Research Article *Open Access*

Journal of Geoscience and Eco Agricultural Studies

ISSN: 3067-7297

DOI: *doi.org/10.63721/25JGEAS0126*

Effects of Sustainable Buffer Materials on the Seismic Performance of Retaining Walls

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Citation: Ayse Edincliler, Bilge Sultan Demirtas (2025) Effects of Sustainable Buffer Materials on the Seismic Performance of Retaining Walls. J. of Geo Eco Agr Studies 2(4): 1-09. WMJ/JGEAS-126

Abstract

Retaining structures play a crucial role in civil engineering by supporting soils, especially in seismically active regions. Earthquake-induced lateral loadings can significantly increase lateral forces and movements on retaining walls, resulting in structural instability. An innovative method to mitigate earthquake hazards is the utilization of compressible and lightweight buffers, such as rubber–sand mixtures and EPS geofoam, behind retaining walls. This study presents a comprehensive literature review of experimental studies that have investigated the effect of a compressible layer on the performance of retaining walls under dynamic loading conditions. It has been demonstrated that seismic buffers have a significant role in decreasing the lateral forces and permanent displacement of the retaining walls. Additionally, this study includes one of the experimental studies in the literature that examines the seismic response of the scaled retaining wall using shake table tests. Test results are given as an example of the buffer application. A rubber–sand mixture is used as a sustainable buffer material. The experimental results are consistent with the literature, demonstrating that the inclusion of a sustainable buffer effectively reduces both acceleration and displacement responses.

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Submitted: 11.12.2025 **Accepted:** 16.12.2025 **Published:** 30.12.2025

Keywords: Retaining Walls, Seismic Performance, Sustainable Materials, Rubber–Sand Mixture, Buffer, Shake Table Tests

Introduction

Retaining walls are key components of infrastructural systems, and their importance becomes more pronounced in earthquake-prone areas. Past earthquakes have shown that retaining structures experienced a wide range of damage, from negligible deformation to total collapse. This is mainly because earthquakes result in a significant increase in lateral earth pressures and deformations of the retaining walls. The failure of the retaining walls causes serious vital and economic problems. For this reason, practical and cost-effective solutions are essential for improving the seismic performance of retaining walls.

Using lightweight and compressible materials is an innovative technique for mitigating earthquake hazards. These materials are placed behind the retaining walls as a seismic buffer due to their various advantageous features, such as low unit weight, low bulk density, and high vibration absorption capacity. Tire waste–sand mixtures and expanded polystyrene (EPS) geofoam are commonly used as a buffer behind retaining walls.

The effectiveness of buffer materials behind retaining walls has been investigated under static and dynamic loading conditions through several experimental studies [1-16]. It has been demonstrated that lightweight materials are highly effective in reducing lateral forces, displacement, and acceleration responses of the retaining walls. Additionally, the level of improvement on the seismic performance of the retaining wall depends on several parameters, such as buffer thickness, buffer density, and the characteristics of the input motions.

This study consists of two main components. In the first part, experimental studies on the use of a buffer behind retaining walls are evaluated. The second part of the study includes an example case that evaluates the seismic performance of a cantilever retaining wall with a buffer. A 1/25-scaled wall model was tested with and without a rubber-sand buffer layer under the real acceleration time histories by performing shake table tests. Increasing the amount of tire waste in the mixture leads to more elastic behavior [17]. Furthermore, the rubber-sand mixture with 30% tire crumb content exhibited the highest damping values in sand–rubber mixtures when the change in tire content (from 10 to 30%) was examined [18]. Therefore, the shaking table tests were conducted using a buffer layer consisting of a rubber-sand mixture with a 30% tire crumb. The previous experimental studies and the results of the example case are assessed in combination.

Literature Review

This section summarizes the experimental studies that investigated the use of lightweight and compressible buffer materials behind the retaining walls.

The rigid retaining wall with EPS geofoam buffer was tested by performing shaking table tests on the experimental model, illustrated in Figure 1 [1-3]. A sinusoidal motion with stepped amplitudes up to 0.8g and a frequency of 5 Hz is used as an input motion. The EPS geofoam was used as a seismic buffer with various densities and elastic moduli [1, 2]. Additional factors, including buffer compression, the dynamic elastic modulus of the inclusion material, the friction angle between the retained soil and EPS geofoam, amplification of excitation, stress release, and creep, have been investigated by Zarnani and Bathurst [3]. The results of the experiments showed that a reduction in the density, stiffness, and modulus of EPS geofoam caused a decrease in the lateral forces acting along the retaining wall. The cohesive (or adhesive) interface shear strength parameters between the backfill soil and EPS geofoam reduced with increasing density of buffer material.

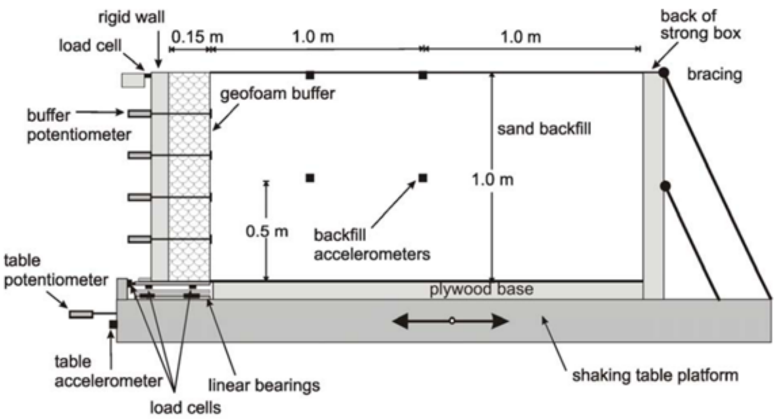

Figure 1: The Experimental Setup and Instrumentation [1-3].

A series of experimental studies has investigated the use of tire-derived materials as seismic cushions behind caisson-type quay walls using both small-scale and large-scale steel box models, as shown in Figure 2 [4-7]. Hazarika [4] evaluated the SAFETY (Stability and Flexibility of structures during earthquake using TYres) technique using small- and large-scale models subjected to sinusoidal and real earthquake motions. The results showed that tire-chip cushions have effectively decreased seismic loads and wall deformations, allowed for reductions in wall dimensions due to the decrease in load, reduced project costs, and provided an environmentally friendly improvement method. Hazarika et al. and Hazarika et al. have performed shaking table tests using a large-scale experimental model, where tire chips were placed behind the quay wall under seismic loading [5,6]. They have concluded that the tire chips led to reductions in lateral forces and permanent displacements and helped prevent liquefaction due to faster dissipation of pore water pressure compared to sand backfill without a cushion. Hazarika et al. (2010) have conducted shaking table tests on a small-scale test setup using a rubber-sand mixture with varying tire chip content under sinusoidal excitations ranging from 0.1g to 0.6g. The cushion layers have reduced both the lateral forces and residual displacements measured on the wall.

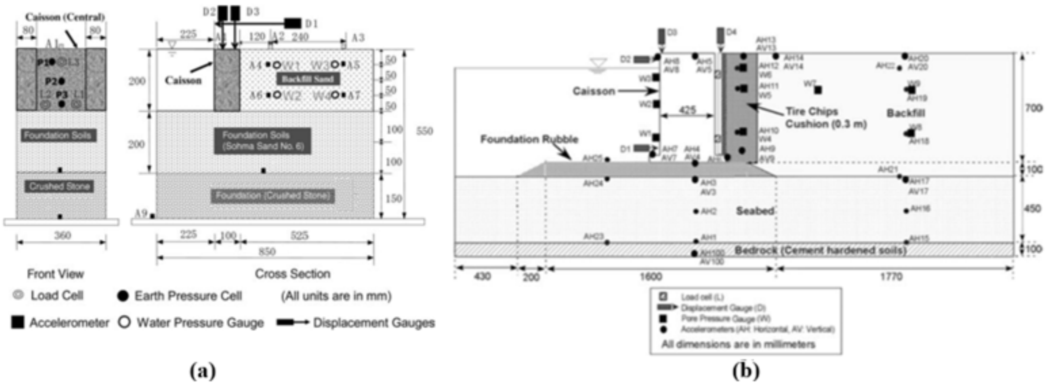

Figure 2: The Small-Scale (a) and the Large-Scale (b) Experimental Models and Instrumentation [4-7].

Ertuğrul et al. Ertuğrul and Özkan and Ertuğrul and Trandafir have investigated the influence of compressible EPS and XPS inclusion layers on lateral earth pressures acting on rigid and flexible retaining walls under static and dynamic conditions [8-11]. They investigated the influence of various parameters, including inclusion thickness, wall height, wall flexibility, inclusion type, and excitation characteristics, by performing shaking table tests on the retaining wall model shown in Figure 3. Ertuğrul et al. have claimed that EPS inclusion reduced lateral earth pressures more effectively for rigid walls than for flexible walls under static loading [8]. Ertuğrul and Özkan indicated that increasing wall flexibility decreased the efficiency of the compressible inclusion, while increasing the thickness of the cushion improved the attenuation effects on the lateral forces

[9]. Ertuğrul and Trandafir reported that reductions in lateral thrust and earth pressure coefficients depend on the inclusion thickness, stiffness, wall flexibility, wall height, and the strength characteristics of the backfill [10]. Ertuğrul and Trandafir have demonstrated that increasing the motion frequency and amplitude results in higher wall displacements and soil settlements in the backfill soil [11]. The compressible layer reduced both lateral forces and wall flexural movements, and XPS exhibited slightly lower load-reduction performance compared to EPS.

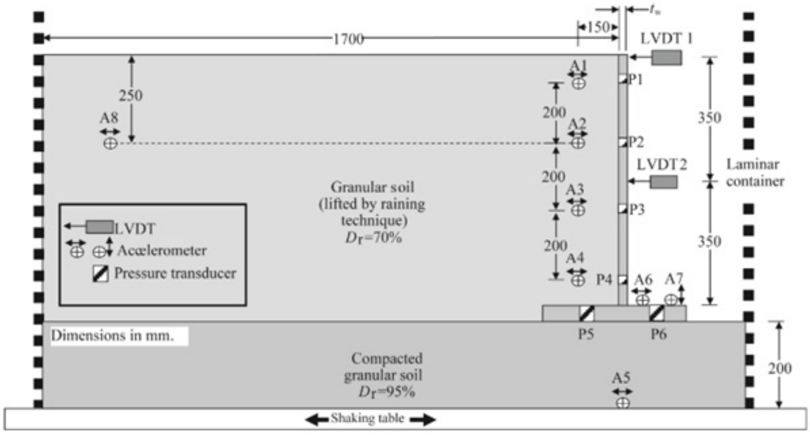

Figure 3: The Experimental Setup and Instrumentation Plan [8-11].

A 1/25-scaled retaining wall model was tested in a rigid-sided plexiglass soil box, as shown in Figure 4, in order to evaluate the influence of lightweight cushion materials on the seismic performance of the retaining wall [12-16]. Demirtaş investigated both EPS geofoam and tire crumb–sand mixtures as cushion layers, examining the effects of cushion thickness, EPS density, rubber content of the tire crumb-sand mixtures, and input motion characteristics [12]. It has been claimed that the seismic behavior of the retaining wall was strongly influenced by cushion material, and EPS geofoam was found to perform more efficiently than the rubber–sand mixtures. Additionally, the increase in cushion thickness resulted in a reduction in the responses of the retaining wall. Edinçliler and Demirtaş have examined the influence of earthquake characteristics on the seismic performance of the retaining wall with a cushion layer with a rubber-sand mixture with 10% tire content [13]. Edinçliler and Demirtaş have evaluated the effectiveness of rubber-sand mixtures under two different earthquake motions [14]. Edinçliler and Demirtaş have investigated the effect of EPS geofoam density under sinusoidal excitation, while Edinçliler and Demirtaş performed shake table tests on EPS geofoam cushion under the real earthquake motion [15,16]. The results of the experiments demonstrated that the inclusion of lightweight materials—particularly EPS geofoam and rubber-sand mixtures— as a cushion behind the retaining wall decreased the acceleration and displacement responses of the retaining wall. Additionally, it is clearly shown that he effectiveness of the cushion depends strongly on material properties and input motion characteristics.

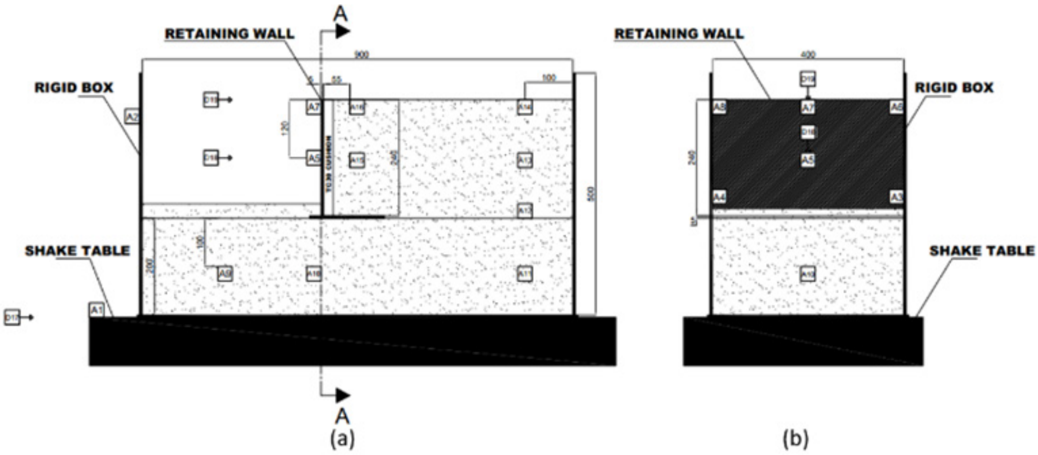

Figure 4: The Experimental Setup and Instrumentation Plan [12-16].

Example Experimental Case

To explain the effectiveness of sustainable buffer materials, shake table tests conducted using a scaled retaining wall model are given as an example. The properties of the materials and the preparation of the test setup are explained in this section.

Materials and Methods

Sand and Tire Crumb

Dry, cohesionless sand and mechanically processed waste tire materials were used in the shake table tests. The grain size distributions of the materials, as given in Figure 5, were determined based on ASTM D422 and D6913 [19,20]. For sand, the uniformity coefficient (Cu), curvature coefficient (Cc), and D50 were calculated to be 2.68, 1.06, and 0.3, respectively. According to the Unified Soil Classification System (USCS), sand was classified as poorly graded sand (SP), and its bulk unit weight was measured as 16.5 kN/m³. The tire crumb has a D50 value of 2.7 mm. The sustainable buffer material was prepared by mixing Silivri Sand and 30% tire crumb by weight, with a unit weight of the mixture measured at 12.5 kN/m³. The buffer layer was placed behind the model retaining wall at a thickness of 2 cm, corresponding to 50 cm in prototype model.

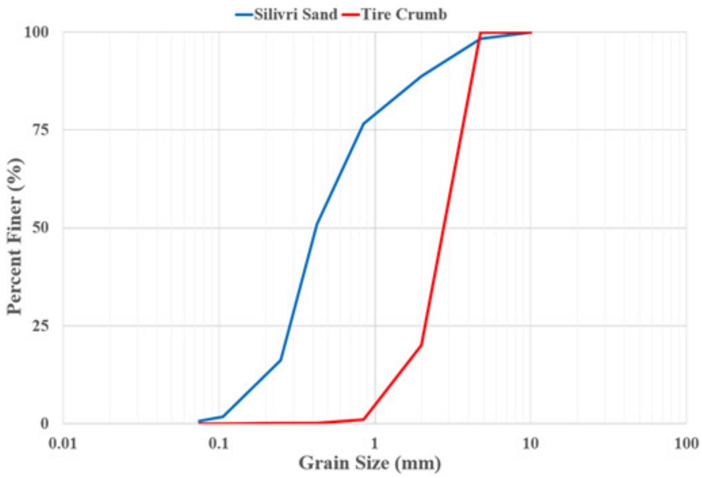

Figure 5: The Grain Size Distribution of Silivri Sand and Tire Crumb.

Wall Model and Soil Box

The physical model is constructed at a scale factor of 1/25, which was selected according to the dimensions of the soil box used in the experiments. The model dimensions are derived using the scaling relations proposed by Iai and developed by Muir Wood et al. and Muir Wood, as summarized in Table 1 [21-23]. The scaled wall model was fabricated from aluminum. The rigid-sided soil box used in the shake table tests has dimensions of 900×400×500 mm and was constructed from transparent plexiglass with a thickness of 15 mm.

Table 1: The Scale Factor for the 1g Shaking Table Test [21].

Variable	For 1g Model	Scale Factor	Variable	For 1g Model	Scale Factor
Length	n	25	Stress	n	25
Density	1	1	Strain	1	1
Acceleration	1	1	Dynamic Time	n0.5	5
Displacement	n	25	Frequency	1/n0.5	1/5

Sample Preparation and Shake Table Tests

The experimental models are prepared with the retaining wall model with and without the TC30 buffer layer. Before placing the sand into the plexiglass rigid box, the inner surfaces are coated with grease oil to better simulate field conditions, reduce wave reflections, and minimize boundary effects. The foundation soil is placed in two layers and compacted to a unit weight of 16.5 kN/m³; the retaining wall model is then placed on top of it. For the case without a buffer, the backfill is poured in two layers and compacted. For the buffered case, a 2-cm-thick TC30 layer is applied behind the wall, followed by the placement and compaction of the backfill soil, as shown in Figure 6. Accelerometers are located during sample preparation at the locations shown in Figure 4.

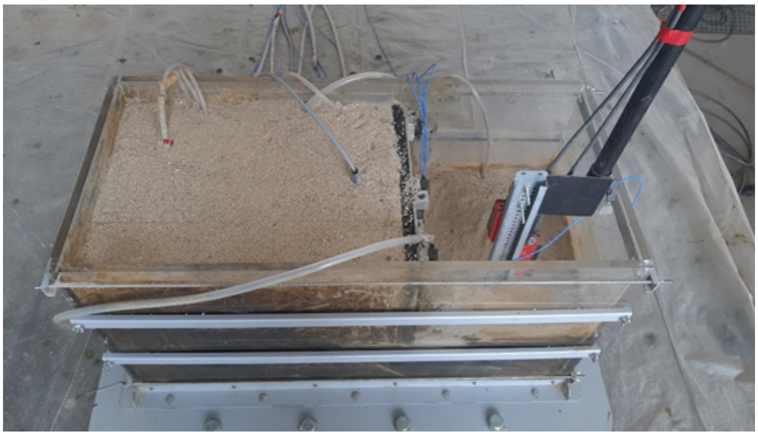

Figure 6: The experimental setup of the retaining wall model with TC30 buffer.

The test setups are subjected to an earthquake recording: the 1940 El Centro Earthquake. Input motion is time-scaled according to the similitude laws proposed by Iai, as illustrated in Figure 7 [21]. During the tests, the acceleration and displacement responses of the retaining wall model were measured.

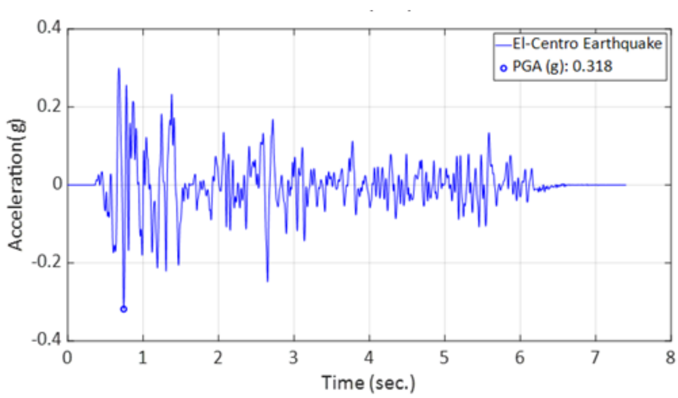

Figure 7: The Scaled Acceleration-Time History of the El-Centro Earthquake.

Results of Shake Table Tests

The results of the experiments are presented in this section, evaluating the acceleration and displacement responses at the top of the retaining wall under the selected input motion with and without the buffer layer.

Acceleration Response: Figure 8 presents a comparison of the acceleration time histories for cases with and without the TC30 buffer under the El Centro Earthquake acceleration record. A peak value of 0.55g is measured at the top of the wall for the only sand model. When the tire crumb–sand mixture is included as the sustainable buffer layer, the peak acceleration is measured at 0.46g, indicating a reduction in transmitted accelerations. The maximum reduction due to the buffer application is approximately determined as 17%.

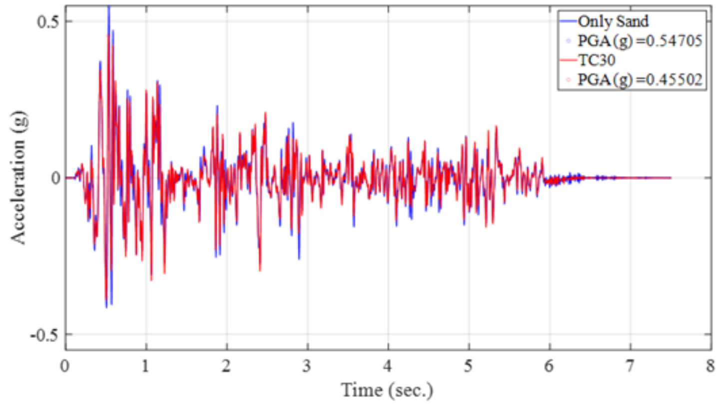

Figure 8: The Comparison of the Acceleration Time Histories of the Wall with and without a Buffer.

The spectral accelerations for the cases with and without the tire crumb–sand mixture are presented in Figure 9. Under the applied input motion, the inclusion of the rubber–sand buffer leads to a reduction in the maximum spectral acceleration from 1.59g to 1.32g, corresponding to a 17.3% decrease.

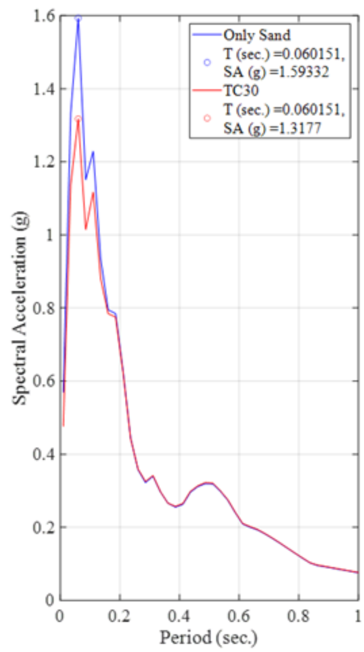

Figure 9: The Comparison of the Spectral Accelerations of the Wall with and without a Buffer.

Displacement Response: The effects of the buffer application on the seismic performance of the retaining wall are not clearly evident in the displacement response, as illustrated in Figure 10. The permanent displacement at the top of the wall decreases from 1.76 cm to 1.64 cm when the tire crumb–sand mixture is placed behind the retaining wall model as a sustainable buffer. An approximate 7% reduction in displacement is observed.

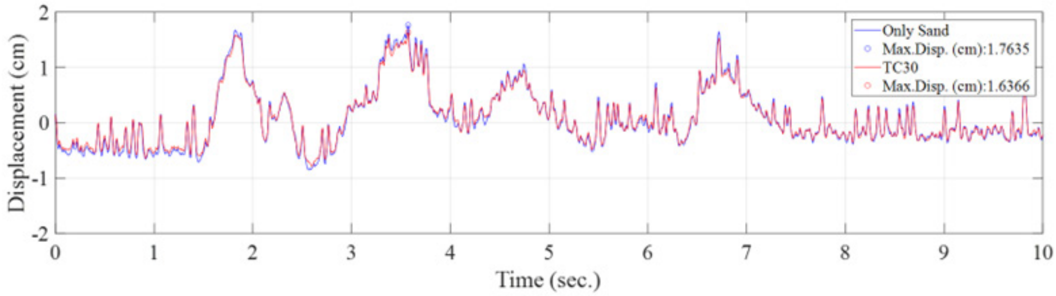

Figure 10: The Comparison of the Displacement Time Histories of the Wall with and without a Buffer.

Discussion and Conclusion

This study presents both an extensive literature review on shake table tests performed on lightweight inclusions behind retaining walls and an experimental investigation on the use of a lightweight, compressible buffer layer to improve the seismic performance of the retaining wall. The literature review has evaluated previous experimental studies on the inclusion of compressible buffer materials, such as EPS geofoam and tire waste-sand mixtures. The effectiveness of the buffer materials in reducing lateral forces, wall displacements, and wall responses has been clearly demonstrated. Furthermore, the cushion type, cushion thickness, and input motion characteristics have a significant role in improving the seismic performance of the retaining wall.

In the experimental study, the effectiveness of the sustainable buffer layer on the seismic performance of the retaining wall is evaluated. Shake table tests have been carried out on the 1/25-scaled retaining wall model. A rubber-sand mixture with 30% tire crumb has been selected as a sustainable buffer material. As an input motion, real earthquake motion is utilized. The results of the experiments showed that the inclusion of the sustainable buffer causes reductions in both acceleration and displacement responses of the retaining wall. Therefore, it was clearly observed that the seismic performance of the retaining wall has been improved due to the application of a buffer layer. The vibration-absorbing capacity, elastic, and compressible behavior of the tire crumb materials resulted in the dissipation of energy transmitted to the retaining wall, which means an improvement in seismic performance.

Overall, the results of the example tests align well with the previous experimental studies examined in the literature review section. The improving effect of buffer layers on the seismic performance of the retaining wall has been clearly highlighted. Additionally, the findings suggest that tire–sand buffers can be a practical, efficient, and environmentally sustainable solution for decreasing earthquake-induced damage. Lastly, it is also important to emphasize that the results presented in this study are valid for reviewed literature study, the model configuration, material properties, and earthquake motions considered in this study.

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