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# EFFECT OF GROUND MOTION CHARACTERISTICS ON THE SEISMIC PERFORMANCE OF RETAINING WALLS WITH TIRE WASTE CUSHION

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## Abstract

Due to the propagating ground motions, earthquakes are one of the most destructive natural disasters. Earthquakes may be devastating especially to the seismic stability of geotechnical engineering structures such as retaining walls. There are three major ground motion characteristics that affect the degree of damage of a structure subjected to seismic loading, which are amplitude, frequency content and duration of motion. The dynamic response of rigid walls subjected to earthquake motions is quite complex. The dynamic wall pressures acting on the rigid walls are highly dependent on the mode and degree of the wall movement and permanent displacements are highly affected by the natural frequency of the rigid wall-backfill system. The use of compressible cushion-like vertical layers behind retaining walls and rigid walls takes increased attention of researches nowadays as these kind of materials are reported to be reducing the static earth pressures and attenuating the earthquake-induced dynamic earth pressures concurrently. However, the proof of concept through numerical simulations is limited in the literature. In this study, a new proposed earthquake mitigation technique involves the use of tire waste-sand mixture as a cushion between the backfill soil and the retaining wall structure is studied under different dynamic motions with different characteristics. Tire wastes (TW) are preferred in many different engineering applications due to their convenient engineering properties such as thermal insulation, permeability, compressibility, stiffness and also high damping. Tire wastes are used in geotechnical applications as lightweight fill, embankment fill, retaining wall backfill, subgrade insulation for roads, and vibration damping layers. 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. The protective cushion layer should provide flexibility, and thereby stability to the structures during earthquakes by absorbing the seismic energy. The aim of this study is to investigate the effect of ground motion parameters on the seismic performance of the proposed retaining wall design with cushion. Thus, a cantilever type of retaining wall with a TW cushion is modelled by a finite element program called PLAXIS and subjected to dynamic motions with different characteristics such as amplitude and duration. Due to the lightweight of the material and high energy absorption properties, the cantilever type retaining wall performed better both under static and dynamic loads, and this study is concentrated on the effect of ground motion parameters on seismic performance of the retaining wall with tire waste cushion.

*Keywords: earthquake, retaining wall, seismic performance, tire waste cushion*

## 1. Introduction

Tire wastes have many different usage areas especially in civil, geotechnical and geotechnical earthquake engineering due to their convenient engineering properties such as thermal insulation, permeability, compressibility, stiffness and also high damping. Composed in various sizes and shapes, tire wastes are mainly used in landfill construction and operations, landfill closures, alternative daily covers, leachate collection systems, gas venting systems, septic system drain fields, subgrade fill and embankments, backfill for walls and bridge abutments, subgrade insulation for roads, vibration dampening layers [1]. Humphrey (2007) mentioned that tire wastes can solve many geotechnical earthquake engineering problems since it is a lightweight material having vibration absorbtion capacity [2]. Beatty (1981) indicated that tire rubber has high damping capacity due to its extremely high elasticity and good fatigue properties [3]. Common application areas of tire wastes in geotechnical engineering includes the lightweight fills, embankment and retaining wall backfills. This study uses tire wastes as a seismic buffer. This proposed method is a new approach to use tire wastes as energy absorption material due to its enhanced damping and stiffness properties compared to sand itself.

Tire wastes and 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. For most practical purposes, tires and tire products function as homogeneous mixtures, but processing can impact physical characteristics as size and shape are altered and as reinforcing wire and fabric are removed [4]. Using tire wastes in construction requires an awareness of the properties and the limitations associated with their use. Edinçliler et al. (2010) investigated the influence of processing techniques on the mechanical properties of tires wastes [5]. They found that the three factors as normal stress, processing techniques, and the tire waste content significantly affect the mechanical properties of the processed tire wastes. Typical processed tire wastes generally used in civil engineering applications are given in Figure 1.


Fig. 1- Typical shapes of different processed tire wastes (not to scale) [5].

Earthquakes pose a great thread to geotechnical engineering structures such as quay walls and retaining walls. These structures are likely to suffer excessive deformation or damages resulting from the increased earth pressure during the earthquake. However, these structures are the key elements of ports and harbors, transportation system lifelines, and other infrastructural facilities. Therefore, it is necessary to implement a cost effective technique to retrofit such structures, hence enhancing their seismic performance. Inclusion of vertical compressible layers called as cushion can be a solution to increase the stability of the retaining structures in seismic regions. One function of the cushion is to reduce 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 [6].

In the literature, two different compressible materials as expanded polystyrene (EPS), which is called geofoam and tire wastes (tire chips and tire shreds) to attenuate earthquake-induced dynamic earth pressures against rigid walls were studied. The use of vertical compressible layers placed against rigid soil retaining wall structures to reduce lateral static earth pressures has been reported in the literature by different researchers [7-9].

A study by Hazarika et al. (2008) describes the use of tire chips as an innovative cost-effective disaster mitigation technique and states the use of the developed technique using tire chips, which is defined as an emerging geomaterial, can be utilized as a seismic performance enhancer of geotechnical structures. This research was explained as an attempt towards developing an environmentally friendly earthquake resistant technique that has a reasonably good balance of cost and performance, for improving the seismic performance of waterfront retaining structures. The function of the tire chips cushion is to reduce the load and restricting the permanent displacement of such waterfront retaining structures during earthquakes by exploiting the compressibility, the ductility and the energy absorbing capacity of tire chips [6-10].

Performing small-scale shaking table tests to examine the concept of reducing static earth forces against rigid wall structures by placing a compressible vertical inclusion between the wall and the backfill has been widely studied in the literature [11-14]. The tests by Zarnani and Bathurst [12] and Zarnani et al. [14] have demonstrated that peak lateral loads acting on the compressible model walls during simulated earthquake loading were reduced by as much as 40% of the value measured for the nominally identical structure but with no compressible inclusion [15].

There are a number of numerical studies in the literature using the finite element model (FEM) code to model rigid wall structures with a compressible inclusion [9]. Related studies consider the static load conditions as well as the performance of retaining wall backfilled with shredded tires by applying design earthquake acceleration-time histories using the commercially available software PLAXIS and compared with that of sand backfill. Results show that the shredded tire backfill significantly reduces the wall tip deflection and maximum shear force and bending moment along the wall [16]. Edincliler and Toksoy (2014) was proposed an earthquake resistant technique for a retaining wall that involves the use of tire crumbs-scrap tire derived material as a cushion between the backfill soil and the structure [17].

The aim of this study is to use a new potential seismic cushion as tire crumb material to mitigate the structural hazard of retaining walls during earthquake loading by considering the lightweight, compressible, and ductile characteristics of the material. This paper describes the numerical study to investigate the use of compressible tire crumb (TC) cushion to attenuate dynamic loads against rigid retaining wall structures. The effects of TC cushion retaining a sand soil were analyzed under real earthquake records. The results of numerical simulations are compared to an identical retaining wall without a cushion layer. The protective cushion layer is expected to provide flexibility, and thereby stability to the structures during earthquakes by absorbing the energy.

## 2. Numerical Study

The objective of this study is to increase the static and dynamic performance of retaining structures. A cantilever type of retaining wall with a TC cushion is modelled by a finite element program called PLAXIS 2D. Due to the lightweight of the material and high energy absorption properties, the cantilever type retaining wall is expected to perform better both under static and dynamic loads. In the numerical study, Model 1 represent the retaining wall model without the cushion whereas Model 2 is the model that contains the proposed cushion layer.

### 2.1 Materials

The sand material used is named as “Silivri Sand” which is locally found around Istanbul region and it is commonly used for highway embankments. According to the USCS system, the sand material is classified as poorly graded sand (SP) with $C_u$: 2.29 and $C_c$: 1.1 [18].

A new cushion material as tire crumb is proposed to use as a compressible material behind the retaining wall. Tire crumb is also referred to as crumb rubber and ground rubber and is a wire-free fine rubber particle made by size reduction from scrap tires. Various size reduction techniques can be used to achieve a wide range of particle sizes down to 600 µm or less. Crumb rubber has been successfully used in a number of civil engineering applications. Crumb rubber can be considered as lightweight aggregate source due to its low specific gravity, which distinguishes it from other recycled aggregate sources [19].

Tire crumb used is a granular material and it is obtained by processing scrap tires. Tire crumb was purchased from a local company in Istanbul (Figure 2). The tire crumb used in the experiments has an aspect ratio of 1-1.5. The grain size distribution curve of tire crumb is represented in Figure 3.

Fig. 2 - Tire crumbs used in this study.

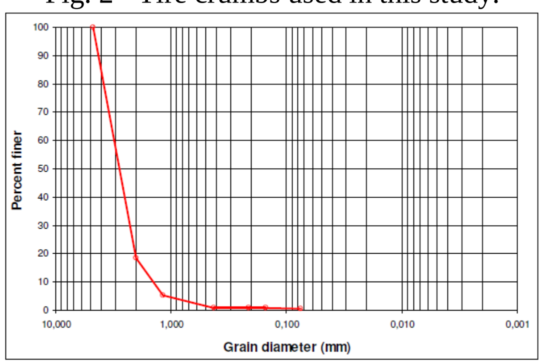


Fig. 3 - Grain size distribution of tire crumbs.

## 2.2 Finite Element Modeling

Numerical studies are performed using the finite element modelling software PLAXIS D 2012 which is a commercially available multi-purpose finite element modelling program and enables to model various types of real geotechnical applications. Plane strain model is used and 15-node triangle option is selected as recommended in the manual which provides very accurate and detailed stress results for complex problems.

Dimensions of the cantilever type retaining wall model is H:7m and L:4.5m. The retaining structure is modelled as a plate element. For the dynamic analysis, prescribed displacement is introduced for the application of the selected earthquake records. And due to prevent unexpected spurious wave reflections and stress concentrations at the boundaries of the model, absorbent boundaries are applied to the model. The cantilever retaining wall model is represented in Figure 4.

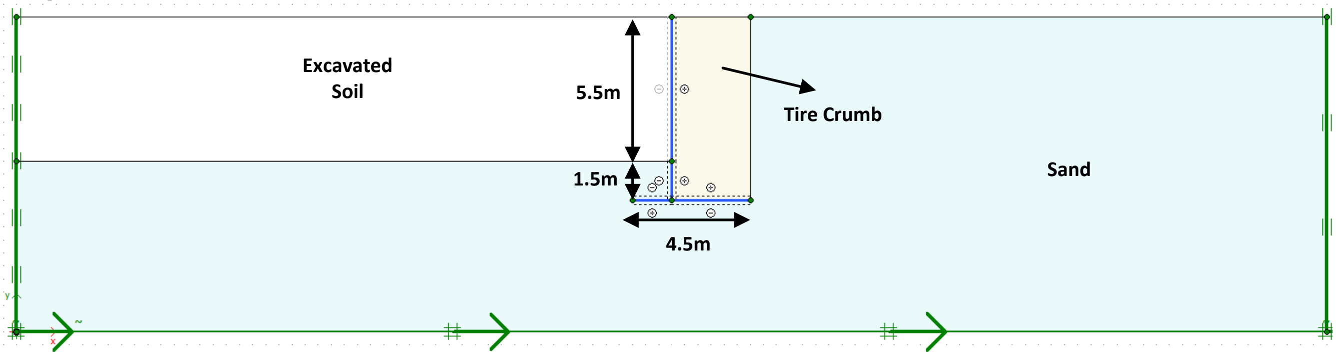

Fig. 4 - Cantilever retaining wall model

The hardening soil model was used to define the material used for the model. The hardening soil model is an advanced model in order to simulate the behaviour of different kinds of soils. The hardening soil model considers both shear hardening and compression hardening situations that is why it is also named as isotropic hardening.

In the numerical models, Silivri sand is used as a backfill material and tire crumbs is used as a protective cushion. The protective cushion is placed along the stem (H=7m.) and heel (W=2m). The material properties are taken from the previous studies with the same kind of sand [16]. Input parameters for Silivri Sand and tire crumbs are represented in Table 1, below.

Table 1 - Input parameters of materials for hardening soil model

| | Sand | Tire Crumb |
|---|---|---|
| $\gamma_{unsat}$ | 16.5kN/m$^3$ | 6.5kN/m$^3$ |
| $c'_{ref}$ | 0kN/m$^2$ | 14kN/m$^2$ |
| Ø | 33° | 24° |
| ψ | 8° | 0° |
| $E_{50}^{ref}$ | 13560kN/m$^2$ | 900kN/m$^2$ |
| $E_{oed}^{ref}$ | 13560kN/m$^2$ | 900kN/m$^2$ |
| $E_{ur}^{ref}$ | 40680kN/m$^2$ | 2700kN/m$^2$ |

Dynamic analyses were performed using two different real earthquake records with different characteristics. These are the El Centro earthquake (PGA=0.36g) and the Kobe Earthquake (PGA=0.68g). Records are obtained from BU-KOERI-BDTIM and used after baseline corrected and filtered from noise contamination. Records vary in amplitude and frequency content parameters as can be seen in Figure 5. The predominant frequencies of the records are 2.1Hz and 4Hz for the Kobe and El Centro Earthquakes, respectively.

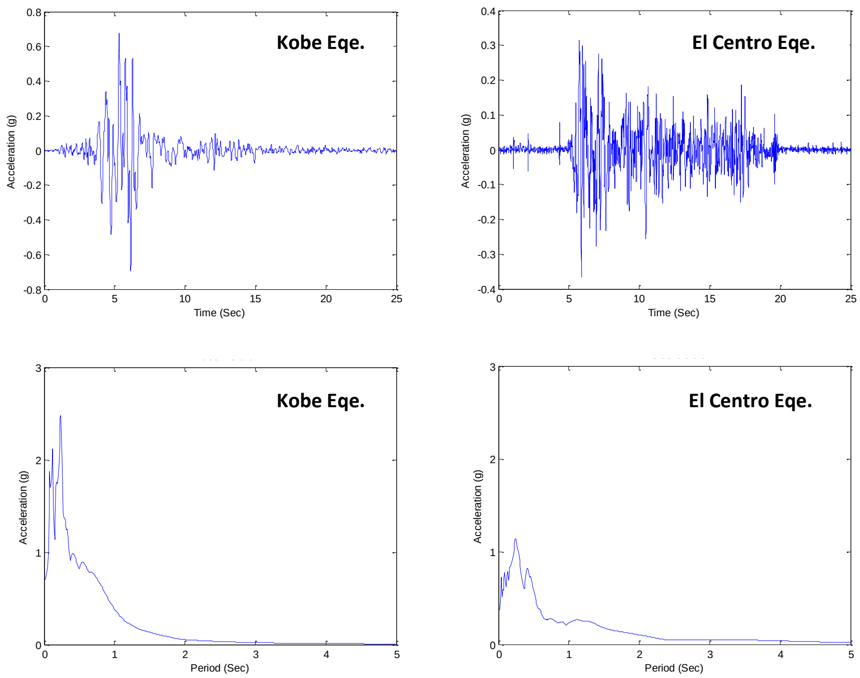


Fig. 5 - Acceleration-Time Histories and Response Spectra of Kobe and El Centro Earthquakes.

## 3. Numerical Results

Numerical results obtained from retaining wall models with/out tire crumb layer are represented by means of total displacements, rotations, axial and shear stresses, bending moments and lateral stresses for static and dynamic cases. Table 2 summarizes the numerical results.

### 3.1 Static Case

Total displacements and lateral stresses occurred under static conditions for both retaining wall models are given in Figure 6 and Figure 7, respectively.

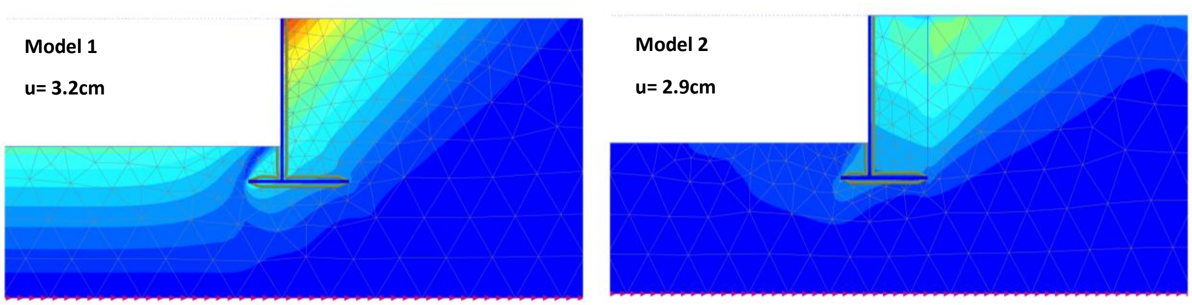


Figure 6. Total displacement contours for retaining wall models under static conditions.

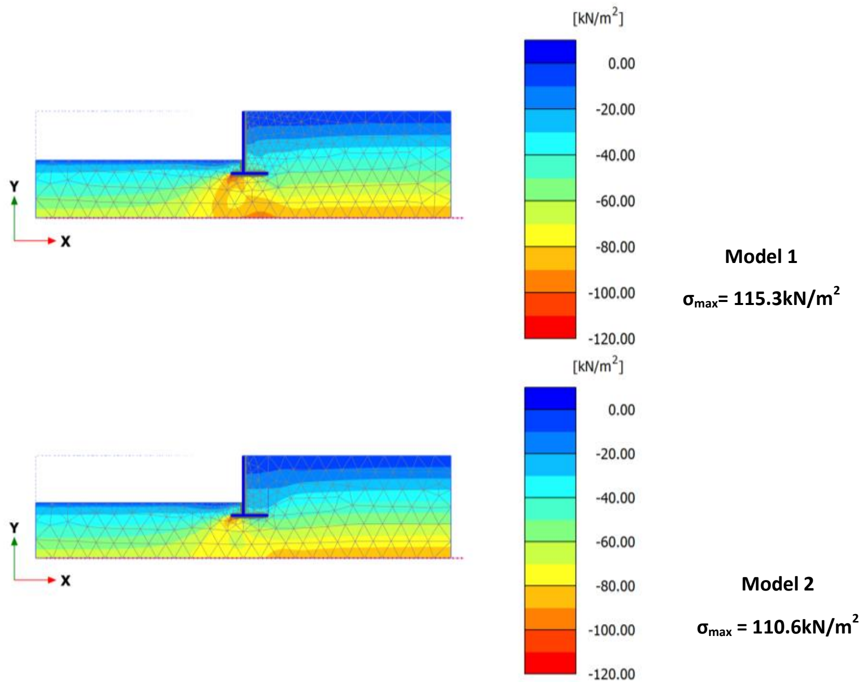


Fig. 7 - Lateral stress contours for retaining wall models under static conditions.

In Figure 6, it is seen that the tire crumb cushion decreases the total displacement values from 3.2cm to 2.9cm under static conditions.

Figure 7 reveals that the lightweight cushion layer can successfully reduce the lateral stress values from 115.3kN/m$^2$ to 110.6kN/m$^2$ under static conditions.

Observed rotations of the retaining wall models with respect to the vertical axis reveal that the results are similar to that of the total displacements (Table 2).. Rotation is directly related with displacement values. Introduction of cushion layer increases the observed rotations from 0.2° to 0.1° in Model 2.

Tire crumb is a lightweight material. The main reason of using a lightweight cushion model is to decrease the axial, shear stresses and the bending moments acting on the wall both in static and dynamic cases. Concurrently, obtained axial stress values are 167.2kN/m and 158.8kN/m for Model 1 and Model 2, respectively.

Similarly, results show that the tire crumb layer is successful at reducing shear forces. Obtained shear forces on the retaining wall model is reduced from 199.7kN/m to 174.0kN/m in Model 2.

By means of bending moments, the proposed cushion layer is capable of decreasing the resultant bending moments from 289.8kNm/m to 231.5kNm/m (Table 2)..

## 3.2 El Centro Earthquake Case

Total displacements occurred under El Centro Earthquake are given in Figure 8 for both models. The effect of tire crumb material on the lateral stress values for Model 1 and Model 2 is shown in Figure 9.

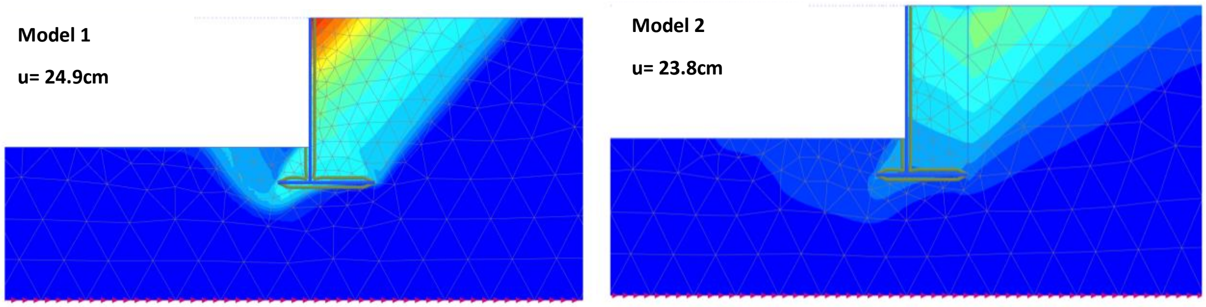


Fig. 8 - Total displacement contours for retaining wall models under El Centro Earthquake.

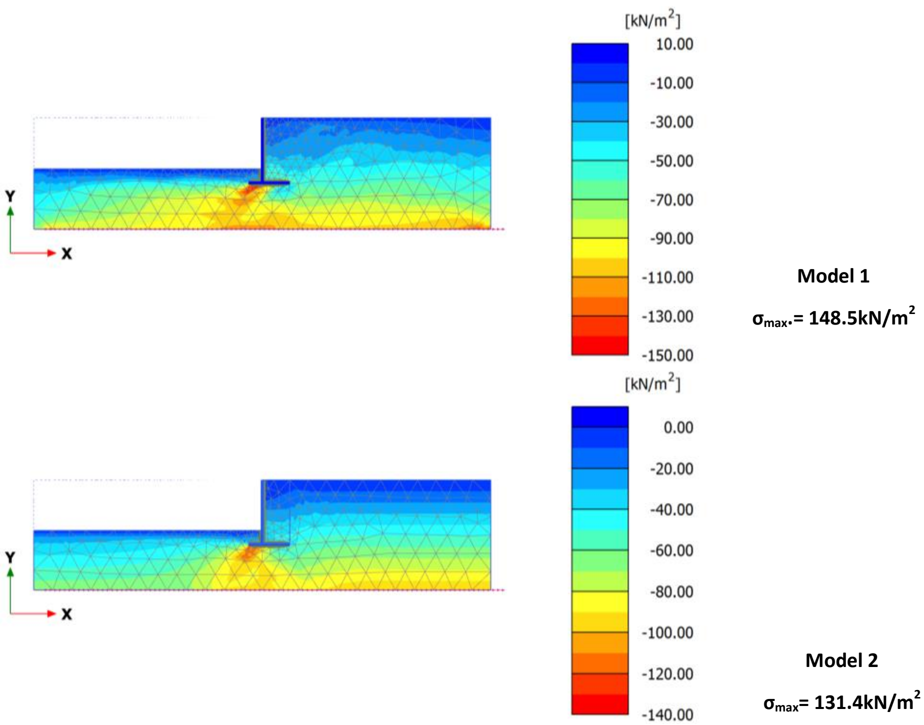


Fig. 9 - Lateral stress contours for retaining wall models under El Centro Earthquake.

Results by means of total displacements show that the cushion layer behind the retaining wall model leads to a decrease in total displacement values. Model 1 outputs a maximum displacement value of 24.9cm, however it is obtained as 23.8cm in Model 2.

It is clearly seen in Figure 9 that the proposed cushion layer works efficiently under dynamic motions. Obtained lateral stresses decreased from 148.5kN/m$^2$ to 131.4kN/m$^2$ in Model 2, when subjected to El Centro Earthquake motions.

Observed rotations of the retaining wall models with respect to the vertical axis reveal that the results are similar to that of the total displacements. Rotation is directly related with displacement values. Introduction of cushion layer slightly decreases the observed rotations from 1.15° to 1.10° in Model 2.

Obtained axial and shear forces are reduced with the introduction of the lightweight cushion layer. Subjected to El Centro Earthquake excitations, axial stress values decrease from 200.8kN/m to 189.1kN/m and the observed shear stresses are reduced from 259.3kN/m to 251.1kN/m in Model 2.

A noticeable decrease in bending moments are observed with the introduction of the tire crumb cushion layer. It is seen that bending moments are obtained to be 420.2kNm/m in Model 1 and 377.4kNm/m in Model 2.

### 3.3 Kobe Earthquake Case

Total displacement contours under the Kobe Earthquake are represented for both models in Figure 10 in addition to the obtained lateral stresses represented in Figure 11.

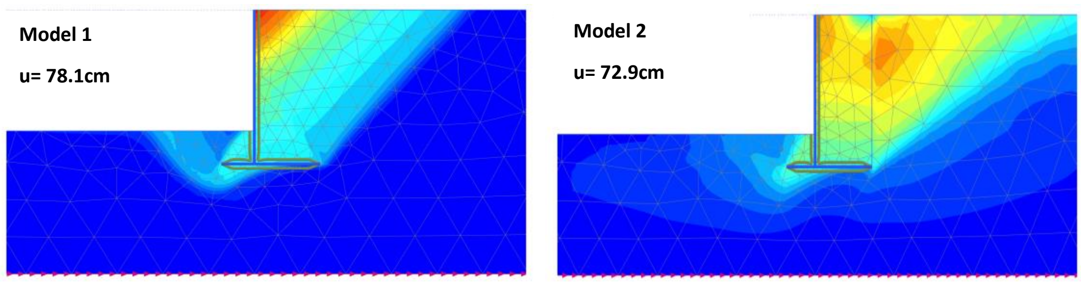


Fig. 10 - Total displacement contours for retaining wall models under Kobe Earthquake.

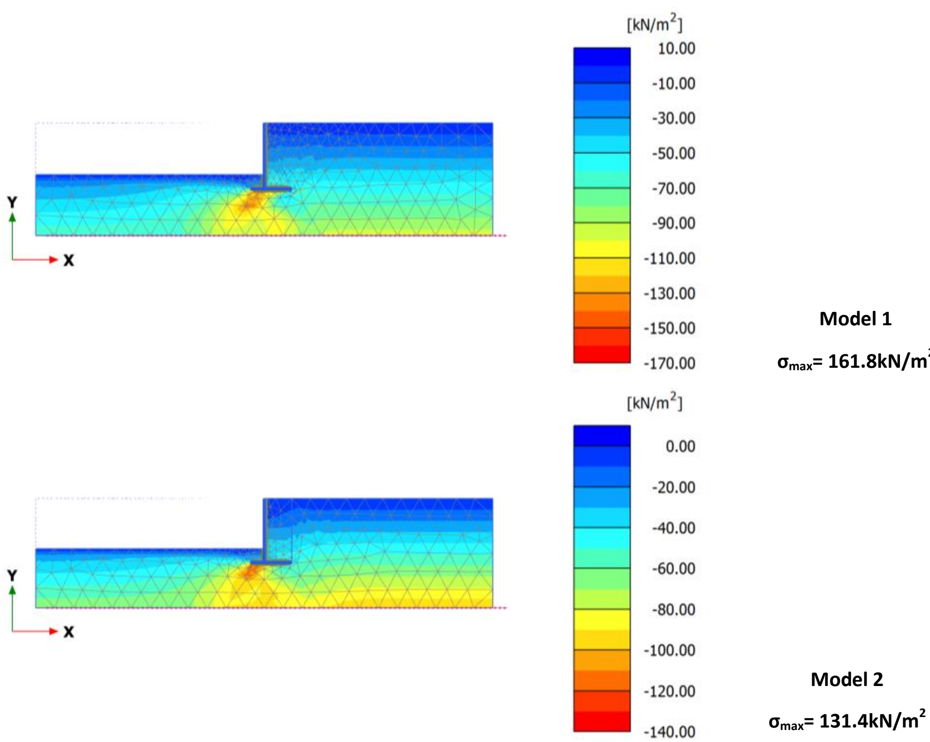


Fig. 11 - Lateral stress contours for retaining wall models under Kobe Earthquake.

Kobe Earthquake excitations affect both models more severe than the El Centro Earthquake case. Obtained total displacement values are 78.1cm and 72.9cm for Model 1 and Model 2, respectively. It is seen that cushion layer leads to a decrease in displacements and rotations under current excitation. Rotations from the vertical axis as a result of the dynamic excitation are 3.4° and 3.0° for Model 1 and Model 2, respectively.

Numerical results by means of lateral stress values indicate that the obtained stress values are reduced from 161.8kN/m$^2$ to 131.4kN/m$^2$ when the cushion layer is introduced to the wall model.

Inclusion of tire crumb layer acts like a cushion behind the retaining wall decreasing the static and dynamic loads. By means of axial stresses, outputs are obtained as 242.4kN/m and 192.3kN/m for Model 1 and Model 2, respectively.

Results of shear stress values are quite similar. Shear stress values successfully decrease from 319.0kN/m to 266.6kN/m in Model 2 with cushion layer.

Resultant bending moments under Kobe Earthquake excitations lead to minor increase with the application of the cushion layer. In Model 1, the observed bending moment is 333.4kNm/m and it is 342.6kNm/m in Model 2.

## 4. Discussions and Conclusions

The aim of this numerical study, which has been performed with the finite element modelling technique, is to improve the seismic performance of retaining walls and to evaluate the effectiveness of the proposed tire crumb cushion layer. Granulated tire is a lightweight material with high energy absorption properties. Performed dynamic analysis indicate that the application of a cushion layer besides the retaining wall model can successfully mitigate the peak transmitted acceleration values and the acceleration distribution along the wall model. As can be seen in Figure 9, the maximum transmitted acceleration values on the retaining wall model is reduced from 2.23g to 1.25g, with a reduction ratio of 44%. It is also notable that the jagged acceleration distribution along the model is smoothened in Model 2 when the tire crumb cushion layer is introduced.

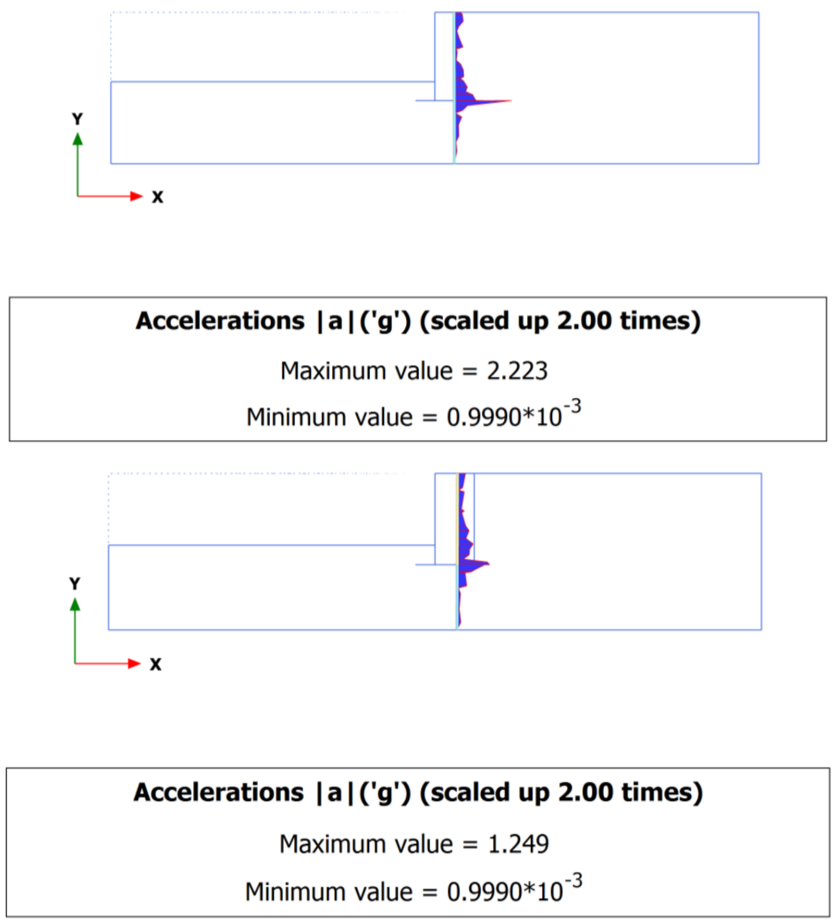


Fig. 9 - Transmitted acceleration distribution under Kobe Earthquake, a) Model 1, b) Model 2.

Given results for both models and excitations are tabulated in Table 2 for ease of evaluation and comparison.

Table 2 - Summary of the numerical results.

| | Static Case | | El Centro Eqe. | | Kobe Eqe. | |
|---|---|---|---|---|---|---|
| | Model 1 | Model 2 | Model 1 | Model 2 | Model 1 | Model 2 |
| Total Displacements (cm) | 3.2 | 2.6 | 24.9 | 23.8 | 78.1 | 72.9 |
| Rotation (°) | 0.2 | 0.1 | 1.1 | 1.1 | 3.4 | 3.0 |
| Axial Stress (kN/m) | 167.2 | 158.8 | 200.8 | 189.1 | 242.4 | 192.3 |
| Shear Stress (kN/m) | 199.7 | 174.0 | 259.3 | 251.1 | 319.0 | 266.6 |
| Bending Moment (kNm/m) | 289.8 | 231.5 | 420.2 | 377.4 | 333.4 | 342.6 |

As can be seen from Table 2, proposed cushion material has high isolation efficiency properties. Performed numerical analyses using the PLAXIS 2D reveal that the application of the proposed cushion layer along the stem of the cantilever type retaining wall is capable of decreasing the axial stress values up to 21% considering both static and dynamic cases. Similarly, shear stresses are reduced by up to 17% when the cushion layer is introduced to the model. Despite the minor increase in bending moments under Kobe Earthquake excitations, tire crumb cushion layer can successfully decrease the affecting bending moments up to 20% in static case and up to 10% under El Centro Earthquake motions. Also obtained lateral stress values clearly indicate that the proposed tire crumb layer is an effective cushion material which is capable of absorbing lateral stresses up to 19% under dynamic motions and up to 4% under static conditions. Another important finding of this study is the improvement of the resultant rotations according to the vertical axis in Model 2, which has a great importance on the static and dynamic stability of such earth structures.

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