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Improving Seismic Performance of Retaining Structures Using A Sustainable Geomaterial

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ABSTRACT: In order to mitigate earthquake hazards of the retaining walls, cost-effective, sustainable and easily applicable solutions can be applied. During an earthquake, the earth pressure on retaining walls significantly increases, resulting in excessive displacements and structural damages. The utilization of lightweight materials as vertical compressible layers, known as cushions, behind the retaining wall is an innovative approach to mitigate earthquake hazards. Waste tire-derived materials-sand mixtures and expanded polystyrene (EPS Geofoam) are some of the lightweight materials used as cushions behind a retaining wall. This study aims to investigate the effects of tire content in the tire waste-sand mixtures on the seismic performance of the retaining wall with a tire crumb-sand cushion by performing a series of shaking table tests. The experiments were carried out using a 1/25 scaled retaining wall model with or without a cushion layer in the rigid-sided soil box under the real earthquake motion. Two different tire crumb contents are considered as the cushion material behind the retaining wall. Shaking table test results showed that increasing tire crumb content has a significant influence on the seismic performance of the retaining wall with the lightweight compressible cushion layer, resulting in up to 17% reduction in acceleration response and 7% decrease in displacement response.

KEYWORDS: Retaining wall, Sustainable geomaterial, Tire crumb-sand mixture cushion, Seismic performance.

1 INTRODUCTION

The three most crucial factors affecting the design, construction, and retrofitting of geotechnical structures against earthquake-induced loadings are cost, environment, and seismic performance. During an earthquake, the earth pressure on retaining walls significantly increases, resulting in excessive deformation and structural damages. To improve the seismic performance of retaining walls cost-effectively, the lightweight materials are utilized as vertical compressible layers, known as “cushions”, behind the retaining wall.

The lightweight materials are utilized in order to reduce gravitational loads, resulting in decreases in bearing loads, settlement, and slope driving forces. Additionally, this improvement method makes the wall design cost-effective because of diminishing the material amount used for wall construction and the cost of lightweight materials compared to conventional backfill. Additionally, these materials have advantageous characteristics, such as low unit weight, low bulk density, and high vibration absorption capacity. Studies by Ertuğrul and Trandafir (2011, 2013), Ertuğrul et al. (2012), Ertuğrul and Özkan (2012), Ertuğrul and Trandafir (2014), Zarnani et al. (2005), Zarnani and Bathurst (2007), Bathurst et al. (2007), Hazarika (2008), and Hazarika et al. (2008) have shown that the use of lightweight cushion layers can reduce lateral forces and permanent displacement of retaining walls under both static and dynamic conditions.

Some materials can be used as lightweight materials, such as chipped bark, sawdust, dried peat, fly ash, slag, cinders, shredded and chipped tire waste, and expanded polystyrene (EPS geofoam) (Nicholson, 2015). The most common type of lightweight material used as a cushion are EPS geofoam and tire waste-sand mixtures.

Foose et al. (1996) investigated the shear strength of sand-tire shred mixtures using direct shear tests, finding that normal stress, sand matrix, unit weight, and shred content significantly influence shear strength. Feng and Sutter (2000) aimed to determine the shear modulus and damping ratio of the granulated rubber-sand mixture, and they found that the tire content strongly influences the shear modulus of the mixture, whereas the damping ratio is not affected significantly. Edinçliler and Yıldız (2022) determined the shear modulus and damping ratio of the mixture of sand and two different types of tire-derived materials. They claimed that the addition of tire-derived materials to the sand significantly affect both the shear modulus and damping ratio in the mixtures, with tire buffing-sand mixtures showing lower damping ratios than tire crumb-sand mixtures. They concluded that the damping ratio of the mixture was influenced strongly by the inclusion of tire-derived materials.

This study aims to investigate the effects of tire content in a tire crumb-sand cushion on the seismic performance of the retaining wall by conducting a series of shaking table tests on the 1/25 scaled retaining wall model without/with the cushion. The cyclic triaxial tests performed by Edinçliler and Yıldız (2022) showed that 30 percent tire crumb addition to the sand by weight (TC30) had the highest damping ratio. As mentioned by Feng and Sutter (2000), tire waste addition with increasing content resulted in more elastic behavior. In the shaking table tests of this study, the cushion with waste tire-sand mixture with 20% and 30% tire crumb content are used as cushion material. The effects of cushion material are evaluated by using the (t) thickness of the cushion material under the 1940 EL-Centro earthquake motion. The performance of the cushion material is obtained by comparing the acceleration and displacement response of the retaining wall.

2 MATERIALS AND METHODS

The information on shaking table tests performed on a 1/25 scaled wall model is given in the following sections.

2.1 *Sand*

The experiments were performed on dry, cohesionless "Silivri Sand". The grain size distribution of sand, determined according to ASTM Standards D422 and D6913, is shown in Figure 1. The uniformity coefficient (C_u) is 2.68, the curvature coefficient (C_c) is 1.06, and the D_{50} value is 0.3. According to the United Soil Classification System (USCS), Silivri sand is classified as poorly graded sand (SP), with a bulk unit weight of 16.5 kN/m³.

2.2 *Tire Crumb*

The grain size distribution of tire crumb, determined based on ASTM Standards of D422 and D6913, is given in Figure 1. D_{50} value was obtained as 2.7. The tire waste material is illustrated in Figure 2. The cushion material consists of waste tire-sand mixtures with tire contents 20% and 30. The cushions were placed behind the model wall at a thickness of 2 cm, corresponding to 50 cm at the prototype wall. The cushions are named TC20/t2 and TC30/t2 based on their tire contents and thicknesses.

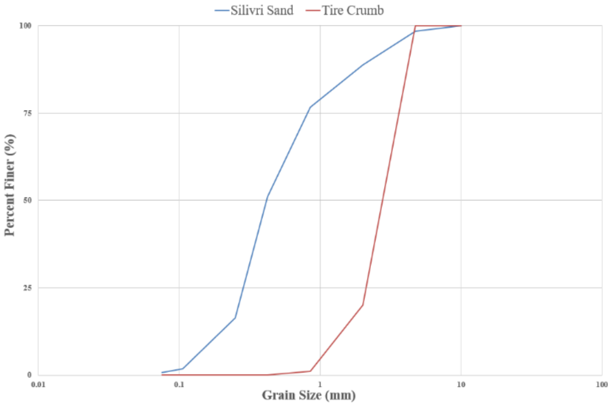

Figure 1. The grain size distribution of Silivri Sand and Tire Crumb.

Figure 2. Tire crumb used in the mixture

2.3 *Experimental Program*

2.3.1 *Wall Model*

In the shaking table tests, a rigid-sided soil box measuring 900x400x500 mm, made of 15 mm thick transparent plexiglass was used. The scaled model was established using scaling laws by Iai (1989), Iai and Sugano (1999) and further developed by Muir Wood et al. (2002) and Muir Wood (2004). In this study, Type III scaling -defined by $\lambda_\rho=1$ and $\lambda_\varepsilon=1$ (Iai and Sugano, 1999)- was adopted with a geometric scale factor of $\lambda=25$. Table 1 summarizes the adopted scale factors and the corresponding parameter values.

Table 1. The scale factor for the 1g shaking table test (Iai, 1989).

Variables	Generalized scaling factors (p/m*)	Scale factors in practice (Type III)	Scale factors (p/m) ($\lambda = 25$)
x (length)	λ**	λ	25
ρ_s (density of soil)	λ_ρ	1	1
ε (strain of soil)	λ_ε	1	1
t (time)	$(\lambda\lambda_\varepsilon)^{0.5}$	$(\lambda)^{0.5}$	5
σ (stress in soil)	$\lambda\lambda_\rho$	λ	25
u (disp.)	$\lambda\lambda_\varepsilon$	λ	25
$\dot{u}$ (vel.)	$(\lambda\lambda_\varepsilon)^{0.5}$	$(\lambda)^{0.5}$	5
$\ddot{u}$ (acc.)	1	1	1
Stiffness of soil	$\lambda\lambda_\rho/\lambda_\varepsilon$	λ	25
Frequency	$\lambda^{-0.5}$	$\lambda^{-0.5}$	1/5

*p/m=prototype/model
**λ=the ratio between prototype and model dimensions

The scaled model, made from aluminum, and the prototype wall along with the 1/25 scaled wall model are depicted in Figure 3.

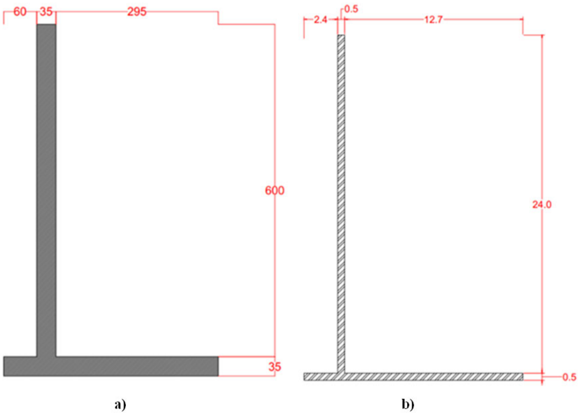

Figure 3. Retaining wall models, a) the prototype wall and b) the scaled wall.

2.3.2 *Sample Preparation*

The shaking table tests both with and without a cushion were carried out on the scaled model of a retaining wall. The foundation soil was placed in two layers and compacted to a density of 16.5 kN/m³. The retaining wall model was then placed on the foundation layer. For the two models with the cushions, a 2 cm thick layer of TC20 and TC30 were placed behind the wall before the backfill soil was placed and compacted into two layers. The experimental setup is illustrated in Figure 4.

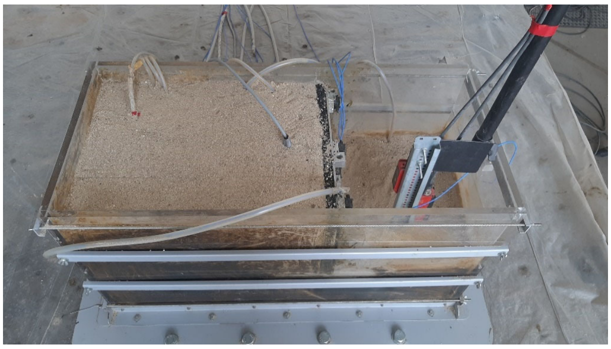

Figure 4. The experimental setup of the retaining wall model with TC30 cushion.

Sixteen accelerometers (A) and three displacement sensors (D) were used to instrument the model, as shown in Figure 5. An accelerometer with a capacity of ±3g was placed on the shake table, while the other accelerometers, each with a capacity of ±20g, were distributed throughout the test setup. Displacement sensors, which are optical distance sensors with a measurement range of 150 - 1200 mm and an absolute measurement accuracy of ±2%, were utilized to measure displacement in the experiments.

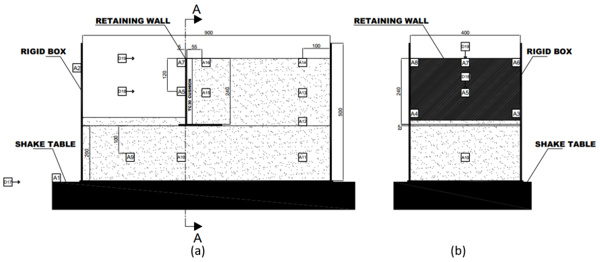

Figure 5. The instrumentation plan a) the side view and b) the cross-section (A-A).

2.3.3 *Shake Table Tests*

The shaking table tests were performed under the real earthquake motion which is the north-south component of the El-Centro earthquake acceleration record. According to the similitude laws proposed by Iai (1989), time scaling was applied to the original earthquake recording using a scaling factor of $n^{0.5}=5$, while the acceleration amplitude was not scaled, as the scaling factor for acceleration is unity. The time-scaled recording was illustrated in Figure 6. Table 2 lists the date, station, predominant frequency, and peak ground acceleration for the selected earthquakes. During the experiments, both acceleration and displacement responses were measured.

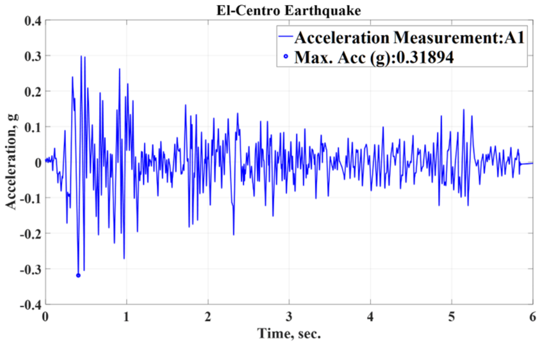

Figure 6. The scaled acceleration-time histories of El-Centro Earthquake (ImperialValley-02).

Table 2. The input motion used in the experimental study.

Name	Date	Station	Comp.	f (Hz.)	PGA (g)
El Centro	18.05. 1940	Imperial Valley-02	N-S	3.4	0.32

3 RESULTS

The effects of tire content of waste tire-sand cushion behind the 1/25 scaled retaining wall model was investigated by comparing the results of the cases with and without cushions.

3.1 *Acceleration Response*

The acceleration-time histories measured at the top of the retaining wall model under the scaled El-Centro Earthquake motion is shown in Figure 7 for cases with and without tire crumb-sand cushion. The amount of reduction in the maximum acceleration for the case with TC20/t2 cushion is 7.4%. On the other hand, the TC30/t2 cushion application resulted in a 16.8% decrease in the maximum acceleration.

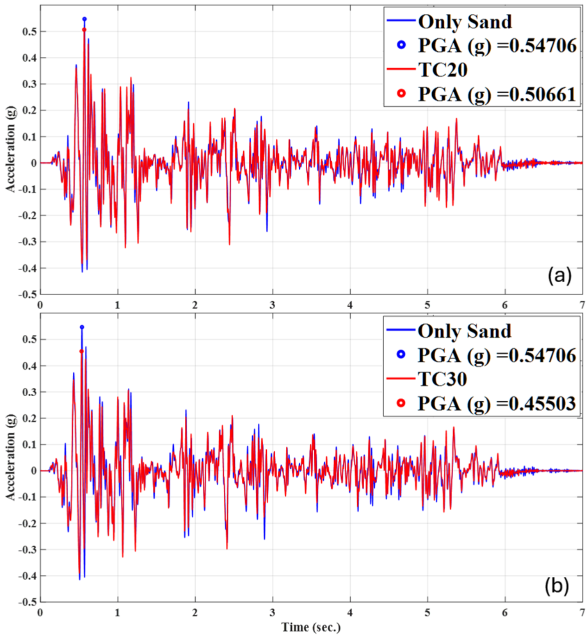

Figure 7. Acceleration time histories at the top of the model wall under El-Centro Earthquake motion (a) for TC20/t2, (b) for TC30/t2.

Figure 8 shows a comparison of the cases with waste tire-sand cushion having 20% and 30% tire content with the only sand backfill. The decrease in maximum spectral acceleration is 7.1% due to the placement of TC20/t2 cushion behind the wall. For the case with TC30/t2 cushion, the maximum spectral acceleration reduces at a rate of 17.3%.

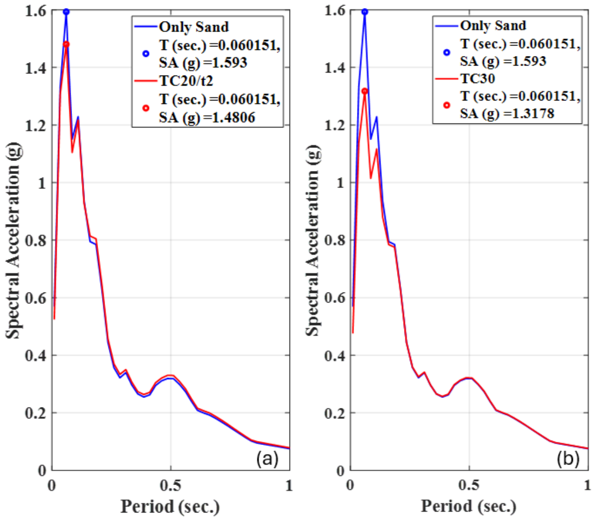

Figure 8. Spectral acceleration under El-Centro Earthquake motion at the top of the model wall (a) for TC20/t2, (b) for TC30/t2.

3.2 *Displacement Response*

The displacement-time histories measured at the top of the wall is shown in Figure 9. The cushion with TC20/t2 caused a 2.3% reduction in maximum displacement value, whereas the amount of decrease in maximum displacement values is 6.8% for TC30/t2 case.

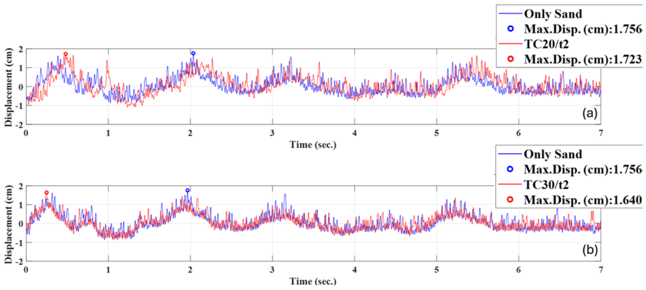

Figure 9. Displacement-time histories at the top of the model wall under El-Centro Earthquake motion (a) for TC20/t2, (b) for TC30/t2.

4 DISCUSSION AND CONCLUSION

The effects of tire content of cushion on the seismic performance of the retaining wall are investigated by carrying out a series of shaking table experiments on 1/25 scaled retaining wall model. The cushions were established using waste tire-sand mixtures with different tire crumb content under the El-Centro Earthquake motion. The comparison of the acceleration and displacement responses of the cases with and without cushion demonstrated the effectiveness of the tire crumb-sand cushion, showing up to about 17% reduction in acceleration responses and approximately a 7% reduction in displacement response.

The results of the experiments show that the seismic performance of the retaining wall improves due to the placement of the cushion layer behind the wall. The improvement in seismic performance may be related to the vibration-absorbing capacity of the tire crumb particles. The elastic nature of these particles allows the tire crumb–sand mixture to dissipate energy when it is placed between the retaining wall and the backfill soil. Damping in a rubber–sand mixture mainly results from friction at the particle contacts and from particle deformation. Sand particles are very stiff and do not absorb much energy, whereas rubber particles deform more easily and therefore dissipate more energy (Feng and Sutter, 2000). Additionally, Edinçliler and Yıldız (2022) indicated that the shear modulus and damping ratio of the sand are strongly affected by the amount of tire crumb included in the mixture. Consequently, the cushion layer composed of tire crumbs and sand decreases the acceleration and displacement response of the retaining wall. These reductions indicate that the cushion layer can effectively mitigate seismic hazards due to its vibration-absorbent and elastic properties.

The experimental results are only valid for the test conditions and input motion used in this study. Future studies for the proposed cushion material are recommended with additional parameters under different earthquake motions.

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