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Seismic Responses of Geogrid Reinforced Wall with Tire Derived Aggregates (TDA) Backfill using Reduced-Scale Shake Table Test

Les réponses sismiques des géogrilles renforcée mur avec des granulats de pneus dérivés (TDA) en utilisant remblai d'essai à échelle réduite table vibrante

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ABSTRACT: This paper reports a preliminary shake table test on a reduced-scale mechanically stabilized earth (MSE) wall with tire derived aggregates (TDA) backfill. The model MSE wall was built inside a steel-frame box on a one-dimensional shake table. The wall was 1.5 m high, 1.2 m deep, and 1.5 m long, and five layers of TDA backfill were reinforced using geogrid. The 1989 Loma Prieta earthquake excitations were scaled up based on a similitude law and were simulated by the shake table with target peak ground acceleration of 1.62 g. Four types of seismic responses were measured: the accelerations in each reinforced backfill layer, the lateral wall face displacements at the bottom, middle, and top of the wall, the dynamic vertical settlements of the wall, and the dynamic vertical stresses within the backfill. These seismic responses were presented and analyzesd. Overall, the MSE wall performed well with no apparent damage. The maximum horizontal deflection of the wall face occurred at the top of the wall and was 7 cm, or 4.7% of the wall height. Due to the difficulty in achieving higher density, the TDA had a small settlement (approximately 2 cm), or 1.3% of the wall height. Limitations of this research were presented at the end of the paper.

RÉSUMÉ : Cet article présente un test préliminaire sur table vibrante d'un mur de terre stabilisée mécaniquement et à échelle réduite (MSE) et fait d'un remblai à base d'agrégats de pneus (TDA). Le mur modèle (MSE) a été construit à l'intérieur d'une boîte dont la charpente est faite d'acier et qui a été placée sur une table vibrante unidimensionnelle. Le mur avait 1,5 m de haut, 1,2 m de profondeur et 1,5 m de long et il était fait de cinq couches de remblai TDA qui étaient renforcées à l'aide d'une géogrille. Les excitations du tremblement de terre de Loma Prieta de 1989 ont été intensifiées à partir d'une loi de similitude et elles ont été simulées sur la table vibrante avec une accélération au sol dont la cible maximale était de 1,62 g. Quatre types de réponses sismiques ont été mesurés: les accélérations de chaque couche du remblai renforcé, les déplacements latéraux de la paroi frontale au bas, au milieu et en haut de la paroi, les fondements verticaux dynamiques de la paroi, et les contraintes verticales dynamiques à l'intérieur du remblai. Ces réponses sismiques ont été présentées et analysées. En général, le mur MSE s'est bien comporté sans aucun dommage apparent. La déviation horizontale maximale de la paroi frontale s'est produite dans la partie supérieure de la paroi et elle était de 7 cm, soit de 4,7% de la hauteur du mur. En raison de la difficulté à obtenir une densité plus élevée, le TDA a subi un léger tassement (d'environ 2 cm) soit de 1,3% de la hauteur du mur. Les limitations de cette recherche sont présentées à la fin du document.

KEYWORDS: Tire derived aggregates, TDA, MSE wall, seismic, shake table test.

1 INTRODUCTION

In each year, there were approximately 280 million waste tires were discarded by American motorists, 40% of which were disposed in landfills, stockpiles, or illegal dumps (FHWA 1997). These stockpiles of tires pose a potential threat to public health, safety, and the environment. Tire shreds, also known as tire derived aggregates (TDA), are pieces of processed and shredded waste tires that can be used as lightweight and quick fills for embankments, subgrades, bridge abutments, and retaining wall backfills. TDA of different sizes have been widely studied as alternative backfills in the past twenty years and vast literature references are available (e.g., Humphrey and Manion 1992; Humphrey 1998; Bosscher et al. 1992; Tweedie et al. 1998; Strenk et al. 2007; Tandon et al. 2007). These references provided understanding of the mechanical characteristics and in-situ performance of embankments or retaining walls using tire shreds or chips.

In contrast to the relatively rich literature on the static behaviors of tire shreds, scarce experimental data are available on the seismic performances of mechanically stabilized walls and bridge abutments with tire shreds/chips as backfills. Tsang (2008) was one of few researchers who studied a rubber-soil mixture backfill under seismic conditions. In his shake table tests, it was found that site response of the backfill was nonlinear and helped absorb incident seismic waves. Furthermore, Tsang (2008) raised the concern for the resonance effects of the new backfill, which should be experimentally tested. The recent shake table tests by Hazarika et al. (2008) on gravity type model caisson protected by a cushioning tire chips found that the tire chips substantially reduced the seismic load against the caisson wall. Helwany et al. (2012) conducted a full-scale shake table test on geotextile-reinforced-soil bridge abutment, using a staged sinusoidal horizontal motion with increasing amplitude up to 1.0 g. The abutment was 3.2 m tall and concrete masonry unit (CMU) blocks were used as the facing. Thorough data analyses of the tests indicated that the model abutment safely withstood the bridge loads while being subject to ground accelerations up to 1.0 g at 3 Hz.

This paper reports a preliminary shake table testing on the seismic responses of a reduced-scale mechanically stabilized 'earth' (MSE) wall using TDA as backfill. Scaled historical earthquake excitations were generated by the one-dimensional shake table. The accelerations of the wall at different elevations, the lateral displacements of the wall face, the vertical settlements and vertical stresses during the simulated 40 seconds of shaking were recorded and analyzed.

2 MATERIALS AND METHODOLOGY

2.1 Material

There are two types of TDA that are used in the USA: type A with a maximum size of 7.5 cm and type B with a maximum size of 30.0 cm. In this research, the TDA was provided by a TDA vendor in California, USA. The size distribution is shown in Figure 1. It can be seen that the material's maximum size is approximately 10 cm, and 76% (by mass) TDA are smaller than 7.5 cm. The TDA was judged to be close to type A.

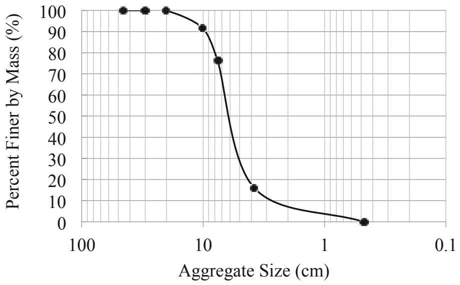


Figure 1. Size distribution of the TDA

Young's modulus of the TDA was also obtained using a large-scale compression test. The dimensions of the TDA sample in the compression test was 112 cm long, 71 cm wide, and 50 cm tall and was confined in a wooden box. The stress-strain relationship, which was not included in this paper due to page limit, showed an apparent upswing trend as the compressive deformation continued. Within 10% strain, the curve appeared to be a linear line, and the Young's modulus of the TDA is approximately 400 kN/m^2. The bulk density of the TDA in the backfill was 721 kg/m^3, which is at the lower end of the density range that is used in the engineering practice. Higher density was not able to be reach due to the compaction capability in the lab. In order to obtain the shear resistance of the TDA, large scale shear testing was conducted. The shear resistance of the TDA was found to be approximately $c = 0$, $\phi = 30°$.

2.2 *Experimental Setup*

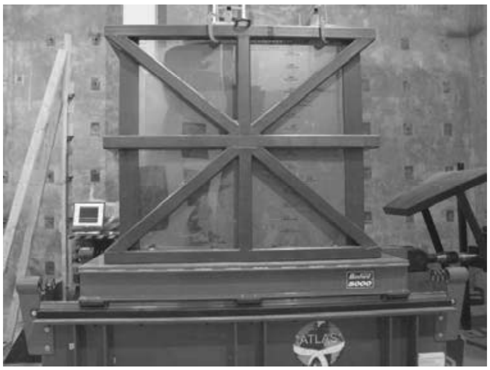


Figure 2. Shake table

A section of reduced-scale MSE wall was built in a 1.5 m × 1.87 m × 1.8 m rigid steel box that was anchored on a 2.4 m × 2.1 m one-dimensional shake table. The load capacity of the shake table is 177.9 kN, the actuator provides 245 kN of hydraulic driving force, and the maximum travel distance of the table is ±12.7 cm. The shake table is capable of replicating recorded historical earthquake motions that are within the table's allowable displacement range. Figure 2 is a photo of the shake table and the box with a retaining wall built inside. Figure 3 shows the completed model MSE wall with TDA backfill.

The model MSE wall's configuration is shown in Figure 4. The wall was 1.5 m high, 1.2 m deep, and 1.5 m long. Five wrap-around layers of reinforced TDA were used. Uniaxial geogrid was used for both reinforcement and containment of the TDA. The spacing and length of each reinforcement layer were determined according to the "Geosynthetic Design & Construction Guidelines Reference Manual" (FHWA 2008) and "Designing with Geosynthetics" (Koerner 2005).

Figure 3. Constructed model MSE wall

The design parameters for the geogrid reinforcement are listed as follows:

- Ultimate tensile strength: $T_{ult} = 54$ kN/m
- Total reduction factors: $\Pi RF = 3.6$
- Allowable tensile strength: $T_{all} = \frac{T_{ult}}{\Pi RF} = \frac{54}{3.6} = 15$ kN/m
- Factor of safety for pullout failure: FS = 1.5
- Height of wall (prototype): $H = 4.5$ m
- External friction angle (δ) between geogrid and TDA: assume $\delta = \phi_{\text{TDA}} = 30°$
- Adhesion between geogrid and TDA: $c_a = 0$.

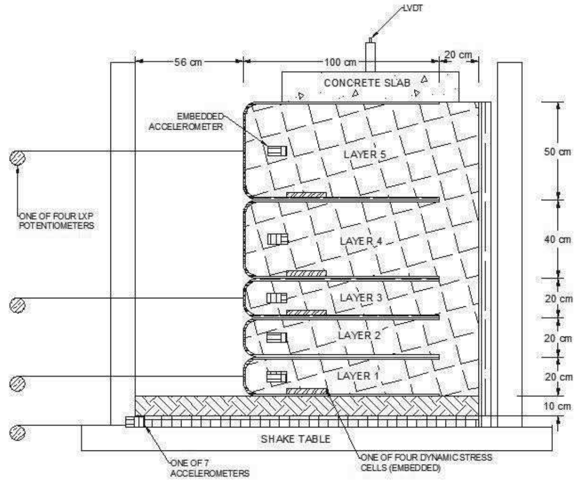


Figure 4. Configuration and instrumentation of MSE wall

Beneath the first layer of the TDA, a 10 cm sand layer was compacted to simulate the friction of the base soil. It is noted that in each of the wrap-around layer, the top geogrid sheet is only half of the length of the bottom geogrid sheet for that layer, since the top wrap-around sheet was not intended to serve as a reinforcement layer. The TDA were compacted using a 15 kg hand hammer with a long handle and 30 cm × 30 cm steel base to reach the target density of 721 kg/m^3. A concrete slab was placed at the top of the wall and anchored to the top layer with ten steel rebar, so that the slab did not move freely during the shaking. The concrete slab simulated a surcharge of 3.4 kN/m^2. Transparent Plaxiglas sheets were used at the interface between the TDA wall and the sides of the box to minimize the friction between the TDA and the boundaries.

Figure 4 also depicts the instrumentations used in the model test. Three linear potentiometers were used to measure the horizontal deflections of the wall face at the bottom, middle, and top layers. The potentiometers were fixed to an inertial frame outside of the shake table, and an inelastic wire connected each potentiometer to the geogrid at the three designated levels. The fourth potentiometer was connected to the shake table in order to measure the actual seismic motions generated by the actuator. The potentiometers were spring-loaded, but the spring force was significantly smaller than the seismic force and therefore did not affect the responses of the walls. The vertical settlements of the MSE wall during the shaking were measured by LVDT transducers that were anchored on the shake table above the concrete slab. The transient vertical effective stresses in the backfill were measured using dynamic soil pressure cells, which were placed flat at the bottom of layers 1, 3, 4, and 5. Wire-free accelerometers were embedded in each of the five layers and were close to the wall face in order to measure the acceleration responses of the backfill. One accelerometer was attached to the shake table and one to the box to measure their acceleration responses as well. A delayed start timer was set in each accelerometer, and the data recording (100 data per second) started at a predetermined time when the shake table test was scheduled to run.

In order to simulate the natural retained soil on the back of and beneath the MSE wall, spring-loaded boards were installed at the back-side and the bottom of the box. The springs were so chosen to provide the same *dynamic stiffness* of dense sand, following the approach suggested by Gazetas (1991). Due to the page limitation, the detailed design of the spring boards is omitted.

2.3 Dynamic Scaling

In this research, the 7.1 magnitude Loma Prieta earthquake of 1989 in Northern California, USA, was simulated. The duration of the displacement-time history was 40 seconds. The earthquake's displacement-time history and acceleration-time history data were from the Pacific Earthquake Engineering Research (PEER) Center Library of University of California, Berkeley and were implemented into the input file to the MTS™ control system of the shake table. Trial shake table tests were run on the empty box, the input and measured displacements and accelerations matched well.

The reduced-scale model MSE wall was intended to simulate a prototype wall of full scale. The geometric scale was chosen to be 1:3 (model:prototype), that is, the model MSE wall simulated an MSE wall of 4.5 m tall in the field. The dynamic stress was scaled based on the dynamic scaling law for the "adequate model" (Moncarz and Krawinkler 1981):

$$a_r = \left(L_r\right)^{-1} \qquad (1)$$

where: dimensional scale $L_r = L_{\text{model}} : L_{\text{prototype}} = 1:3$, acceleration scale $a_r = a_{\text{model}} : a_{\text{prototype}} = 3:1$. Therefore, the input accelerations were three times of the actually recorded accelerations in the field.

3 RESULTS AND DISCUSSION

The original acceleration-time history for the Loma Prieta earthquake recorded at the particular site had a maximum acceleration of 0.54 g. This value was multiplied by 3, according to Equation (1), so that the input maximum acceleration was 1.62 g in the model test. Figure 5 shows the input ground acceleration-time history and the measured acceleration-time history of the shake table. It is clear to see that the input values are similar to the measured values. The difference may be due to the weight of the box and the MSE wall, which caused the box to be heavy and moving less.

Figure 6 shows the lateral deflections of the MSE wall face at the bottom and top layers during the 40-second shaking. The deflections were obtained by subtracting the absolute, measured displacements of the table from the absolute, measured displacements of the wall face at each time stamp. The maximum displacement of each layer matched well with the acceleration variation of the table shown in Figure 5 — the maximum displacement occurred at the same time when the acceleration was the highest. The top layer had the maximum horizontal deflection of positive 2.0 cm (into the wall) and negative 7.0 cm (away from the wall). The bottom of the wall had the least movements between positive 0.3 cm and negative 0.6 cm. The maximum deflection of the wall face was 4.7% of the wall height. Bulging was not noticeably observed.

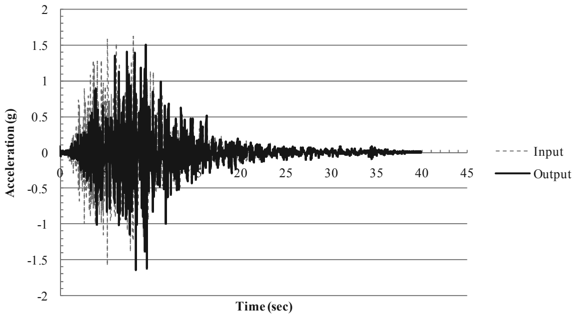
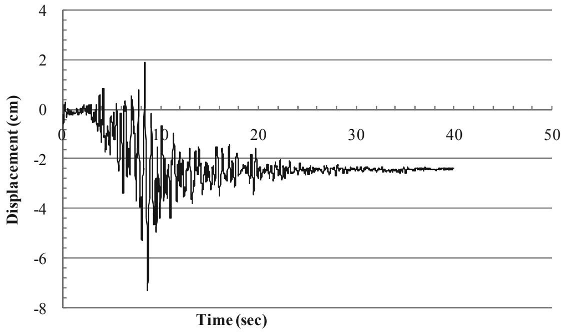
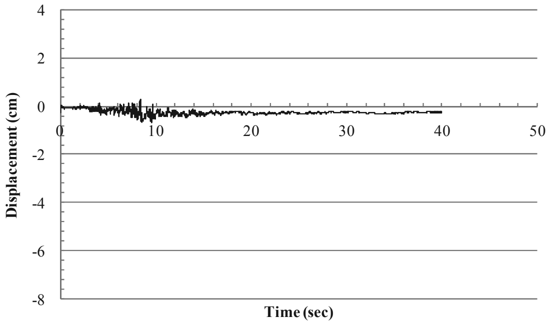


Figure 5. Scaled Loma Prieta earthquake acceleration-time history



(a) Top layer displacement



(b) Bottom layer displacement

Figure 6. Lateral displacements/deflections of TDA wall face, relative to table movement

Table 1 lists the measured maximum accelerations in each layer of the MSE wall during the test. The maximum acceleration of the shake table was 1.89 g. The measured accelerations generally increased toward the top of the wall, matching well with the increased lateral displacements from the bottom to the top of the wall face.

Table 1. Measured maximum accelerations of the shake table and the backfill (the values are in g)

Shake table	Box	Layer 1 (bottom)	Layer 2	Layer 3	Layer 4	Layer 5 (top)
1.89	1.56	1.75	1.87	1.77	2.16	2.25

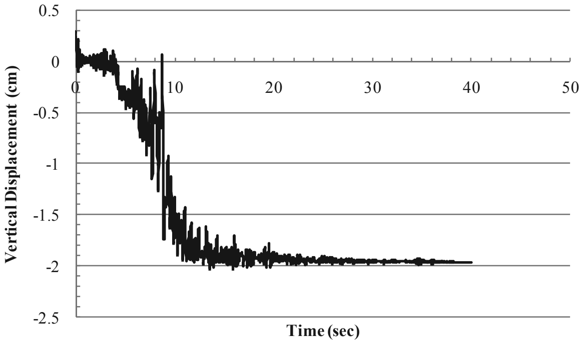


Figure 7 Seismic vertical settlements of MSE wall (measured at the top of the backfill)

Figure 7 shows the seismic vertical settlements measured by the LVDT transducers at the top of the wall. Two LVDT transducers were positioned at the top and they recorded similar settlements. Therefore, only the readings from one LVDT were shown in the figure. In the first 10 to 15 seconds, a maximum vertical settlement of approximately 2 cm was recorded. After that, the settlement remained at approximately 2 cm. This initial settlement could be due to the lack of complete compaction of the TDA. Due to calibration errors, the vertical stresses that were recorded by the dynamic soil pressure cells in the backfill were considered incorrect and were not presented in this paper.

4 CONCLUSIONS AND LIMITATIONS OF THIS RESEARCH

This paper presents a preliminary experimental research on the seismic responses of a reduced-scale geogrid-reinforced retaining wall with TDA backfill under the simulated Loma Prieta earthquake excitations. The research used a shake table to produce the scaled earthquake motions. Overall the wall with TDA backfill performed well with no apparent damage. The maximum horizontal deflection of the wall face occurred at the top of the wall and was 7 cm, or 4.7% of the wall height. Due to the difficulty in achieving higher density, the TDA had a small settlement (approximately 2 cm) in the first 10-15 seconds, or 1.3% of the wall height.

This experimental study has several limitations. (1) The geogrid's tensile strength was not scaled, this could result in an over-reinforced wall. (2) The reinforcement was based on static design. Seismic design using the methodologies presented by Helwany et al. (2012) and by National Concrete Masonry Association (NCMA 2010) may change the internal configuration of the MSE wall and consequently the seismic behavior. (3) The scaling law used in the model test should be improved to consider the scaling of the TDA-geogrid composite material properties. (4) External (global) stability, such as deep-seated rotational failure that can be caused by earthquakes, cannot be simulated in this test due to the shallow soil depth. Because of these limitations, extrapolation of the model results to the field is premature at this stage. This research work is continued to address the limitations in (1), (2), and (3). Furthermore, numerical model using Plaxis is being developed to simulate the laboratory conditions (including the boundary conditions, material properties, and seismic excitations). Using the same conditions, the numerical model can be calibrated using the model test results; then the numerical model can be used to predict the seismic performance of this type of retaining walls in the field.

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