Effects of seismic cushions on seismic performance of quay walls: Numerical Study

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ABSTRACT: Experiences from previous major earthquakes including the 1995 Kobe Earthquake, the 1999 Kocaeli Earthquake and the 2011 Tohoku Earthquake showed that ports and their structural components are exposed to a great seismic risk. Considering the importance of port facilities to the national economy, engineers should pay great attention to the seismic performance of such structures. Different improvement methods for quay wall structures are available. Previous studies showed that the geofoam compressible inclusions and tire crumb-sand mixtures (TC) are successful to reduce the effects of earthquake-induced dynamic forces against rigid earth retaining wall structures and capable of attenuating the dynamic loads. The aim of this study is to determine the effectiveness of the two different lightweight cushion materials to mitigate the potential seismic hazards of the quay walls using the finite element software. This study covers the geofoam layer inclusion and tire waste-sand cushion techniques in a comparative manner. Two different earthquake records were used for the dynamic analysis and the results were evaluated and compared by means of the effectiveness of the proposed cushions under seismic loadings. Results showed that geofoam inclusion against the quay wall structure can successfully reduced the earthquake-induced dynamic earth pressures and permanent displacements whereas it was revealed that the proposed TC cushion layer in this study has a negative influence on the dynamic stability of the quay wall model for the applied dynamic motions.

Keywords: Quay walls, earthquake, geofoam, seismic performance, tire-sand inclusions

1 INTRODUCTION

Marine structures are quite susceptible earthquake induced hazards. As the severity and quantity of major earthquakes have increased recently, mitigation of earthquake hazards of port and marine structures should attract great attention. Considering the importance of such structures to the local, national, regional and even global economy, the vulnerability of such lifelines must be a matter of concern for engineers.

Recent major earthquakes of the 1995 Hyogo-ken Nanbu Earthquake, the 1999 Kocaeli Earthquake, the 2010 Haiti Earthquake and the 2011 Tohoku Earthquake clearly show that such strong earthquakes can severely affect port facilities in minor to major scales (Azeloglu et al., 2014). Extensive damage at the Port of Kobe during the 1995 Hyogo-ken Nanbu earthquake illustrates how vulnerable port systems are to earthquakes. It is reported that the Port of Kobe was heavily damaged during the 1995 Great Hanshin Earthquake. Destructive seismic waves moved the cassion type walls up to 5m seaward with up to 2m of settlement and 4 degrees of tilting (Iai et al., 1996). After the 1999 Kocaeli Earthquake, many container cranes were overturned due to the settlement and the extreme permanent displacements of the quay walls at the Derince Port in Kocaeli, Turkey (Boulanger et al., 2000). Port structures are also very important for the post disaster response of the region in which the earthquake has occurred despite receiving little attention from the earthquake community (Jacobs et al., 2010).

In a port facility, the transhipment of materials and goods are provided by cranes that move alongside the ship and those crane structures are located on quay walls which can be defined as earth-retaining structures at which ships can berth. Stability and safety in addition to the economy is considered and basic design criteria including sliding, overturning and allowable bearing stress are taken into consideration for designing stage of quay walls. For rational design methods of retaining structures that has been pursued for several decades, deformations ranging from slight displacement to catastrophic failure have been observed in many earth retaining structures during the recent major earthquakes (Li et al., 2010).

Dynamic performance of quay walls has been studied by a number of researchers. With performing shaking table and centrifuge tests, researchers investigated the reasons such as liquefaction that lead to the permanent displacement of quay walls (Kohama et al., 1998, 2000; Kim et al., 2005). Dynamic response of gravity quay walls is strongly affected by non-linear soil behaviour. Development of excess pore pressures and accumulation of shear and volumetric strains both at the retained and the foundation soil produced shear strength degradation (Iai et al., 1996; Gerolymos et al., 2015).

Geofoam, which is a super lightweight geosynthetic product is a material composed of foam. This engineered product takes increasing interest of researches due to its unique static and dynamic properties. Both experimental and numerical studies are performed to investigate the effectiveness of expanded polystyrene (EPS) geofoam buffers in reducing the seismic earth pressures on geotechnical structures such as retaining walls. The results from such parametric analyses have been compiled into design charts that quantify seismic isolation efficiency as a function of geofoam buffer thickness and density, wall height, dynamic stress-strain properties of the retained soil mass, and characteristics of the base input excitation (Pelekis et al., 2000; Hazarika 2001; Hazarika and Okuzono 2002, 2004; Zarnani and Bathurst 2005, 2006; Athanasopoulos et al., 2007; Zarnani and Bathurst 2009). Also, Lin et al., 2010 mentioned that EPS geofoam has superior cushion properties due to the individual air bubble body which is a capable of reducing the impact and vibration effects.

The use of vertical compressible layers placed against rigid soil retaining walls to reduce static lateral earth pressures has been reported in the literature by different researchers (Partos and Kazaniwsky 1987; Horvath 1997; and Karpurapu and Bathurst 1992). Hazarika et al., (2008) mentioned that tire cushion reduces the load against the structure due to energy absorption capacity of the cushion material. Another function is to curtail permanent displacement of the structure due to inherited flexibilities derived from using such elastic and compressible materials.

Tire wastes (TW) are commonly used in many different engineering applications due to their convenient engineering properties including thermal insulation, permeability, compressibility, stiffness and also high damping. In addition, a further reason to such convenience is their differentiated sizes and shapes. Scrap tires can be managed as whole, slit, shred, chip, ground, or crumb rubber according to transformation by means of a mechanical size reduction process into a collection of particles, with or without a coating of a partitioning agent to prevent agglomeration during production, transportation, or storage (Edinçliler 2007; Edinçliler et al., 2010). Recently, a new seismic buffer proposed to use tire wastes as energy absorption material due to its enhanced damping and stiffness properties compared to sand itself.

Edinçliler and Toksoy (2014) investigated the performance of retaining wall with tire crumb (TC) cushion by applying design earthquake acceleration-time histories using PLAXIS software and compared with that of only sand backfill. The TC cushion inclusion significantly reduced the maximum shear force and bending moment along the retaining wall for a more economical wall design.

The aim of this study is to determine the effectiveness of two different lightweight cushion materials on seismic performance of quay walls. EPS geofoam and tire waste-sand mixtures are used to increase the seismic performance of quay walls. In literature, both of the materials are defined as superior materials with high vibration absorption properties. Seismic cushions with the same thickness were placed against the rigid quay wall. Numerical studies were performed using the commercially available finite element software of PLAXIS and dynamic analyses were performed using the real earthquake records obtained from Boğaziçi University. The results are compared to an identical structure without a seismic cushion.

2 NUMERICAL STUDY

In this numerical study, a quay wall with two different cushion layer defined as EPS geofoam (Model 2) and tire crumb-sand (TCS) layer between the backfill and the wall (Model 3) is modelled. Considering the super lightweight of both materials and high energy absorption properties, the caisson type quay wall model is expected to perform better both under static and dynamic load conditions. Results obtained from the identical quay wall model with no cushion layer (Model 1) are used for the evaluation the results.

2.1 Numerical Modelling

Finite element analyses were performed using PLAXIS 2D software which is a multi-purpose finite element modelling program capable of modelling various types of real geotechnical applications. Plain strain model is selected and 15-node triangle elements option is preferred. In the dynamic analysis, prescribed displacement along the x-axis is introduced to the model in order to apply the selected earthquake motions for this study. Due to prevent unexpected spurious wave reflections and stress concentrations at the boundaries of the model, the model mesh is created large enough and absorbent boundaries are introduced to the model.

Dimensions of the proposed caisson type quay wall are H=15m and W=10m. Water depth is considered as 10m and the quay wall model has 13m high backfill soil. The quay wall is modelled as a plate element in the software. Finite element model is represented in Figure 1.

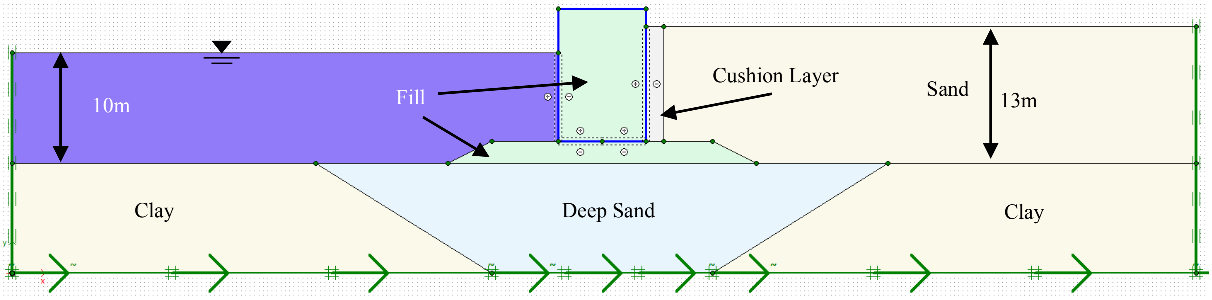

Figure 1: Finite element model representing the quay wall with cushion layer.

2.2 Material Properties

In order to find the optimum sand-tire waste mixture ratio for dynamic analysis, the results of the previous laboratory tests with tire waste-sand mixtures were compiled and evaluated (Edinçliler et al., 2004; Edinçliler et al., 2010). A series of static tests were conducted on only sand and mixtures of tire crumb-sand (TC-S) in percentages of 10, 20 and 30 by weight (Cagatay 2008). By using the same material compositions, cyclic triaxial tests were also performed under three different confining pressures which are 40kPa, 100kPa and 200kPa (Yildiz 2012). Overall evaluation of the previous experimental studies showed that the best seismic performance were obtained for tire crumb-sand mixtures having 70% sand + 30% tire crumb by weight (TC30). By considering the best seismic energy absorption potential of TC30 in both the experimental (Yildiz 2012) and numerical study (Adir 2013). TC30 with the highest damping property is selected as a TCS cushion material.

All materials including the cushion layer are modelled with Mohr-Coulomb soil model. Parameters of soils, TC30 and geofoam cushion layers are given in Table 1. The parameters of the geofoam is obtained from the similar studies and ASTM 6817.

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

Parameters	Sand	Clay	Stiff Sand	Fill	Geofoam	TC30
γ_{unsat}	16.5kN/m^3	16kN/m^3	17 kN/m^3	19 kN/m^3	0.2 kN/m^3	13.8 kN/m^3
c'_{ref}	0kN/m^2	14kN/m^2	0 kN/m^2	5 kN/m^2	35 kN/m^2	30.6 kN/m^2
Ø	33°	24°	35°	35°	30°	35.5°
ψ	8°	0°	5°	10°	0°	0°
E	13560kN/m^2	9000kN/m^2	42000 kN/m^2	200000 kN/m^2	6000 kN/m^2	20000 kN/m^2

Quay wall is modelled as a plate element in the model. Flexural rigidity of the plate is E7.5E^6 with an element thickness of 1m.

2.3 Dynamic Loads

Dynamic analyses were performed using two different real earthquake records with different characteristics. These are the Kocaeli Earthquake (PGA=0.23g) and the Kobe Earthquake (PGA=0.68g) motions. Records are obtained from BU-KOERI-BDTIM and used after baseline correction. Earthquake records with different amplitude and frequency content are given in Figure 2. The predominant frequencies of the records are 3.5Hz and 2.1Hz for the Kocaeli and Kobe Earthquakes, respectively.

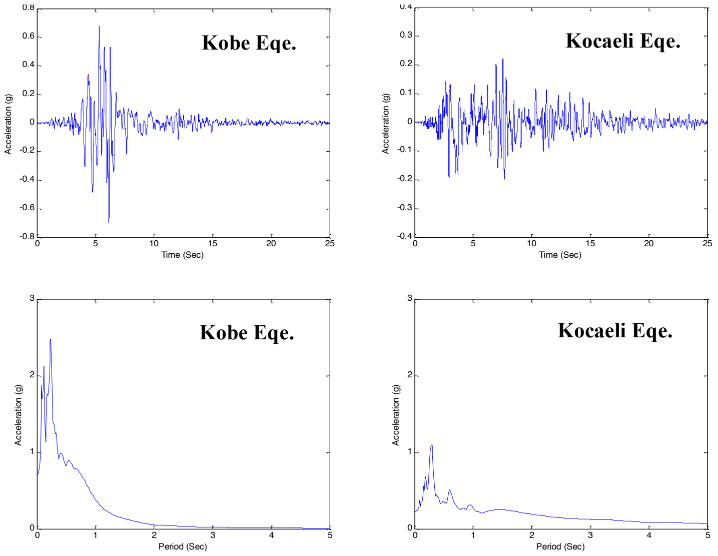

Figure 2: Acceleration-time histories and response spectra of Kobe and Kocaeli Earthquakes.

3 RESULTS

Numerical results obtained from quay wall models with/out EPS geofoam and TCS cushion are represented by means of total displacements, rotations, axial and shear stresses and bending moments for both earthquake records.

3.1 Results of the Kocaeli Earthquake

Total displacement contours after the Kocaeli Earthquake excitations are represented in Figure 3. Total displacements of the quay wall model with no cushion layer are given in Model 1 whereas Model 2 shows the displacement contours with EPS geofoam cushion and Model 3 represents the displacement distribution of the model with TCS cushion.

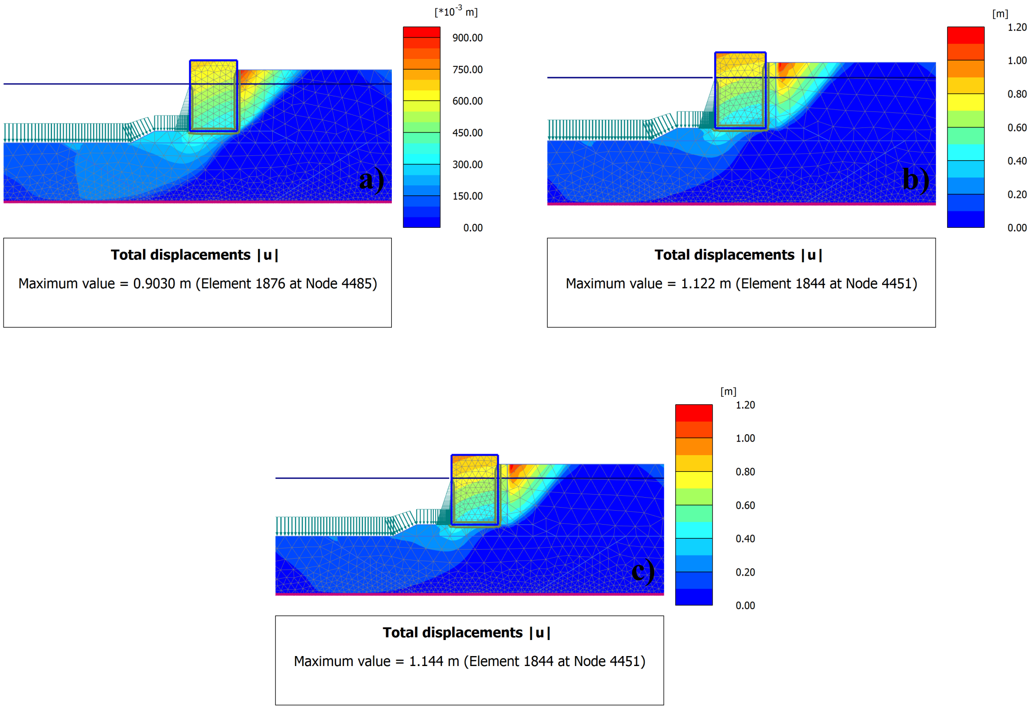

Figure 3: Total displacement contours under Kocaeli Earthquake, a) Model 1, b) Model 2 and c) Model 3.

Numerical results for the quay wall models subjected to the Kocaeli Earthquake motion revealed that the geofoam layer behind the quay wall model leads to an increase in total displacements. Model 1 has a maximum displacement value of 0.9m, whereas it is obtained as 1.12m in Model 2. In Model 3, where the TCS cushion layer is placed behind the quay wall model, displaced 1.14m which is a bit higher than the geofoam cushion case.

Rotations of the quay wall models with respect to the vertical axis revealed that the results are similar to that of the total displacements. Rotation is directly related with displacement values. Inclusion of geofoam layer behind the quay wall model increases the observed rotations from 1.34° to 2.14° in Model 2. The inclusion of TCS cushion leads to a bit increase by means of rotation with 2.18°.

Both materials of EPS geofoam and TCS are considered as super lightweight materials. Using such cushions as a layer behind a quay wall model decreased the axial, shear stresses and the bending moments acting on the wall both in static and dynamic cases. Concurrently, obtained axial stress values are 470.8kN/m, 457.1kN/m and 463.8kN/m for Model 1, Model 2 and Model 3, respectively.

Results clearly show that the proposed cushion layers are successful at reducing shear forces. Obtained shear forces on the quay wall model is reduced from 433.9kN/m to 423.3kN/m in Model 2. TCS cushion seems to be less effective than geofoam layer with obtained shear force of 433.6kN/m.

Obtained bending moment values under the Kocaeli Earthquake excitations show that both cushion materials can successfully decrease the resultant bending moment values from 1232kNm/m to 1204kNm/m in Model 2 and to 1212kNm/m in Model 3.

3.2 Results of the Kobe Earthquake

Obtained total displacement contours after the Kobe Earthquake are represented for Model 1, Model 2 and Model 3 in Figure 4.

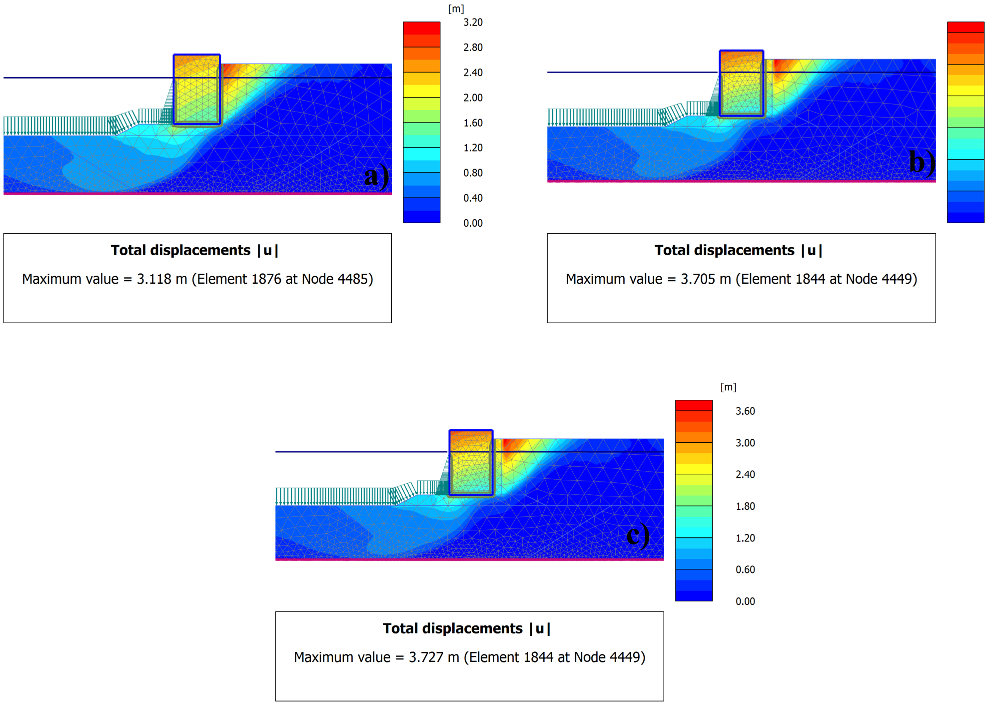

Figure 4: Total displacement contours under Kobe Earthquake, a) Model 1, b) Model 2 and c) Model 3.

More severe deformations are observed in all three models under the Kobe Earthquake excitations than the previous earthquake record. Obtained total displacement values are 3.12m, 3.71m and 3.72m for Model 1, Model 2 and Model 3, respectively.

Similar to the previously obtained results, application of cushion layers behind the quay wall model leads to a bit increase in total displacements and rotations from the vertical axis. Under Kobe Earthquake record, rotations of the models are observed as 4.33°, 6.98° and 7.00° for Model 1, Model 2 and Model 3, respectively.

As previously mentioned, included cushion layers act like a energy absorption system behind the quay wall decreasing the static and dynamic loads effecting on the model. By means of axial forces, outputs are obtained as 654.1kN/m, 619kN/m and 625.6kN/m for Model 1, Model 2 and Model 3, respectively.

Resultant shear stress values follow the same trend. Cushion effect decrease the shear stress values from 599.9kN/m to 570.3kN/m in Model 2 and to 565.6kN/m in Model 3.

Numerical results subjected to Kobe Earthquake motion show that the inclusion of cushion layers has a negligible effect in bending moments. Geofoam cushion decreases the bending moment from 1399kNm/m to 1398kNm/m in Model 2 whereas TCS cushion increases it to 1402kNm/m.

4 DISCUSSIONS

Performed numerical study with the finite element modelling technique aims to improve the seismic performance of quay walls and to evaluate the effectiveness of two different proposed cushions defined as EPS geofoam and TCS in a comparative manner. Both cushion materials are lightweight materials with high energy absorption properties. Figure 5 represents the maximum transmitted acceleration values on the quay wall model for each case. Evaluation of numerical dynamic analyses shows that inclusion of a cushion layer against the quay wall model can successfully decrease the peak transmitted acceleration values and the acceleration distribution along the wall. As seen in Figure 5, the maximum transmitted acceleration values on the quay wall model is reduced from 3.45g to 0.96g and 0.98g in Model 2 and Model 3, respectively. The reduction ratio of the transmitted acceleration values is calculated as 72% in Model 2 and 71.6% in Model 3.

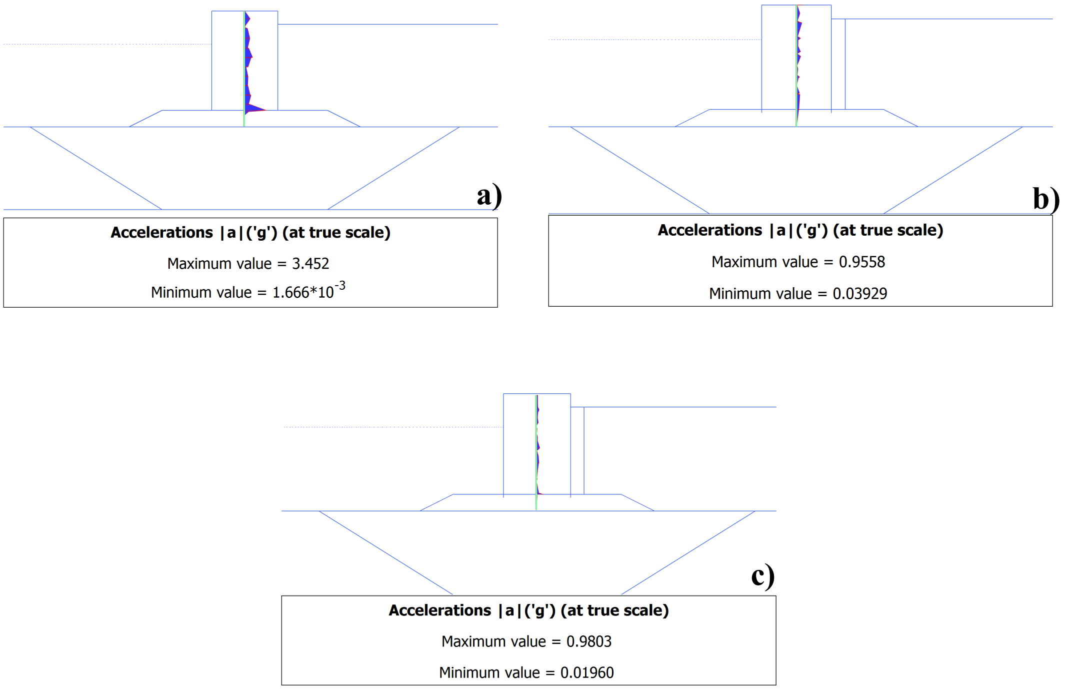

Figure 5: Transmitted acceleration distribution under Kobe Earthquake, a) Model 1, b) Model 2 and c) Model 3.

Obtained results from all quay wall models under the dynamic loads are tabulated in Table 2 for ease of evaluation and comparison.

Table 2. Numerical results.

Performance parameters	Kocaeli Earthquake			Kobe Earthquake		
	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3
Total Displacements (m)	0.90	1.12	1.14	3.12	3.70	3.73
Rotation (°)	1.34	2.14	2.18	4.33	6.98	7.00
Axial Stress (kN/m)	470.8	457.1	463.8	654.1	619	625.6
Shear Stress (kN/m)	433.9	423.3	433.6	599.9	570.3	565.6
Bending Moment (kNm/m)	1232	1204	1212	1399	1398	1402

As can be inferred from Table 2, both cushion materials can significantly decrease the resultant axial and shear forces after subjecting to the seismic excitations. The inclusion of geofoam layer reduces the maximum axial stress by 3% under Kocaeli Earthquake and up to 5.4% under Kobe Earthquake excitations whereas in Model 3, the reduction ratio is calculated as 1.5% and 4.4% under Kocaeli and Kobe Earthquakes, respectively. By means of shear stresses, EPS geofoam can reduce the maximum values by 2.4% and 5% for Kocaeli and Kobe Earthquakes, respectively. However, TCS cushion can decrease the shear stress values only 0.1% under Kocaeli Earthquake but 5.7% under Kobe Earthquake excitations. Bending moments are less likely to be affected by the proposed cushion layers in dynamic analysis. As given in Table 2, quay wall model was subjected to a higher damage state under Kobe Earthquake excitations than the Kocaeli Earthquake. This is related to the higher PGA value and frequency content of the Kobe Earthquake record. On the other hand, it is important to highlight that particularly in Model 3, total displacement values and related rotations according to the vertical axis increase a bit when cushion layers are included to the model.

5 CONCLUSIONS

This preliminary study aims to improve the seismic performance of quay walls by including different cushion layers against the quay wall. Dynamic analyses were performed with the help of the software PLAXIS 2D. Three different finite element models are created and subjected to real earthquake records of Kocaeli Earthquake and Kobe Earthquake. Dimensions of the models are identical but Model 2 includes an EPS geofoam layer and Model 3 has a TCS cushion layer. Thickness of those cushions are equal (2m). Evaluation of the results reveal that the proposed cushion materials acts as a vibration absorption material that significantly diminished the transmitted accelerations. Comparison of axial and shear stresses and bending moments on the quay wall models clearly supports this statement. Considering all evaluation parameters in this study, EPS geofoam cushion may be a better option than tire waste-sand cushion. It is possible to obtain different results under different dynamic loads. In addition, one major limitation of using this kind of super lightweight compressible materials is the excessive displacements and rotations.

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