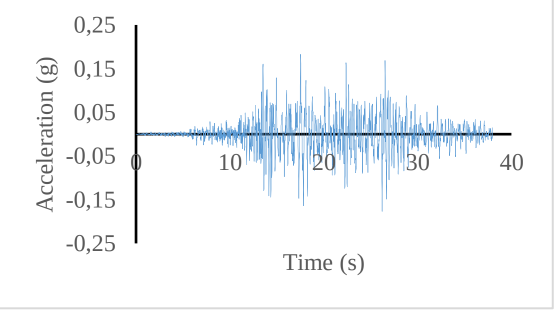

Figure 3. Gökçeada Earthquake accelerogram (Meteoroloji Station)

3 RESULTS

Performance indicators were selected as total displacements and transmitted accelerations The results of Model 1 and Model 2 under Kocaeli Earthquake excitations can be seen in Figure 4 and Figure 5, whereas the results of Model 1 and Model 2 subjected to Gokceada Earthquake motions are given in Figure 6 and Figure 7.

In Figure 3, unreinforced embankment dam gets severe damage under the dynamic motions of destructive Kocaeli Earthquake. Most of the damage occurs to be behind the dam where impounding effect of the water takes place. Total displacement value is observed to be 3.31m. Transmitted acceleration distribution taken from the central section of the dam (Figure 3) reveals that the acceleration distribution dramaticly changes according to the water level. Peak transmitted acceleration value is observed to be 0.69g inside the dam body.

However, the acceleration at top is determined as 0.42g.Due to the geogrid reinforcement, Model 2 displaces 1.90m under Kocaeli Earthquake record and it is concentrated toward the front side of the dam where reinforcement zone ends (Figure 4). Due to geogrid reinforcement, transmitted accelerations could reach up to 0.36g inside the dam body and to 0.19g at top.

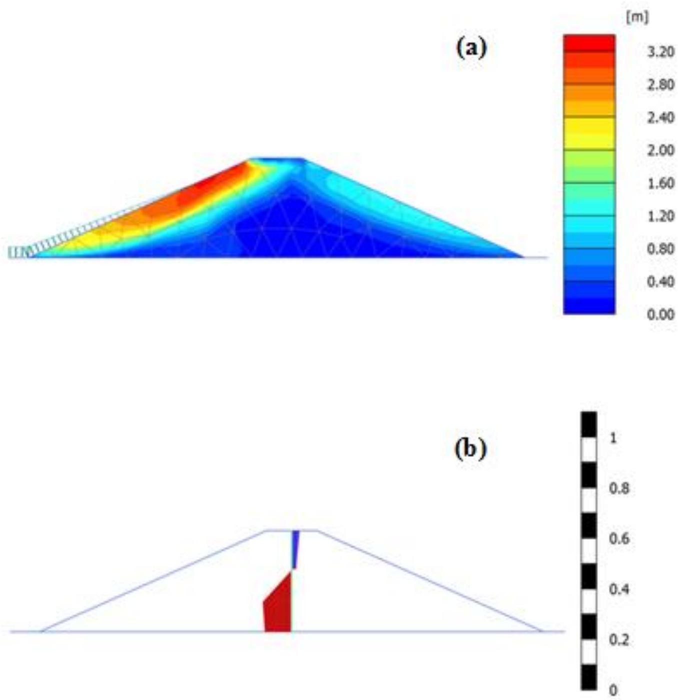

Figure 3. Model 1 under Kocaeli Earthquake, a) Total displacement distributions; b) Transmitted peak accelerations

Dam models are less affected by the dynamic motions of the Gokceada Earthquake as it is relatively less destructive. Model 1 subjected to Gokceada Earthquake record experience 23cm of total displacement and it is mostly concentrated behind dam (Figure 5). Transmitted accelerations peak around the middle height with 0.27g and lessens slightly at top with 0.2g.

Due to the geogrid reinforcement effect, Model 2 deforms very slightly with a total displacement value of 11cm due to Gokceada Earthquake excitations. Transmitted accelerations reaches up to 0.21g inside the dam model and to 0.16g at the top of the model as can be seen in Figure 6.

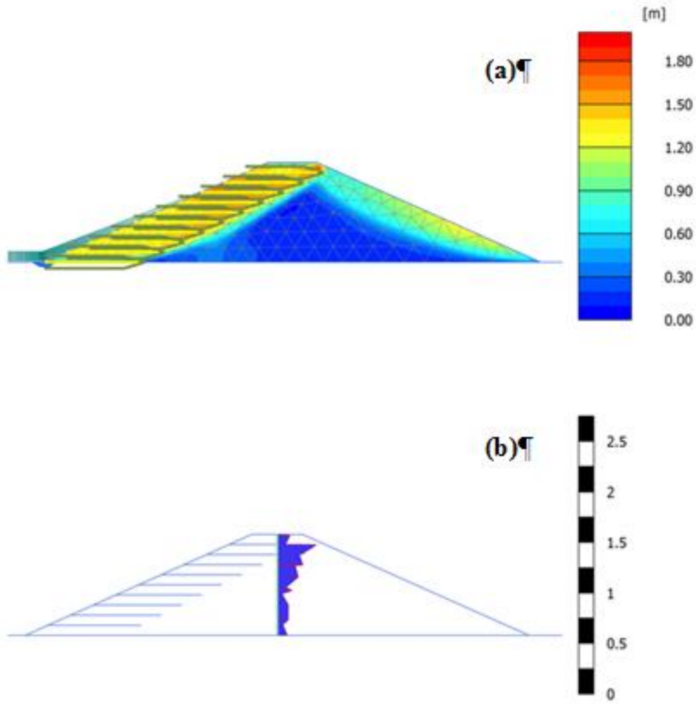

Figure 4. Model 2 under Kocaeli Earthquake, a) Total displacement distributions; b) Transmitted peak accelerations

DISCUSSION OF THE RESULTS

A series of numerical dynamic performance analyses were performed in order to evaluate the effects of geosynthetic reinforcement technique to improve the seismic response of embankment type earth dams. Based on the selected performance indicators as total displacements, transmitted accelerations and A.F. values, the numerical results have been evaluated in a comparative matter as given in Table 2.

Table 2. Numerical results

Kocaeli EQE	**Total Disp.(m)**	**Acc. (g)**	**Acc. at top (g)**	**A.F.**
Model 1	3.31	0.69	0.42	1.31
Model 2	1.90	0.36	0.19	0.59
Gokceada EQE				
Model 1	0.23	0.27	0.20	1.11
Model 2	0.11	0.21	0.16	0.89

Results reveal that geosynthetic reinforcement technique using sequential geogrid layers has a noticeable effect on the seismic response. Total displacements and displacement concentrations at the embankment slope are successfully reduced.

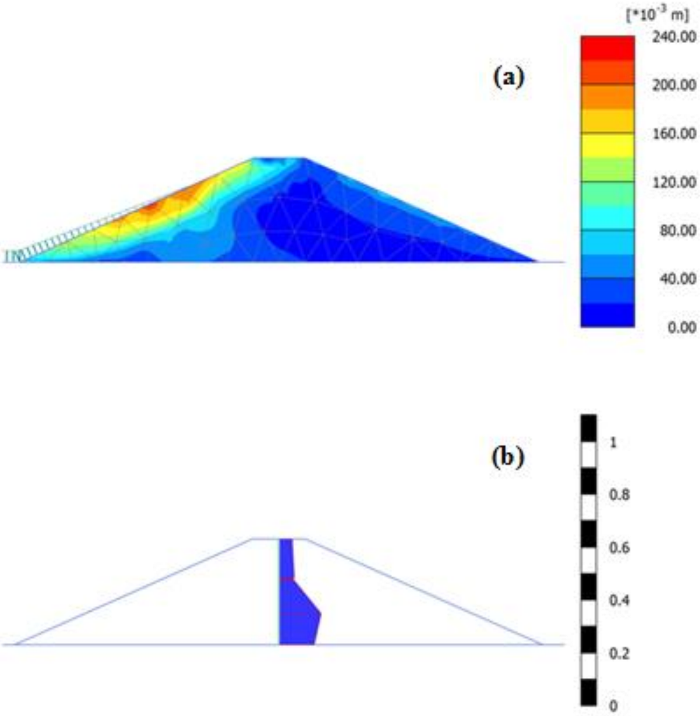

Figure 5. Model 1 under Gokceada Earthquake, a) Total displacement distributions; b) Transmitted PGAs

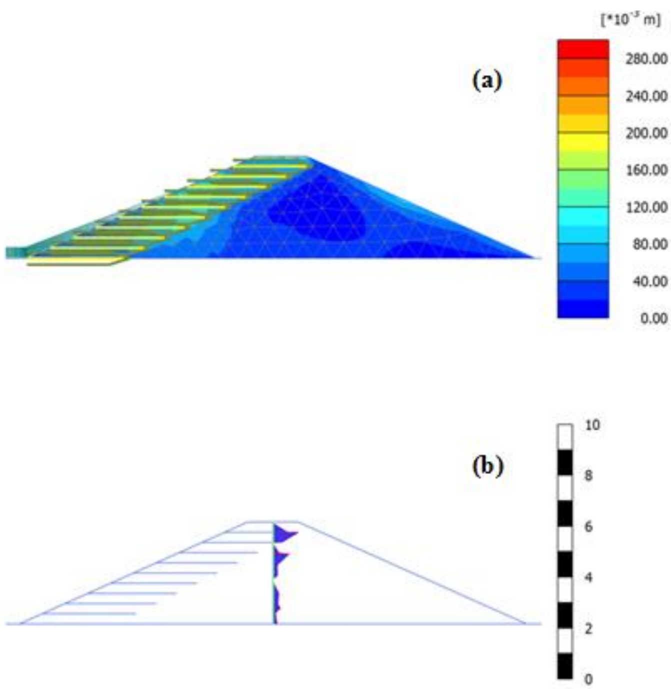

Figure 6. Model 2 under Gokceada Earthquake, a) Total displacement distributions; b) Transmitted PGAs

Total displacements are decreased by 42.6% and 52.2% in Model 2 under Kocaeli Gokceada Earthquake records, respectively. Due to the additional tensile strength and increased energy absorption capacity, transmitted accelerations are significantly reduced by up to 47.8% inside the dam and up to 54.8% at the crest. In Table 2, calculation of the Amplification Factors (A.F.) clearly shows that dynamic motions travelling through the embankment body deamplifies due to the existence of geogrid reinforcement zone. A.F. values are 20% and 55% less in reinforced dam models subjected to Gokceada and Kocaeli Earthquakes, respectively.

5 CONCLUSIONS

The numerical results of a series of dynamic response analysis clearly indicate that the proposed reinforcement technique is successful for such earth structures. Comparison of the dynamic responses upon pre-defined performance indicators between unreinforced and reinforced models reveal that the inclusion of a reinforcement zone give a significant difference. Due to the additional tensile strength is applied to the structure, resisting forces noticably increases which reduces the total displacements. Similarly, as geosynthetics absorbs the dynamic energy, less dynamic force is transmitted to the structure which leads to reduced transmitted accelerations within the structure itself. It should be kept in mind that this results are directly related with the studied models in this study. Different results can be achieved with different configurations under different earthquake excitations.

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