Seismic Response of Gravity-Cantilever Retaining Wall Backfilled with Shredded Tire

N. Ravichandran[1] and E. L. Huggins[2]
[1]*Glenn Department of Civil Engineering, Clemson University, 320 Lowry Hall, Clemson SC 29634*
[2]*AMEC Environment & Infrastructure, 4000 Meadow Lake Dr., Suite 125, Birmingham AL 35242*
[1]*E-mail :* nravic@clemson.edu; Phone: (864) 656 2818
[2]*E-mail :* Eleanor.Huggins@amec.com; Phone: (205) 733-7668

ABSTRACT: Using shredded tires as an alternative backfill material for retaining walls is an effective method for recycling a common and abundant waste material. In this paper, the engineering properties of the shredded tire from various sources were compiled; retaining walls were designed for static and seismic conditions using the mean properties following LRFD method and compared with that of conventional granular material. The performance of retaining wall backfilled with shredded tires was then investigated by applying design earthquake acceleration-time histories using advanced finite element software and compared with that of sand backfill. In addition, a detailed parametric study was conducted to quantify the effect of variations in shredded tire properties and earthquake loadings. Results show that the shredded tire backfill significantly reduces the wall tip deflection and maximum shear force and bending moment along the wall. Parametric studies on the shredded tire properties determined that cohesion has the greatest effect on the shear force and wall tip deflection. The friction angle showed the most influence on the bending moment in the wall. Quantitative and qualitative analysis of wall response with variations in shredded tire properties provide guidelines for the design of walls to be backfilled with shredded tires and for the selection of backfill materials.

1. INTRODUCTION

Approximately 78% of the more than 270 million discarded tires in the United States are disposed of as whole tires in landfills or illegal dump sites. When disposed of in tire dumps or dumped unlawfully waste tires pose a risk to the public by presenting a fire, health, and environmental hazard, while also collecting water to create a breeding ground for harmful mosquito populations. In addition, the tires are easily ignited and, once ignited, trap air, making the fire nearly impossible to extinguish. Uncontrolled tire burning produces liquid oil and toxic substances that are then released into the environment. The large numbers of waste tires and growing tire dump sites have driven the tire recycling industry to seek new and better ways to utilize waste tires including the use of shredded tires in civil engineering applications. Among these applications is the use of shredded tires as a backfill for retaining walls. The other major application of the waste tire is in the transportation industry in which ground tires are used as an Asphalt Modifier, Stress Absorbing Membrane Interlayer (SAMI) prior to asphalt overlay and as expansion joint material in lieu of asphalt impregnated fiber. Shredded tires are an attractive substitute for conventional backfill materials because they are lightweight, economical, and readily available in most projects. In order for shredded tires to be used for such purposes, however, their performance in conjunction with conventional retaining structures must be evaluated for both static and seismic loading scenarios that the system might encounter.

Most salient to the successful recycling of a material are: (i) assessing the environmental safety, (ii) ensuring material availability and economics, (iii) defining engineering properties and durability, (iv), developing diverse suite of applications, (v) demonstrating success in field quantitatively, and (vi) training technical personnel on engineering and assessment with recycled materials. Though shredded tire waste tire has many of these characteristics, it's effectiveness as a replacement for conventional retaining wall sand fill has yet to be determined: specifically it's performance in the retaining wall under seismic loading and the variations of the properties in the shredded tires themselves. The former is an important consideration if shredded tires are to be used as a cost effective backfill material for walls constructed in seismically active zones. The latter is important because the literature shows that the engineering properties of the shredded tire varies with size, gradation, exposed metal content, tire type, test method, and shredding procedure and machinery. In their survey of tire processors, Eldin and Piekarski (1993) found that the size range of the tire shreds was mainly determined by the type of machine and the settings used which varied for each processor. Also the type of tires shredded at different facilities can vary. A study by Moo-Young et al. (2003) showed that this variation in size affects hydraulic conductivity, shear strength, and compressibility. Because these three properties are vital to the performance of a backfill material, the suitability of tire chips may depend on the gradation and size range available. An increase in shred size increased hydraulic conductivity and shear strength, both of which are favorable, also increased the compressibility, which is less desirable (Moo-Young et al. 2003). These property variations and the resulting effects on shredded tire backfill behavior and wall performance must be quantified and the design of the retaining wall must take into account these uncertainties appropriately. In a study by Kaggwa (2005), probabilistic methods were applied to a case study and constructed facilities to diagnose damages to geotechnical structures. Similarly, parametric studies like that in this study can hopefully statistically determine how shredded tire variation and other factors such as seismic loading can cause damages or unsatisfactory performance before a structure is in place and determine the magnitude of such potential damage through numerical modeling rather than case study. This study seeks to investigate these considerations in the use of shredded tires as a backfill for retaining structures.

Although there is no case study on the performance of the retaining walls backfilled with shredded tires subjected to dynamic loads, researchers have conducted full scale (Tweedie et al. 1998) and model scale (Garcia et al. 2011) experiments to understand the lateral earth pressures exerted on vertical walls under static loading condition. In their full scale experiment on a 4.88 m high wall backfilled with shredded tire under at-rest and active conditions Tweedie et al. (1998a and b) determined that the lateral earth pressures for the at-rest condition was about 45% lower than the values expected for a conventional granular backfill and 35% for the active condition. Similarly, from a series of centrifuge model tests, Garcia et al. (2011) determined that the lateral earth pressures predicted by conventional earth pressure theories are greater than the actual lateral pressures measured. The lateral movement required to reach active or passive conditions also differs from the values reported in the design manuals. Both of these studies reveal the economic benefits of using the shredded tire as the retaining wall backfill.

In this paper, the authors describe their compilations of the geotechnical data published in previous papers with an appropriate tire chip size and laboratory test method. The mean and standard deviations values of the key parameters are calculated to show the variation of the properties with different size and test method. These values are used to conduct finite element study on the dynamic response of a coupled retaining wall-shredded tire backfilled. A detail parametric study on the variation of shredded tire properties and loading type is also presented to support the previous conclusion on the potential application of shredded tire as a retaining wall backfill.

2. PROPERTIES OF SHREDDED TIRE AND DESIGN BENEFITS

In order to determine the appropriate engineering properties of the shredded tire backfill to use in the design and numerical analysis, a literature survey was performed and the values for different properties were tabulated from these sources. The values of key parameters are shown in Table 1 based on the source from which they came and the nominal size of the tire shreds. The mean values and standard deviations of each of the parameters are shown at the bottom of the table. This selection of sources covers a wide range of tire chip sizes as well as the different testing techniques and types of study.

A major potential design benefit of replacing conventional sand backfill with shredded tire chips is their low unit weight. This is especially helpful in areas where the underlying soil may be soft and unable to sustain the load of a retaining structure and heavier backfill material on the heel and the toe of the wall. Cecich et al. (1996) found that the unit weight of shredded tires ranged from 5.51-5.86 kN/m^3, which was less than a third of the weight of comparable sand backfill. These findings are supported by that of Lee et al. (1999) in which they showed that shredded tires had a dry unit weight of 6.3 kN/m^3, and also in which even the rubber-sand mixture with 40% tire chips by weight had a unit weight of 12.51kN/m^{3}which is significantly lower than that of pure sand (Lee et al. 1999). In a study by Warith et al (2004), the values for unit weight were very similar with compacted unit weights that ranged from 6.38kN/m^3 to 8.24kN/m^3, indicating that these significantly lower unit weight values can translate into significant design changes in retaining walls. In retaining walls designed in similar study by Cecich et al. (1996), the use of shredded tires reduced both the volume of backfill required and the dimensions of the retaining structures required to meet structural and geotechnical standards. Because the structures were carrying a lesser load from the backfill, the risks of overturning, sliding, and strength failures were reduced and a less intense design was required for the same criteria and application.

In addition to a reduction in unit weight, shredded tires have shown similar properties to conventional backfill materials in lab tests and static loading scenarios, with any differences not negatively affecting the design when walls were considered under static loads. In their extensive examinations on tire chip samples, using ASTM specified tests (particularly large scale direct shear testing), Moo-Young et al. observed that the friction angle varied from 15 to 29 degrees with an increase in chip size from less than 50 mm to 200-300 mm (Moo-Young et al. 2003). This was compared to the results of the same direct shear test on clean silica sand which exhibited a friction angle of 34 deg (Moo-Young et al. 2003). This indicates that generally the friction angle of tire chips is slightly lower than that of conventional sand (Moo-Young et al. 2003). These findings coincide with that from a study by Cecich et al. (1996) in which the properties of tire chips were obtained for use as a retaining wall backfill. Here, the friction angle for the tire chips (nominal size of 12.5 mm) was 27 deg and the cohesion was 7.038kPa (Cecich et al. 1996). The design of three retaining walls of different heights based on these parameters was then compared to the design of the walls based on a cohesion less sand backfill with friction angle of 38 deg. The differences in properties proved advantageous as the walls designed for tire chip backfill showed significantly greater factors of safety for sliding and overturning than those designed for a typical sand backfill (Cecich et al. 1996). This means that in this case, the properties of tire chips not only maintained the safety of the retaining wall expected with conventional backfill but, in fact, increased the stability of the design.

One concern beyond conventional performance considerations is the potential fire hazard posed by shredded tire backfill. This hazard has been the subject of extensive research, most notably a case study by Tandon et al. (2007) in which an embankment backfilled with shredded tire was monitored for settlement, temperature, air and water quality, and other performance criteria specific to shredded tires. This study confirmed that the shredded tires had insulating qualities, which can be beneficial in preventing ground freeze, but can be of concern in terms of potential combustion. Though no evidence of self-heating was found, and although the temperature of the tire layers remained only slightly higher than ambient temperatures, temperatures in the embankment fluctuated less than that of surrounding air, suggesting that the tires acted as an insulator (Tandon et al. 2007). In air samples from the embankments, all organic compound levels were well below the level necessary for combustion to occur (Tandon et al. 2007). This, along with more intricate studies of shredded tire embankments suggests that that shredded tires exceed the conventional performance criteria regarding safety.

3. INITIAL WALL DESIGN AND DISCUSSION

The problem considered consists of a gravity cantilever retaining wall as shown in Figure 1 with a design height of 6.1m (20 ft). The retaining wall was designed based on seismic provisions provided by National Cooperative Highway Research Program (NCHRP) Report 611 (Anderson et al. 2008) and the mean shredded tire properties. The mean values were calculated by tabulating the published data in a table as shown in Table 1. The wall with conventional granular material backfill consisted of a clean sand with friction angle of 34 deg. and unit weight of 18.86 kN/m^3. Design began with a static design following the American Association of State Highway Officials (AASHTO) Load and Resistance Factor Design (LRFD) procedures, involving three applicable load cases and checks for eccentricity, bearing capacity, and sliding. Once the static design had been established, the NCHRP recommended method for seismic design was applied to adjust the wall dimensions. Since the El Centro earthquake time history was one of the earthquakes being applied to the model in the numerical study, the seismic design values for a site located in El Centro, CA, were used in the seismic design of the wall. This was intended to reproduce a scenario where a wall designed using available design criteria is subjected to a particular ground motion that may occur in the area. The designs resulted in toe and heal lengths of 1.52 m and 4.57 m, respectively for the sand backfill and 3.96 m and 1.22 m for the shredded tire backfill.

An important observation from the initial design is that the resulting dimensions of the retaining structure for the shredded tire backfill are not typical in that the wall has a long toe and short heel. This is because during the seismic analysis the inertia of the heavy concrete wall coupled with the low weight of the shredded tire backfill created difficulties in satisfying the eccentricity requirement. Because the shredded tire backfill was so light and because excess excavation behind the wall was undesirable, the toe, rather than the heel was increased to extend the moment arm and satisfy eccentricity requirements with a minimal footing dimension and excavation requirement.

Table 1 Properties of shredded tires gained from the literature

Source	Nominal Tire Size [mm]	Compact Unit Weight [kN/m^3]	Permeability [cm/s]	Friction Angle [deg]	Cohesion [kPa]	Young's Modulus [kPa]	Poisson's Ratio
Cecich et. al (1996)	12.5	5.51-5.86	0.033-0.034	27	7.038	--	--
	--	6.97	--	22	5.746	--	--
Youwai and Bergado (2003)	16	6.72-7.37	--	30	--	--	0.33
Lee et. al (1999)	50	6.3	--	21	17.5	3394.4	--
Moo-Young et. al (2003)	50	6.25	0.20	15	0.3943	--	--
	50-100	7.25	0.55	32	0.3735	--	--
	100-200	6.5	0.75	27	0.3735	--	--
	200-300	6.25	0.85	29	0.3497	--	--
Shalaby and Khan (2005)	50-300	See Below	0.10	19-25	8-11	See Below	0.30
	75	5.89-6.87	See Above	See Above	See Above	1100	0.30
Warith et. al (2004)	75	6.38-8.24	13.4-0.67	--	--	--	--
Humphrey et. Al (1993)	38	6.064	--	25	8.6	770	0.32
	51	6.299	--	21	7.7	1130	0.28
	76	6.074	--	19	11.5	1120	0.20
Yang and Kjartanson (2002)	10*	5.73	--	32	0	1129	0.28
	10**	5.73	--	11	21.6	1129	0.28
	10***	5.73	--	18.8	37.7	1129	0.28
Average		**6.399**	**1.843**	**23.4**	**9.19**	**1362.7**	**0.29**
Standard Deviation		**0.659**	**n/a**	**5.87**	**9.87**	**n/a**	**n/a**

*Direct Shear Test where 10% strain is the failure criterion
**Triaxial Test where 10% strain is the failure criterion
***Triaxial Test where 20% strain is the failure criterion

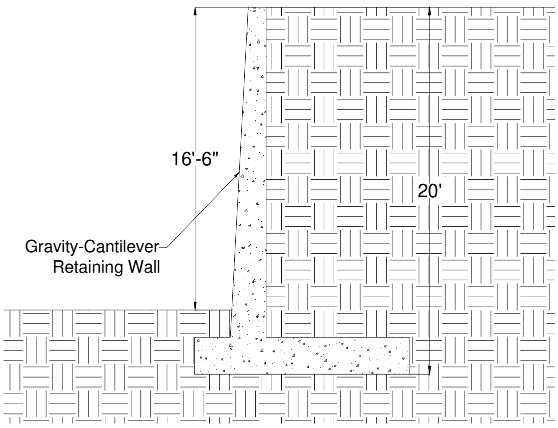


Figure 1 A sketch of the problem being considered

The implications of such a design are considered when analyzing the performance of the retaining wall as discussed later.

Summarized in Table 2 are the comparison of the volume of excavation requirements for walls designed based on each of the backfill materials and the percentage of savings. The walls designed for shredded tire backfill provide a significant savings in the three main areas of cost in retaining wall construction: excavation, backfill purchase or borrow, and concrete quantity. In addition, as the shredded tires are inexpensive or even provided free of charge for the cost of transport, they not only reduce the quantity of backfill required, but also reduce the cost of that same backfill quantity.

Table 2 Comparison of material requirements for shredded tires and conventional sand backfills

Material Item	Sand Backfill	Tire Backfill	Percent Savings
Minimum Excavation (m^3)	10.73	4.36	59.4%
Backfill Quantity (m^3)	10.73	4.36	59.4%
Concrete Volume (m^3)	1.98	1.73	12.9%

4. FINITE ELEMENT MODEL DEVELOPMENT AND SIMULATION PROCEDURE

For this study, all modeling of the retaining structure and soil was performed using the 2-D version of the finite element software PLAXIS that is considered as a reliable and advanced finite element software for geotechnical applications involving static and dynamic loadings. The code is validated for many geotechnical engineering problems with and without structural inclusions including retaining walls, deep excavations with sheetpile walls, and dynamic analysis of soil and soil-structure systems (PLAXIS 2D 2011a and b).

The problem consists of a gravity-cantilever retaining wall in a saturated in-situ soil and backfilled with shredded tire/conventional sand. The higher-order (15-node) triangular elements were used to spatially discretize the simulation domain. Using higher-order elements will increase the accuracy of the simulated results for a given number of elements. The schematic of the simulation domain with a sample finite element mesh is shown in Figure 2. For all of the cases simulated in this study, the Standard Fixities and Standard Earthquake Boundaries options were applied. In PLAXIS, the Standard Fixities option fixes the vertical sides of the model against translation in the x-direction while fixing the base against translation in both the x- and y-directions. The Standard Earthquake Boundaries option includes absorbent boundaries on the vertical sides of the soil body and apples a dynamic prescribed displacement to the base of the model. The prescribed displacement is defined by the input of a displacement-, velocity-, or acceleration-time history, the latter two of which are converted, using Newmark integration, to a displacement-time history. Except the parametric study on the type of loading, the El Centro 1940 earthquake acceleration-time history, shown in Figure 3(a), was applied to the base of the finite element model using this prescribed displacement. The horizontal boundaries at the top of the model were traction free.

The stress-strain behaviors of the in-situ soil and backfill materials (shredded tire/sand) were represented by the Hardening Soil model which is suitable for dynamic analysis while the structural components were represented by linear elastic beam

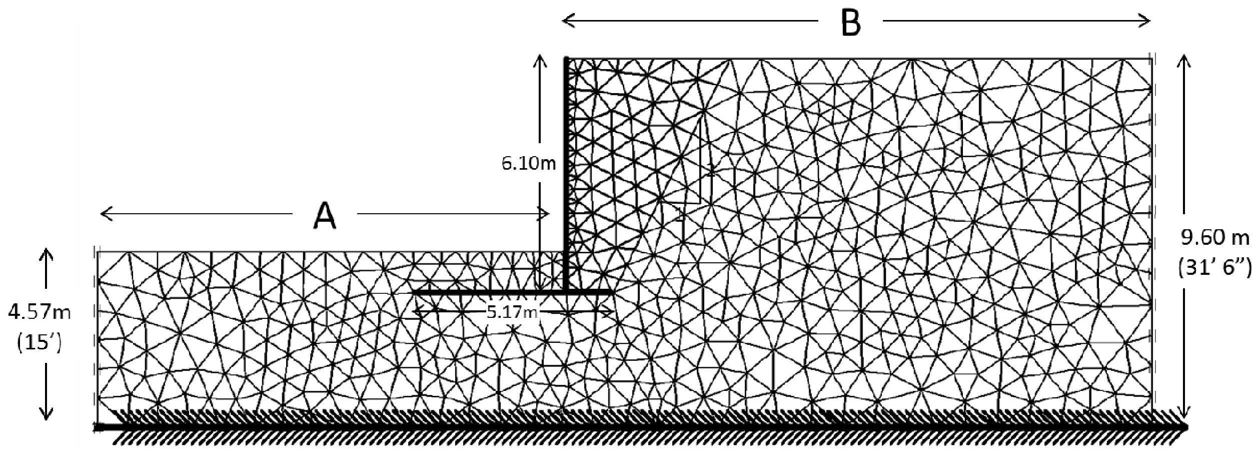


Figure 2 Schematic of the simulation domain and sample finite element mesh

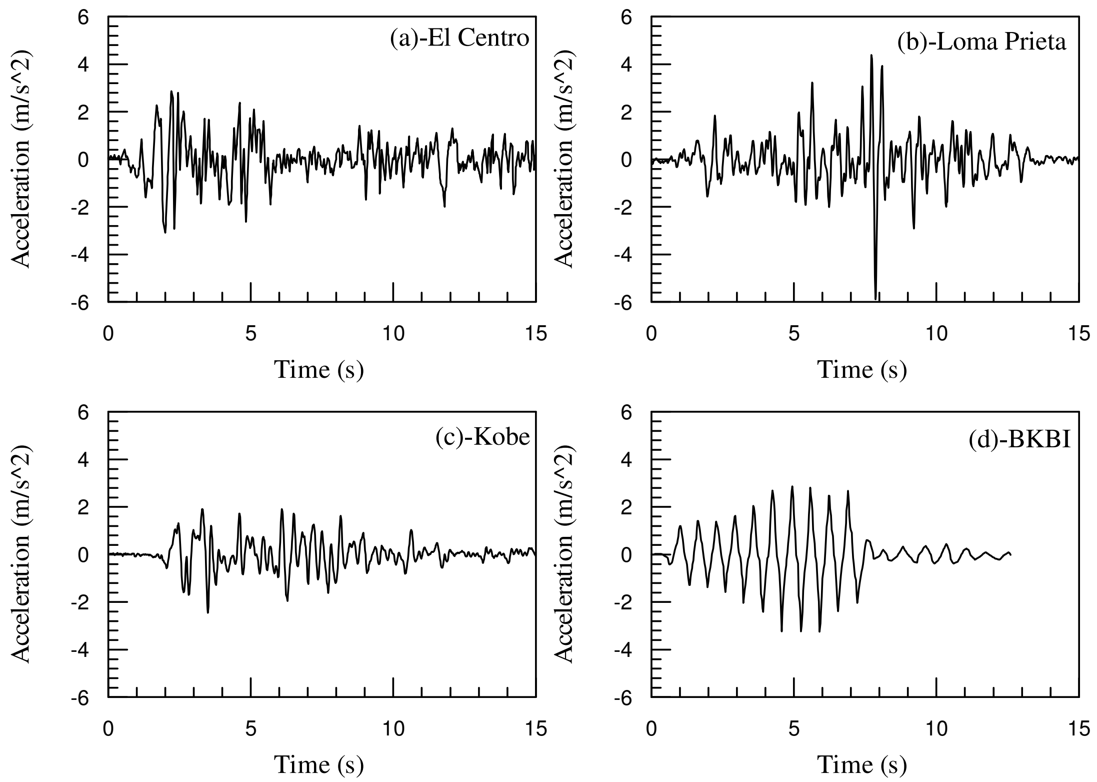


Figure 3 Earthquake acceleration-time histories used in this study

(called plate in PLAXIS) elements. The properties of the structural elements used in this study are shown in Table 3. A brief description of the Hardening Soil model and the determination of the model parameter are provided in a subsequent section.

The size of the simulation domain (dimensions A and B as shown in Figure 2) and fineness of the spatial discretization of the simulation domain (number of finite elements) were determined through mesh and size sensitivity analyses, briefly described below, to eliminate the modeling error in the computed responses.

Table 3 Properties of the retaining wall structural components

Property	Stem	Footing
Linear Stiffness, EA (kN/m)	$1.271x10^7$	$1.694x10^7$
Flexural Stiffness, EI (kNm^2/m)	221320	525231
Weight (kN/m/m)	10.77	14.35
Average Thickness (m)	0.4572	0.6096
Poisson's Ratio	0.12	0.12

4.1 Mesh Sensitivity Study

In order to select the appropriate mesh fineness for the study model, a sample model was created with in-situ material, backfill material, and a retaining wall for which we varied the number of finite elements to select the most appropriate finite element mesh. Four meshes were considered in this study: Coarse (121 triangular elements and 1059 nodes), Medium (262 triangular elements and 2225 nodes), Fine (473 triangular elements and 3967 nodes), and Very Fine (1061 elements and 8747 nodes) meshes in PLAXIS. First, the displacement-time history for the retaining wall tip was compared for each mesh as shown in Figure 4(a), in which the fineness of the mesh did not appear to greatly affect the displacement of the wall tip. Secondly, the shear and moment distributions along the wall stem were observed at the end of the dynamic loading cycle for each of the meshes, the results of which are shown in Figure 4(b) and (c), respectively. Here, though the mesh fineness caused little change in the computed wall response, the finer meshes do tend to converge in both the shear and the bending moment distributions. Based on these results, the Very Fine mesh was selected as the most appropriate mesh fineness for further studies.

4.2 Size Sensitivity Study

For the size sensitivity study, the Very Fine mesh previously selected, the width of the model was varied. Five cases were observed: Case 1 where A=7.62m (25') and B=10.67m (35'), Case 2 where A=9.14m (30') and B=12.19m (40'), Case 3 where A=10.67m (35') and B=13.72m (45'), and Case 4 where A=12.19m (40') and B=15.24m (50'). The displacement time history for the tip of the retaining wall is shown for all four cases in Figure 5(a). From these results, it is clear that though the model width affected the tip displacement behavior, there was some observance with an increase in model size. Though the three largest sizes showed the best convergence, there was some variation between Case 2 and Cases 3 and 4 early in the dynamic load and between Case 3 and Cases 2 and 4 later in the loading. Because a larger model only serves to reduce misleading effects of the numerical boundary conditions, and because Case 4 most consistently converged with other results throughout the numerical test, it was considered most appropriate based upon the wall tip displacement. Next the shear and moment distributions in the wall were observed following the dynamic loading sequence for all cases. These results, illustrated in Figures 5(b) and (c) again show how the size used in Case 4 allows for differences in the wall behavior. Here the Case 4 model displayed a less restricted response in the shear and bending moment of the wall. This decrease in boundary based restriction and the better convergence in the wall tip displacement indicated the suitability of Case 4 as model geometry for future study.

The finite element model with the dimensions of A=12.19m (40') and B=15.24m (50') with Very fine mesh (1061 elements and 8747 nodes) was used for investigating the dynamic response of retaining walls backfilled with shredded tires.

5. HARDENING SOIL MODEL AND MODEL PARAMETERS

It is important to consider the variations of modulus and damping with strain to ensure an accurate analysis of any systems subjected to dynamic loads. In this study, the stress-strain behavior of the soil and the shredded tire are represented by the Hardening Soil model available in PLAXIS. This model is an advanced multi-part hyperbolic model that improves upon conventional elastic-perfectly plastic models and simpler hyperbolic models by including parameters to encompass the modulus reduction of soil and include better approximations of plastic strain and dilatancy. The main components of this model are stress dependent stiffness, plastic strain due to multiple types of loading, unloading and reloading characteristics, and failure criterion. The key input parameters for this model are the secant modulus at 50% of the failure stress at the reference confining pressure ($E_{50,ref}$), initial tangent modulus for the oedometer loading ($E_{oed, ref}$), unloading and reloading modulus at reference confining pressure ($E_{ur, ref}$), power dictating the stress-modulus dependency (m), Mohr- Coulomb cohesion (c), Mohr- Coulomb friction angle (ϕ'), dilatancy angle (ψ) and permeability (k).

First, this model allows for exponential stiffness changes with applied stress and strain using the input of the fitting parameter "m." Coupled with the input of the initial tangent modulus of elasticity, this model creates a hyperbolic shear stress-strain curve that depicts a continuous modulus reduction for each strain value. Other modulus inputs dictate the loading and unloading behaviors and the secant modulus to further complete the hyperbolic curve. This curve, in conjunction with the Mohr-Coulomb parameters dictating the failure envelope, allows for a much more precise characterization of the soil behavior particularly through loading and unloading cycles imposed by seismic loading. The model parameters were calibrated using the experimental data available in the literature (Youwai and Bergado 2003) following the procedure outlined in the manual (PLAXIS 2D 2011c). The calibrated model parameters and their variations for parametric and reliability study are summarized in Table 4.

6. PERFORMANCE COMPARISON-SAND VERSUS SHREDDED TIRE BACKFILL

As discussed in the design section of this study, walls designed for use with shredded tire fills provide an initial cost cutting benefit in terms of wall and backfill materials as well as excavation and construction costs. These initial benefits make shredded tire fill appear to be a good alternative to sand fills. In this portion of the study, the two retaining walls with two different backfill materials were modeled and the performance of the retaining wall in terms of wall deflections, shear forces, and bending moments was observed based on conventional vs. alternative fills. The wall tip deflection-time history is shown in Figure 6a. This graph represents the relative displacement of the wall tip to the base of the stem throughout the dynamic loading application. It is apparent from this graph that the shredded tires produced a lower deflection in the wall stem than the conventional sand backfill in terms of deflection amplitude and total maximum deflection experienced during the loading progression. The wall backfilled with conventional sand also sustained a more permanent wall deflection at the end of the dynamic loading, indicating that shredded tires may also offer benefits of resiliency. Such resiliency is likely due to both the overall lower deflections and the lower modulus, but comparable limit strength of the two fill materials. Though these walls were designed to retain the fill with which they were modeled, the wall backfilled with the shredded tires exhibited a greater deflection control than the wall backfilled with sand. This is consistent with expectations based upon the static behavior of walls backfilled with shredded tires.

In addition to observing the wall deflection, the maximum shear and moments experienced at different points along the wall were observed. Figures 6b and 6c show the shear force and bending moment envelopes, respectively for each of the fill materials during the dynamic loading. These plots show the maximum shear and bending moment experienced along the wall. Conventional signs for both the shear and moment are used such that a positive shear force is induced by a force pushing the wall away from the backfill and a positive moment bends the wall away from the fill as well. At first glance, it is clear that the shear force and bending moment induced in the wall are less throughout the wall height when shredded tires are used in lieu of conventional sand fill. Of greater importance in these comparisons, however, is the distribution and shapes of the envelopes.

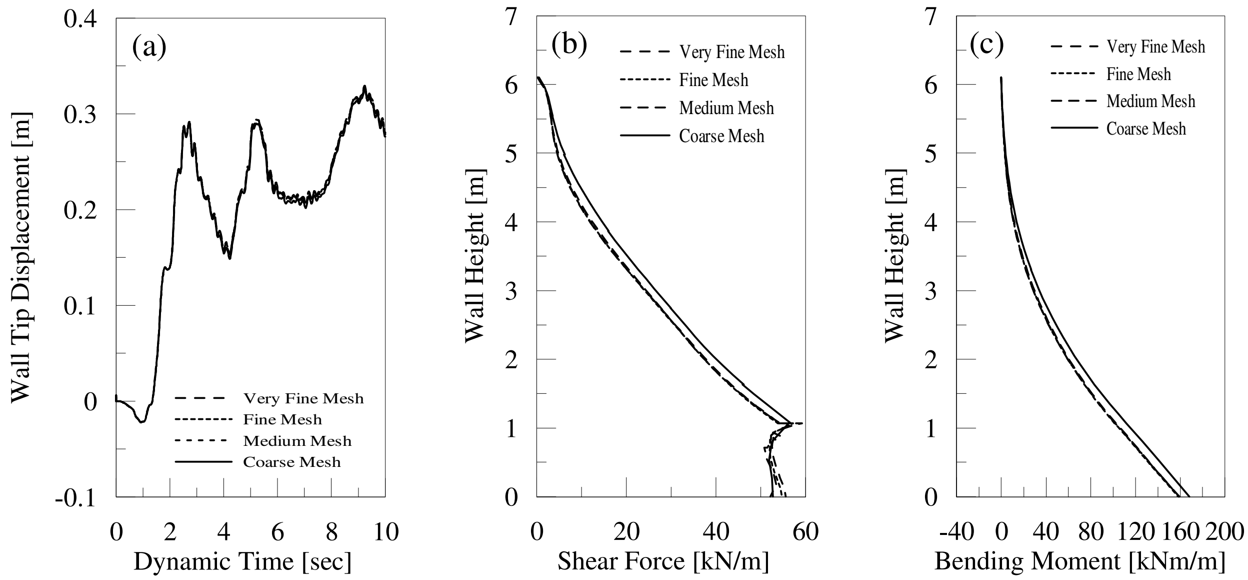


Figure 4 Results of mesh sensitivity study (a) tip displacement-time history, (b) shear force distribution, and (c) bending moment distribution at the end of dynamic loading

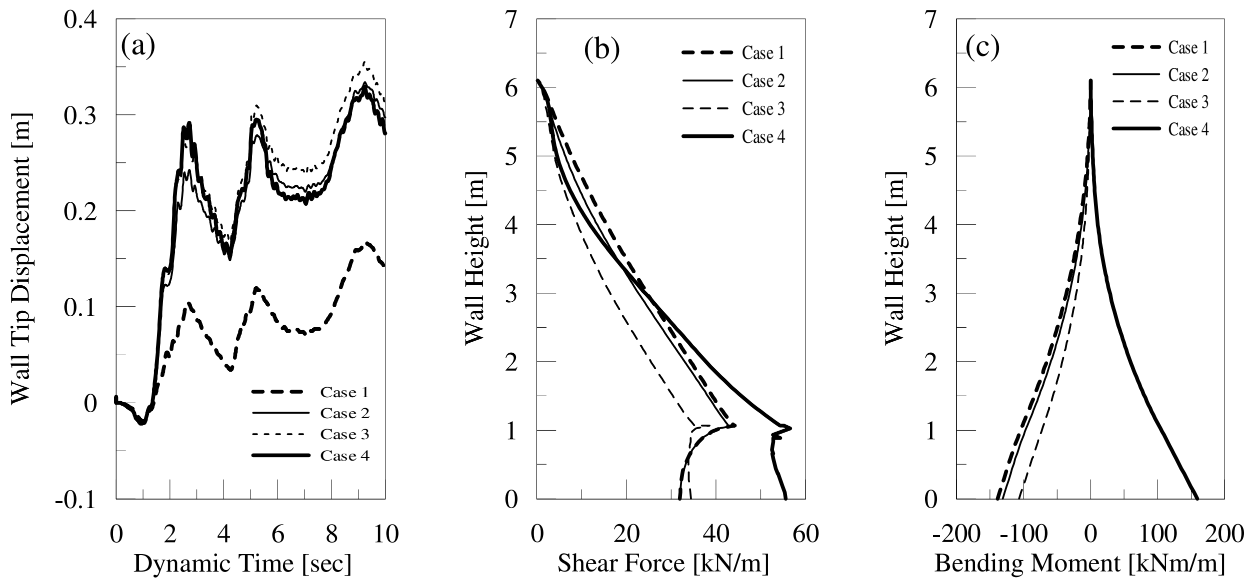


Figure 5 Results of size sensitivity study (a) tip displacement-time history, (b) shear force distribution, and (c) bending moment distribution at the end of dynamic loading

The shredded tires tend to induce negative shear forces across more of the wall height than the sand backfill, quite possibly due to the cohesion of shredded tire fills, which is usually absent in conventional sand backfills. Because shear strength in retaining wall design is accommodated based on maximum absolute values of shear not dependent on whether these values are positive or negative, there should be no significant reinforcement design alterations required as far as presence and location of shear reinforcement. Based on this fact, shredded tire fills would reduce the need for shear reinforcement and not require significant redesign.

In observing the bending moment distribution, though the distributions of maximum bending moments are very similar between sand and shredded tires, the magnitude is greatly reduced with the shredded tires. The magnitude and distribution of the maximum negative moment experienced by the walls backfilled with shredded tires and sand were very similar. From a reinforcement design perspective, this is a positive thing to note. Unlike shear reinforcement or strength, moment reinforcement designs are based upon magnitude and direction of the internal moments. Consequently, a significant change in either negative moment magnitude or distribution would necessitate changes in the reinforcement design. Because the walls with both backfills exhibited similar moment distributions, conventional reinforcement design would be appropriate for walls backfilled with shredded tires, though reductions in moment magnitude could translate into less reinforcement.

In order to better capture potential design benefits of shredded tire fills, maximum values of deflection, shear, and moment were summarized and compared (see Table 5). Here it can be seen that the reduction in maximum deflection for the shredded tire backfill was more than 43 %. Reductions in shear force and moment induced in the wall stem were even greater than the deflection reduction. These reductions definitively show that shredded tire backfills, when the wall geometry is designed for them appropriately, can not only reduce costs and amounts of materials for wall construction, fill, and excavation, but can reduce demands on the retaining wall itself. As previously stated, this could provide benefits in steel reinforcement requirements as well as creating less deflection in which sensitive structures may be affected.

Table 4 Hardening Soil model input parameters for parametric study

Material	$E_{50,ref}$ (kPa)	$E_{oed,ref}$ (kPa)	$E_{ur,ref}$ (kPa)	m	c_{ref}(kPa)	Φ (deg)	ψ	K (cm/sec)
In-Situ C-Phi Soil	37000	80247	111000	1	20	28	0	$1.16x10^{-6}$
Sand	25000	59560	75000	0.5	0	28	0	$1.16x10^{-3}$
Tires - (μ)	1440	1786	4320	1	9.19	23.4	0	1.843
Tires - (μ_{φ}+3σ)	1320	1786	3960	1	9.19	41.01	11.01	1.843
Tires - (μ_{φ}+2σ)	1380	1786	4140	1	9.19	35.14	5.14	1.843
Tires - (μ_{φ}+1σ)	1400	1786	4200	1	9.19	29.27	0	1.843
Tires - (μ_{φ}-1σ)	1520	1786	4560	1	9.19	17.53	0	1.843
Tires - (μ_{φ}-2σ)	1600	1786	4800	1	9.19	11.66	0	1.843
Tires - (μ_{φ}-3σ)	1720	1786	5160	1	9.19	5.79	0	1.843
Tires - (μ_c+3σ)	1600	1786	4800	1	38.8	23.4	0	1.843
Tires - (μ_c+2σ)	1560	1786	4680	1	28.93	23.4	0	1.843
Tires - (μ_c+1σ)	1500	1786	4500	1	19.06	23.4	0	1.843
Tires - (μ_c-1σ)	1400	1786	4200	1	0	23.4	0	1.843
Tires - (μ_{γ}+3σ)	1440	1786	4320	1	9.19	23.4	0	1.843
Tires - (μ_{γ}+2σ)	1440	1786	4320	1	9.19	23.4	0	1.843
Tires - (μ_{γ}+1σ)	1440	1786	4320	1	9.19	23.4	0	1.843
Tires - (μ_{γ}-1σ)	1440	1786	4320	1	9.19	23.4	0	1.843
Tires - (μ_{γ}-2σ)	1440	1786	4320	1	9.19	23.4	0	1.843
Tires - (μ_{γ}-3σ)	1440	1786	4320	1	9.19	23.4	0	1.843

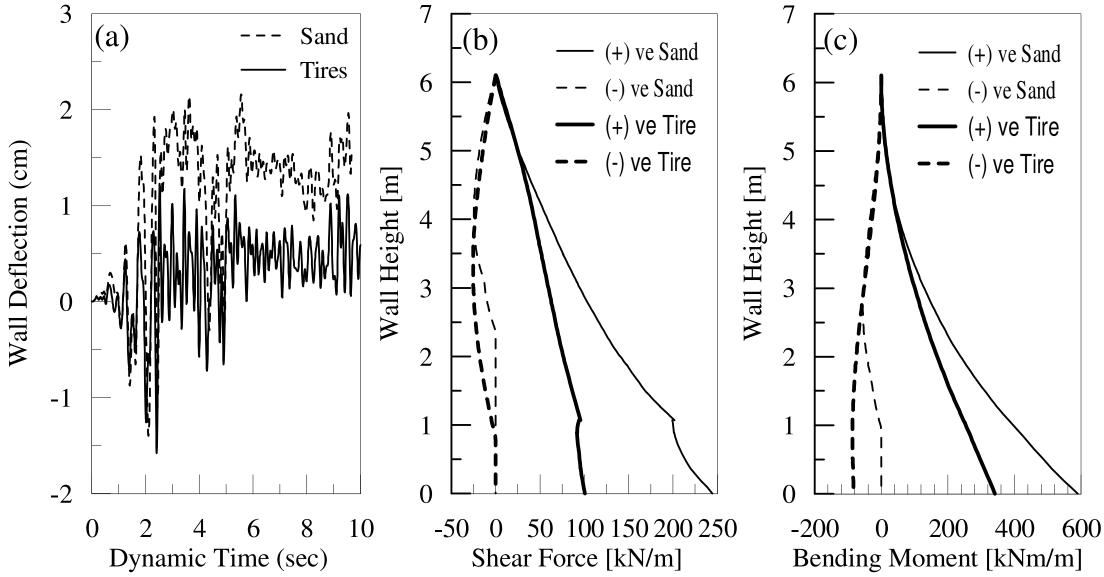


Figure 6 Comparison of wall tip deflection and maximum shear and moment envelopes for sand and shredded tire fills

Table 5 Comparison of maximum responses for sand and shredded tire backfills

Case	Max Wall Deflection [cm]	Percent Savings	Max Shear Force [kN/m]	Percent Savings	Max Moment [kNm/m]	Percent Savings
Conventional Sand Backfill	2.16	43.2 %	244.46	58.8 %	589.52	42.1 %
Shredded Tire Backfill	1.23		100.66		341.20	

7. PARAMETRIC STUDY

7.1 Variation in Shredded Tire Properties

As seen in Table 1, the values for many of the parameters show significant variation based on the tire shred size and the tests performed to obtain the properties. This indicated a need for a parametric study to quantify these variations and the effects on retaining structure design and performance. The friction angle, cohesion, and unit weight of the shredded tire backfill were of most interest as these are the parameters used in the design of retaining structures. Thus the mean and standard deviation of these values were determined and used to construct the variations shown in Table 3. The variations consist of the mean shredded tire values as a control case and cases that vary the friction angle, cohesion, and unit weight by one, two, and three standard deviations above and below the mean value. Each of these variations was simulated in PLAXIS with the retaining structure and in-situ soil remaining the same. The computed maximum wall deflection, maximum shear force, and maximum bending moment are tabulated in Table 5 and also shown as a bar chart in Figure 7.

From Figure 7a, we can see that the friction angle variation produces only a small variation in the response which is difficult to distinguish graphically during much of the dynamic loading, but that the shredded tires with higher friction angle produce a greater deflection in a wall than shredded tires with a lower friction angle. Because the $(\mu_{c'}-1\sigma)$ case has a cohesion value of zero, it is the lowest cohesion tested and is included in Figure 7 rather than the response for three standard deviations below the mean. Again, the cohesion of the shredded tires causes no dramatic change in the wall behavior except in the $(\mu_{c'}-1\sigma)$ case where the cohesion is zero. It is noted that a lack of cohesion reduces the amount of deflection in the wall for almost the entire loading cycle, whereas the increased cohesion slightly increases the wall deflection. The variation in unit weight shows no dramatic change in the wall response based on variation in the unit weight, but shredded tires with a lower unit weight do produce slightly lower wall deflections.

This analysis shows a consistent trend in all of the response criteria for variations in the fiction angle and cohesion: reductions in the shear strength parameters produce less deflection, lower shear force, and lower bending moments in the wall stem. An initial inspection shows that the reduction in material strength and quality actually have favorable results in regards to wall performance. Such a favorable result is probably due to the unorthodox wall dimensions necessary to accommodate the shredded tire properties in seismic design, particularly the long toe and short heel that result from the light weight of the shredded tires. The resulting eccentricity of such a wall is on the heel side of the center rather than on the toe side of the center point as it is in conventional walls causing the wall to tend to rotate toward the bank. This would mean that the reduction in strength in the backfill material would actually reduce pressures on the wall in the event that the wall tended to rotate backward instead of forward, particularly during seismic loading. Additionally, Figure 7(b) and (c) show that, much like the deflection results, the shear and bending moment variations produced in the wall are quite small in comparison to the magnitude of these values even for up to three standard deviations above or below the mean. This indicates that though the variations in the shredded tire properties may be great, the resulting variation in the wall response is relatively low.

Though a variation of the unit weight does not produce a clear trend in the response of the retaining wall when viewed quantitatively, it does produce varying responses in the system. This behavior is probably more related to damping characteristics of the wall and backfill system that are related to the mass of the backfill material. Further investigation of this variation in response is warranted to clarify the correlations between the wall response and the variation of the shredded tire unit weight.

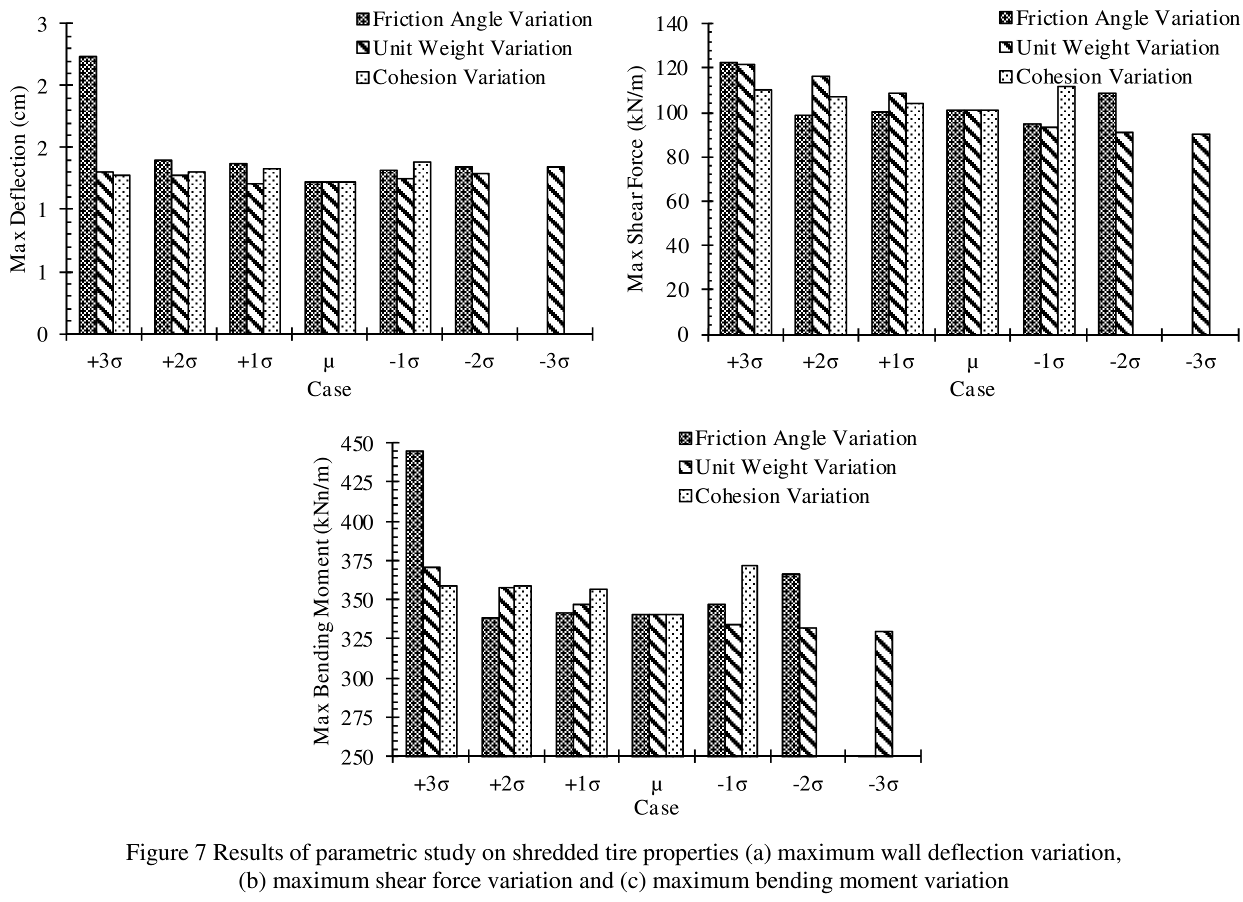


Figure 7 Results of parametric study on shredded tire properties (a) maximum wall deflection variation, (b) maximum shear force variation and (c) maximum bending moment variation

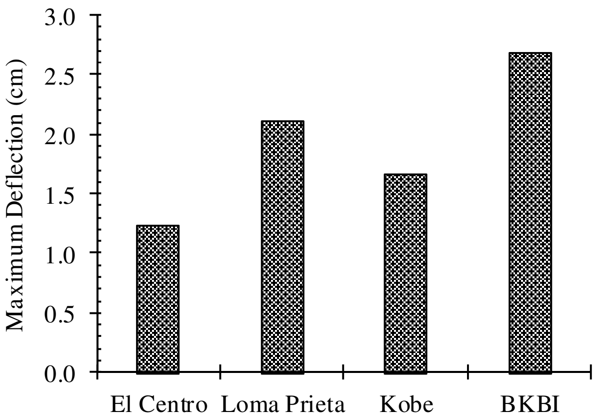
8. VARIATION IN INPUT MOTION

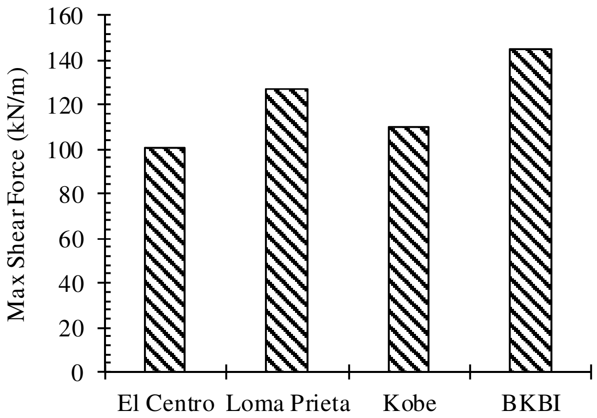
In addition to considering variations in shredded tire properties, considering variations in loading experienced by the soil-wall-backfill system is also necessary. The wall was designed for construction in El Centro, California, but it is known that it could experience earthquakes with different amplitudes, frequencies, and other characteristics. To observe the effects of these variations, four earthquake time histories were applied to the model and the responses were compared. They are: (i) the El Centro 1940 earthquake shown in Figure 3(a), (ii) the San Francisco 1989 earthquake as recorded in Loma Prieta, California shown in Figure 3(b), (iii) the Kobe 1995 earthquake from Kobe, Japan shown in Figure 3(c), and (iv) the synthetic BKBI earthquake shown in Figure 3(d). Each of the time histories were applied with several steps corresponding to the number of points and intervals available in the input file as recommended by PLAXIS.

A graphical observation of the acceleration-time histories indicates that using this set of time histories represents a variety of amplitudes and frequency characteristics. For instance, though the BKBI earthquake motion has a lower frequency, it still maintains a greater amplitude of acceleration.

Similarly, though the Loma Prieta earthquake exhibits a smaller amplitude motions for much of the duration with a higher frequency, it displays a sudden and brief increase in the amplitude. The Kobe and El Centro earthquake time histories are more similar in frequency content and amplitude but nonetheless show differences in the applied acceleration.

In order to better quantify the variation in the response due to loading variation, bar charts were used to summarize the maximum wall tip displacement, bending moment and shear force values experienced by the wall over the entire shaking period. The maximum wall tip displacement, maximum shear force and maximum bending moments are shown in Figure 8a, 8b and 8c, respectively. Here it is evident that the BKBI motion with the lowest frequency and comparable amplitude produces the largest deflection, shear force and bending moment in the wall compared to the Loma Prieta motion, with the largest amplitude and relatively higher frequency. Though the El Centro and Kobe earthquakes produced similar bending moment responses, the difference in wall tip deflection is significant. Again, it is important to note that each response parameter remains within a reasonable range and thus the wall is expected to perform acceptably even when the motion experienced varies.





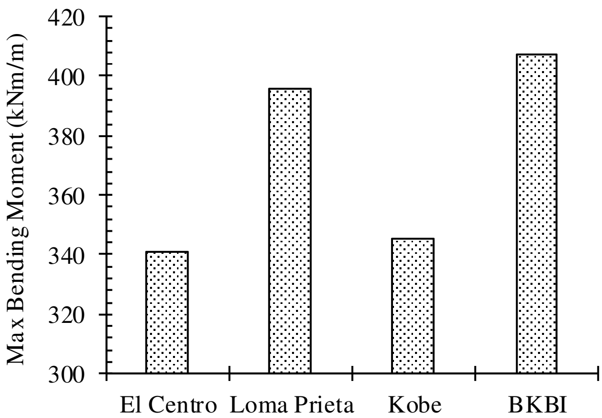


Figure 8 Results of parametric study on loading (a) maximum wall deflection variation, (b) maximum shear force variation and (c) maximum bending moment variation

9. RELIABILITY ANALYSIS AND DISCUSSION

In order to further quantify the effects of the variations in shredded tire properties on wall performance, the results from the parametric study were considered in a reliability analysis. For this analysis, a simplified version of the First Order Second Moment (FOSM) Method was used. Equations (1)and (2) are the two full equations used in the FOSM Method to describe the mean (μ_d) and variance (σ_d^2) of the response based on the parameters being varied.

$$\mu_d = f\left(\mu_{\phi'}, \mu_{c'}, \mu_\gamma, x_{other}\right) \quad (1)$$

$$\sigma_d^2 = \left(\frac{\partial d}{\partial \phi'}\right)^2 \sigma_\phi^2 + \left(\frac{\partial d}{\partial c'}\right)^2 \sigma_{c'}^2 + 2\left(\frac{\partial d}{\partial \phi'}\right)\left(\frac{\partial d}{\partial c'}\right)\left(\rho \sigma_\phi \sigma_{c'}\right) \quad (2)$$

where d is the wall tip deflection, γ is the unit weight of the shredded tires, ϕ' is the friction angle of the shredded tires, c' is the cohesion of the shredded tires, x_{other} are the other shredded tire input parameters, and ρ is the correlation coefficient between the two variables being considered, here c' and ϕ'. Equation (1) describes the mean response as a function of the properties of the shredded tires being varied in the parametric study. Equation (2) gives the standard deviation of the response, here deflection, in terms of variations two of the properties, here friction angle and cohesion. In this study, the mean response was evaluated using PLAXIS with the input of the mean shredded tire properties. This equation can be simplified to achieve Equation (3), the one used in this reliability study.

$$\sigma_d^2 = \left(\Delta d_{\phi'}\right)^2 + \left(\Delta d_{c'}\right)^2 + 2\rho\left(\Delta d_{\phi'}\right)\left(\Delta d_{c'}\right) \quad (3)$$

Here, each of the d is the wall deflection and

$$\Delta d = \frac{1}{3}\left(\left|\frac{d_i^{+3} - d_i^{-3}}{6}\right| + \left|\frac{d_i^{+2} - d_i^{-2}}{4}\right| + \left|\frac{d_i^{+1} - d_i^{-1}}{2}\right|\right).$$

As before, this shows the equation for the wall deflection in terms of the variation in the cohesion and the friction angle of the shredded tire backfill, but this equation was similarly used for other variable pairs and wall response criterion.

The deflection gradient (Δd), shear gradient (ΔV), and moment gradient (ΔM) were calculated according to the recorded responses from each of the variables considered. In order to determine the correlation coefficient for each variable pair, the covariance between the unit weight and cohesion, between the friction angle and the cohesion, and between the unit weight and the cohesion were obtained from the values shown in Table 1. Once the covariance values were determined for each pairing, the correlation coefficient for each pair was calculated using the following equation.

$$\rho = \frac{v[x, y]}{\sigma_x \sigma_y} \quad (4)$$

where v[x,y] is the covariance of the two variables in question and the σ_x,σ_y are the standard deviation of each variable in the pair. The values for the covariance and correlation for each pair of variables is shown in Table 6.

Based on the above described calculations, the effects of varying each pair of shredded tire properties were determined and the resulting mean and standard deviation in the wall responses are shown in Table 6. First, correlations between the different properties can be observed for the shredded tire backfill. The friction angle and cohesion are most closely correlated statistically and are also inversely correlated, meaning the increase of one variable to above the mean value results in a corresponding decrease in the other variable. Similarly, the unit weight and cohesion are inversely correlated but to a lesser degree. Though there is a direct correlation in the concurrent increase between the unit weight and the friction angle, it is not closely correlated. Through these correlations and the response results from the wall, we can demonstrate how inherent uncertainties in these properties work together to affect the wall response.

Based on reliability analysis results, the wall deflection was most significantly affected by variations in the friction angle and cohesion as well as the unit weight and cohesion. Thus, the cohesion appears to be the factor most affecting wall deflection, which is consistent with the graphical observations. The pairings of unit weight and cohesion as well as the friction angle and cohesion similarly had a significantly greater effect on the shear force in the wall. In the case of the bending moment applied, however, the unit weight and friction angle as well as the friction angle and cohesion have the greatest impact on the bending moment and the standard deviations produced in the bending moment by these parameters is significantly greater than that produced by join variation of the unit weight and the cohesion. This suggests that the friction angle is likely the most influential parameter in determination of the bending moment particularly in conjunction with variations in cohesion which affects the wall deflection and shear so significantly.

Table 6 Reliability analysis of data from the parametric study

Unit Weight and Friction Angle		**Friction Angle and Cohesion**		**Unit Weight and Cohesion**	
Covariance	ρ-value	Covariance	ρ-value	Covariance	ρ-value
1.274	0.329	-31.849	-0.550	-1.738	-0.267
Variation in Maximum Wall Deflection [cm]					
μ_d	1.228	μ_d	1.228	μ_d	1.228
σ_d	0.026	σ_d	0.022	σ_d	0.025
Variation in Maximum Shear Force [kN/m]					
μ_V	100.66	μ_V	100.66	μ_V	100.66
σ_V	7.670	σ_V	2.208	σ_V	6.183
Variation in Maximum Moment [kNm/m]					
μ_M	341.20	μ_M	341.20	μ_M	341.20
σ_M	9.274	σ_M	4.792	σ_M	6.494

10. CONCLUSION

The design and performance of retaining walls backfilled with shredded tire and subjected to dynamic loads were evaluated through advanced finite element simulations followed by parametric studies on shredded tire properties and loading and reliability analysis. Evaluation of property variations across many studies of shredded tire properties showed that cohesion exhibited the most variation among shredded tire specimens. Additionally, the friction angle and cohesion exhibited the most closely correlated variation. From the reliability analysis it was observed that the friction angle and cohesion of the shredded tires produced the most variation in wall behavior overall with cohesion showing the most effect on the shear and the wall deflection while friction angle showed the most influence over the bending moment. The cohesion is primarily governed by the amount of exposed metal content in the tire shred specimen, indicating that variations in the amount of exposed metal produced by the processing of the shredded tires must be particularly emphasized when either shear or wall movement and settlement are a primary concern. Friction angle variations are primarily due to the size of the tire shreds and thus this is a consideration when the primary concern is bending moment in the wall. These factors should be taken into consideration when selecting and screening shredded tire backfill for certain designs and applications.

For all cases considered here, however, the shredded tire backfill performed adequately even under seismic loadings and considering material property variations. Such performance, combined with comparisons showing a significant cost benefit indicates the viability of shredded tires as substitutes for conventional sand backfill even in structures in zones of strong seismic activity, such as El Centro, CA. By placing more emphasis on material selection and a greater concept of design practices best suited for walls backfilled with shredded tires, designers can improve both the economy and performance ofthis sustainable material. Further research can be conducted to on full scale or small scale models to measure the dynamic performance and verify the finding of this research. Upon verification of the model, design guidelines can be developed for use in practice.

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