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CENTRIFUGE CHARACTERIZATION AND NUMERICAL MODELING OF THE DYNAMIC PROPERTIES OF TIRE SHREDS FOR USE AS BRIDGE ABUTMENT BACKFILL

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ABSTRACT

Two model tests were performed on tire shred fills to document the dynamic elastic material properties of tire shreds using the large centrifuge at UC Davis. The tests were considered to be "element" tests of tire shred material properties, rather than the more typical centrifuge modeling of a site profile. As these were the first tests using tire shred material on the UC Davis centrifuge, new construction and instrumentation techniques were developed. New geophysical wave sources for use with tire shreds were developed to identify reasonable material properties to use in FEM analyses. In addition to the geophyical testing for elastic material parameters, each tire shred fill was shaken with a suite of earthquake and sinusoidal motions using the servo-hydraulic shaking table mounted on the centrifuge.

A two-dimensional finite element model using the elastic material parameters identified from the centrifuge tests was used to explore the effects of incorporating tire shred fills with varying geometries in bridge abutment backfills. Modal analyses were used to examine the effects of including shreds on the abutment natural frequency. Results of these preliminary analyses are mentioned briefly.

INTRODUCTION

In recent years, shredded tire material has been used as a lightweight fill in geotechnical engineering (e.g., Humphrey et al. 1998, Tweedie et al. 1998). Using tire shreds as lightweight backfill material has several potential benefits. Of particular interest for this project is the behavior of tire shred material used as lightweight backfill for bridge abutments, and the resulting dynamic characteristics of the constructed abutment.

The large centrifuge at UC Davis was used to document the dynamic elastic material properties of tire shreds. The tests were considered to be "element" tests of tire shred material properties, rather than the more typical centrifuge modeling of a site profile. The centrifuge offered a relatively large size model container as compared to conventional dynamic element tests (e.g. resonant column tests). Elastic wave propagation velocities were measured to determine material parameters for use in FEM analyses. New wave sources were developed and extensive arrays of instrumentation were used to measure wave propagation velocities in multiple directions. Data from displacement transducers and from multiple video cameras were used to track geometric changes of the model from the increased self-weight.

Centrifuge test data were also collected regarding the dynamic behavior of tire shreds over a broad spectrum of dynamic/seismic shaking scenarios. Extensive instrumentation recorded input, surface, and downhole-shaking amplitudes at numerous locations within the models, resulting in a comprehensive set of dynamic site response data under controlled laboratory conditions. The centrifuge data archive represents the first experimental information regarding the dynamic behavior of tire shreds and may be used to further explore the application of tire shreds in seismically active regions.

CENTRIFUGE MODEL TESTS

Geotechnical materials such as soil and tire shreds have nonlinear mechanical properties that depend on the effective confining stress and stress history. The centrifuge applies an increased "gravitational" acceleration to reduced-scale physical models in order to produce identical self-weight stresses in the model and prototype. The one-to-one scaling of stress enhances the similarity of geotechnical models and makes it possible to obtain accurate data to help solve complex problems such as dynamic soil-structure interaction.

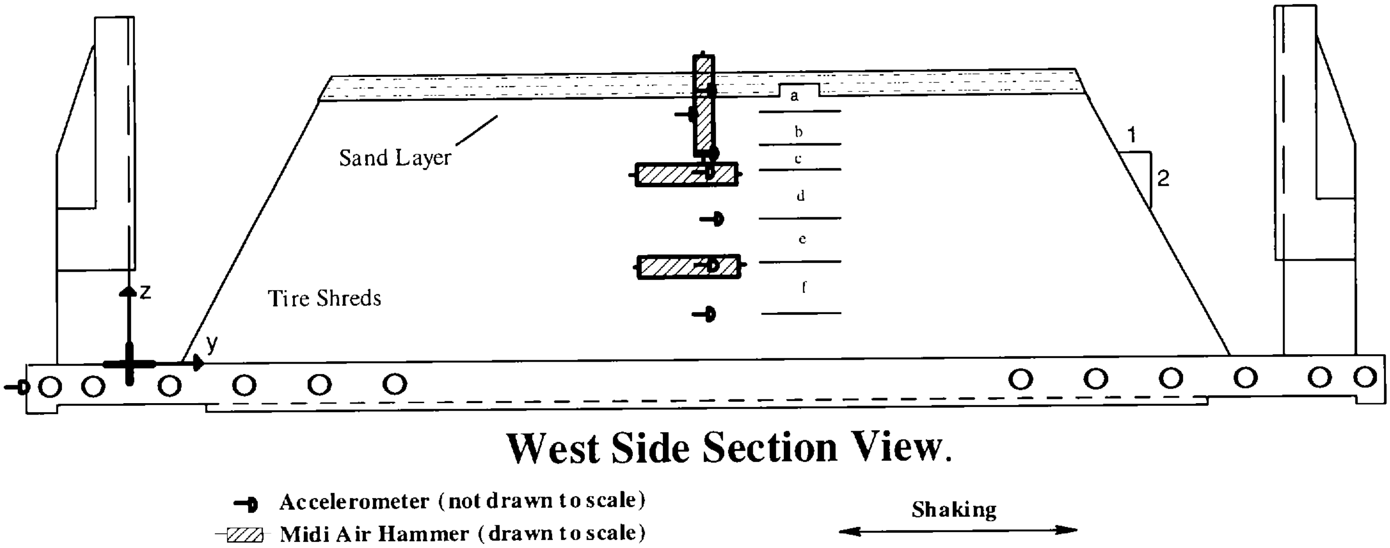

Fig. 1: Initial AES02 model configuration in the Rigid Container, January 2000 (scale = 1:12)

Centrifuge model testing provides data to improve our understanding of basic mechanisms of deformation and failure and provides benchmarks useful for verification of numerical models. The centrifuge model testing presented herein included dynamic site response tests using two sizes of tire shreds. A wide range of shaker input motions were used to generate a database on the potentially nonlinear dynamic behavior of the tire shreds. Small air-hammers recently developed at UC Davis [Arulnathan et al. (2000)] were modified and used to measure the very small strain compression- (P-) and shear- (S-) wave velocities in three directions.

Tire Shred Fill Construction

Two models were constructed of tire shreds in a rigid container, each to a height of approximately 40 cm. Instrumentation consisted of longitudinal, transverse, and vertical arrays of accelerometers, temperature sensors, and horizontal and vertical displacement transducers. A typical model profile is shown in Fig. 1. Note, only select instruments are shown. Over thirty transducers in various arrays were sampled in dynamic events. In these tests the centrifuge-induced increases in self-weight were varied from 10 to 20 to 40 g. Prototype length is scaled directly by g-level; thus, doubling the g-level roughly doubles the prototype depth of the soil profile. Since the natural frequency of the soil profile is inversely proportional to its depth, doubling the depth of the layer approximately halves its natural frequency. The testing schedule thus represents an array of models where the natural frequency of the site is varied through changing the centrifuge acceleration.

The tire shreds for each model were collected from conveyor belts at shredding facilities to ensure representation of materials as used in construction. The average tire shred in the first test, AES01, was 12 cm in length, 9.5 cm in width, and 0.8 cm in thickness, and included exposed steel belts. The tire shreds typically showed some curvature, which varied based on the section of tire from which the shred came (i.e., side wall or tread). The specific gravity was measured to be 1.28. In the second test, AES02, the shreds had undergone considerably more processing, with the average shred being 3 cm in length, 2.5 cm in width, and 0.8 cm in thickness. Virtually all of the steel reinforcing material had been removed from these shreds. The specific gravity for these shreds was found to be 1.08.

Experiments in a 25 cm x 25 cm container were performed to determine the maximum achievable compaction for each shred type. These experiments also helped establish the most reasonable way to compact the shreds at model scale. In the field, large vibratory rollers are often used for construction. At model scale, the most effective compactor was found to be a pneumatic air hammer (i.e. a "powderpuff"), set at a low air pressure. Resulting maximum densities were 5.32 kN/m^3 in AES01 and 5.88 kN/m^3 in AES02.

Each model was built in lifts, with each lift ≈ 7.5 cm in depth prior to compaction. The compaction rate was 10 passes with the pneumatic air hammer after each lift. A freestanding slope was created at each end (see Fig. 1). A 4-cm thick sand layer was placed on top of the tire shred lifts to represent the cover layer found in field construction and to provide a surcharge. This sand was compacted with a vibratory compactor and was kept separate from the tire shreds using geotextiles.

Model Testing

Each model (AES01 & AES02) was tested over two days following the same basic testing procedure. On the first day of testing the g-level was increased to 10 g. In flight P- and S-wave velocity measurements were taken. Hammers were triggered remotely during the test to introduce high frequency waves to the model while wave propagation was recorded using the various accelerometer arrays. After all of the velocities were recorded at a particular g-level, the servo-hydraulic shaker was used to input a small step-wave to the base of the fill layer and the response of all instruments were recorded. After this small shake, the g-level was increased to 20 g, and then to 40 g, and the data collection procedures were repeated at each g-level.

The second day of testing consisted of shaking the fill layer using the servo-hydraulic shaking table. Various earthquake motions and sinusoidal motions of varying frequency and amplitude were input at 10, 20, and 40 g.

Each test is described completely in a Center for Geotechnical Modeling Data Report [Rosebrook et al. (2000 a, b)]. The reports include a complete chronology of each test and describe the models in detail. The reports (with the data files) can be downloaded from the web site for the Center for Geotechnical Modeling at http://cgm.engr.ucdavis.edu.

IDENTIFICATION OF MATERIAL PARAMETERS

Shredded tire material is thought to be highly anisotropic. Placement, compaction, and overburden pressure result in cross-anisotropy that affects the mechanical response of the backfill. Recent experiments by Heimdahl and Drescher (1999) have shown, for example, that the in plane (horizontal) Young's modulus is about three times greater that the out of plane (vertical) modulus. In these centrifuge tests, elastic material properties were quantified by measuring the propagation of P- and S-waves.

The shear modulus (G) of a material can be found from the measured S-wave velocity (V_s) and using the equation $G_{ij} = V_{sij}^2 \rho$. In this equation, i is the direction of wave propagation, j is the direction of particle vibration (polarization), and ρ is the material mass density. Note that G, V, and ρ all scale 1:1 between model and prototype on the centrifuge. As the strain induced by the shear wave approaches zero, G approaches G_{max}.

Small air-hammers have been used successfully to study S-wave velocities on the centrifuge at UC Davis in tests involving sand [e.g., Arulnathan et al. (2000)]. The air-hammers consist of a small-diameter rigid tube with a soft piston. Regulated air pressure is ported to either side of the piston through a four-way valve. Firing the hammer involves pressurizing one side of the chamber and venting the opposite side, which shoots the piston from one end of the chamber to the other. The piston hitting the end of the chamber imparts a P-wave off the end of the chamber and S-waves propagating radially away from the longitudinal chamber walls. The S-wave particle vibration is thus parallel to the chamber length. The exterior chamber walls are roughened to ensure maximum transmission of S-waves to the soil.

In the tests presented herein, wave propagation from two horizontally-oriented and one vertically-oriented wave sources (see Fig. 1) were recorded with longitudinal (y), transverse (x), and vertical (z) arrays of horizontally-oriented accelerometers and by vertical and longitudinal arrays of vertically-oriented accelerometers. This resulted in velocities for vertically-propagating horizontally-polarized S-waves (V_{zy}), horizontally-propagating horizontally-polarized S-waves (V_{xy}), horizontally-propagating vertically-polarized S-waves (V_{yz}), and vertically and horizontally propagating compression (P) waves.

The results for vertically-propagating horizontally-polarized S-waves from AES02 (smaller shreds) are presented in Fig. 2. Seismic waves are often considered to be vertically-propagating horizontally-polarized S-waves in 1-D analyses. While it is clear the velocity increases with increasing vertical stress, there is considerable scatter in the experimental data.

For reference, the variation of V_s with σ_v' for a loose sand is included in Fig. 2. The line shown was defined using the empirical relationship by Seed and Idriss (1970):

$$\frac{G_{max}}{p_a} = 21.79 K_{2max} \sqrt{\frac{\sigma_m'}{p_a}}, \qquad (1)$$

where K_{2max} is a function of the sand's relative density and other characteristics. A value of 35 was used herein. V_s and σ_v' were calculated from the above relationship by using the equations $G = \rho V_s^2$ and $\sigma'_m = (\sigma'_v + 2\sigma'_h)/3$, and by assuming $\rho = 1.7$ Mg/m^3 and setting $K_o = 1 - \sin\phi'$ (with $\phi' = 34°$) for normally consolidated soils.

A reference line for normally consolidated high plasticity clay was defined for Fig. 2 using Hardin's (1978) equation as shown below:

$$\frac{G_{max}}{p_a} = \frac{625}{(0.3 + 0.7e^2)} \sqrt{\frac{\sigma_m'}{p_a}} \qquad (2)$$

To plot the clay reference line on Fig. 2 from eq. 2, it was necessary to determine the void ratio, mean stress, and density of the clay. It was assumed that $G_s = 2.65$ and $K_o = 0.5$ for normally consolidated clay. The void ratio, a function of depth, was calculated from $e = e_{LL} - C_c \text{Log}(\sigma_v'/8)$, with $C_c = 1.46$ and $e_{LL} = 4.16$. These parameters were obtained by correlations from Wroth and Woods (1978) for LL = 157 and PI = 100. The resulting reference line should correspond to a high plasticity, normally consolidated clay.

Discussion of Measured S-Wave Propagation

To obtain an estimate of the maximum shear modulus, the strain levels induced by the hammers should be small to avoid nonlinear stress-strain behavior. It is also desirable to minimize the wavelength of the generated waves relative to the distance between accelerometers and any reflective boundaries. These considerations and the physical constraints of the data acquisition system and material properties can

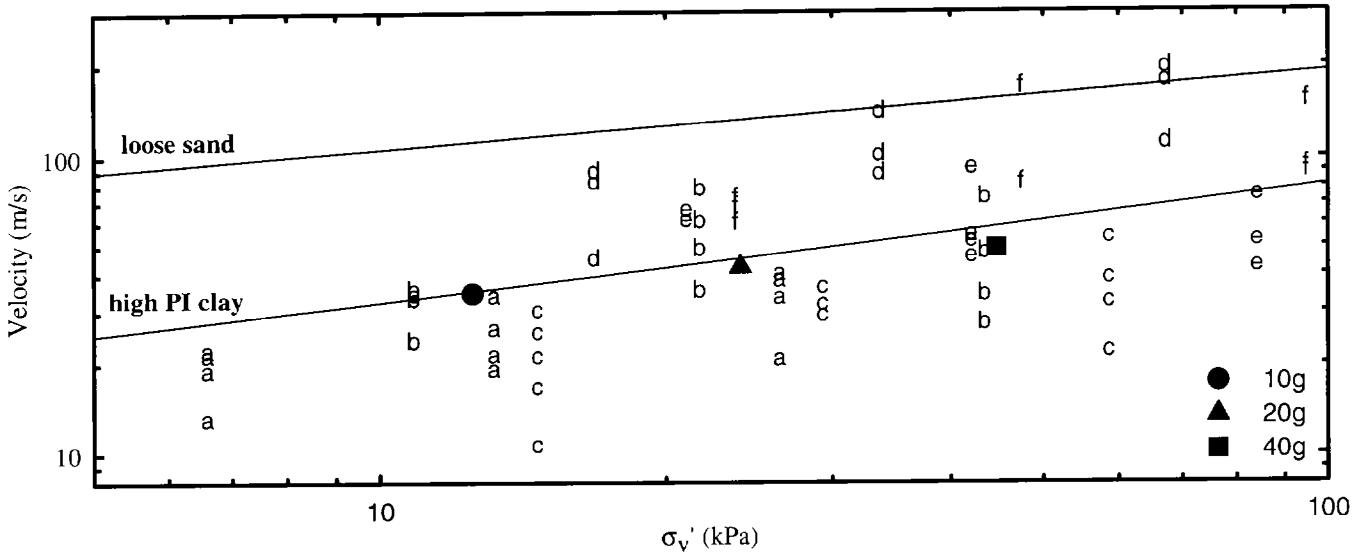

Fig. 2. Velocities from vertically-propagating horizontally-polarized shear waves. Text labels correspond to depth intervals defined in Fig. 1. Solid symbols back-calculated from step-wave motions.

produce conflicting design optimizations for the wave source. The final version of the shear air-hammer used by Arulnathan was arrived at after trials using different hammer dimensions, piston materials, and air sources. Each of these parameters had a significant effect on the nature of the waves produced, including frequency content, magnitude, and clarity. The qualitative effects of the parameter variations were generally consistent with expectations, but a reasonably complete analysis would be necessary to predict the effects quantitatively. The final design was arrived at through trial and error, as the cost of making several hammers was inexpensive compared to performing detailed analyses [Arulnathan et al. (2000)].

New air-hammers were developed for the tire shred project. With sand grain sizes on the order of 0.15 mm, the dimensions of Arulnathan's hammers are large relative to individual particles. However, with tire shreds, the original hammers were no longer large compared to individual particles. We thus redesigned the hammers to be as large as possible relative to the shred size while being as small as possible to create short wavelength, local waves. The hammer design was also changed to maximize P-waves. In the design we attempted to account for the effects of changing the chamber dimensions and material, piston material, and air source using the experience gained developing the hammers used by Arulnathan.

The new hammers were used for the first time in AES01. Unfortunately, very little information was captured in this test. The tire shred size was large (12 cm in length, 9.5 cm in width, and 0.8 cm in thickness) compared to the hammer size (15 cm length, 2.5 cm diameter) and the accelerometer size (1.6 cm length, 0.7 cm diameter). There may not have been adequate coupling between the hammers and the shreds, or between the shreds and the instruments, for the very short wavelength S- and P-waves. The piston also may not have been firing at higher g-levels due to too small air-porting.

The shreds in AES02 were much smaller than in AES01 (3 cm in length, 2.5 cm in width, and 0.8 cm in thickness), and coupling between the hammer and the shreds was expected to be better. In addition, the air ports to the hammer were increased for AES02, increasing the power of the air hammers. This resulted in much more reliable source waves and considerably more useful data, as shown by the results in Fig. 2. Still, there is considerable scatter in the measured velocities for a given stress level.

It is possible that much of the scatter present in Fig. 2 is due to local waves travelling on indirect paths through the course tire shred mesh. The relative sizes of the smaller shreds, the air-hammers, and the accelerometers are shown in Fig. 3. With only a few tire pieces between adjacent accelerometers, it is not difficult to imagine a small shear wave travelling along a more complex path rather than a straight line. As mentioned previously, the shaking table was used to impart small step-displacements to the base of the model at each g-level. This resulted in a global shear-wave across the entire model base. The propagation velocities of the global shear waves were back-calculated for the AES02 model and are plotted as solid symbols in Fig. 2. For these events, the velocity was found to be essentially constant through the model depth at each g-level. These points lie within the scatter defined by measuring the velocity of local S-waves and appear to provide a more consistent trend. This would indicate that the correct wave propagation velocity is bounded by the experimental scatter.

Monitoring the changing model geometry was also critical to interpreting the dynamic centrifuge data. Calculated wave velocities are strongly dependent on the wave travel distance, which was directly affected by the large self-weight vertical

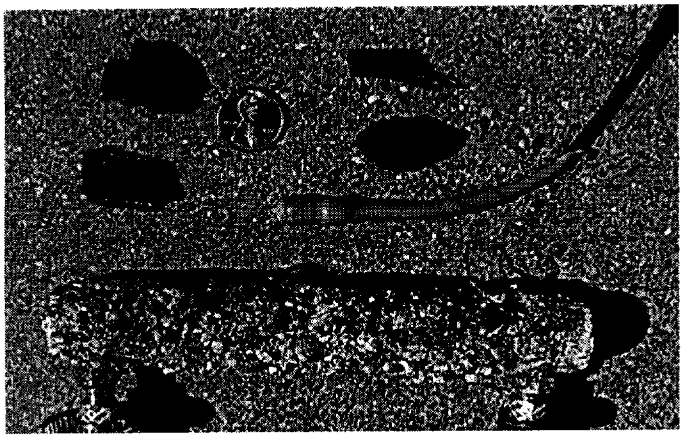

Fig. 3. Tire shreds from AES02 together with an air hammer and accelerometer. Shreds on the left are viewed in plan, shreds on the right in cross-section.

strains of the shred profiles. Video images taken of the shred profile were analyzed to track displacements, and thus internal strains, of the profile, while vertical settlement transducers where used to verify the video analysis. Vertical coordinates of the instrumentation, recorded while constructing the shred profile, were transformed according to the video analysis results for each g-level. The data reports, Rosebrook et al. (2000 a, b), describe the video analysis in detail and include the transformations as used. Wave velocity was taken as the wave travel time divided by the distance traveled. The transformed instrument geometry was used to calculate distances between instruments, while wave travel speed was taken by comparing adjacent accelerometer traces in an array.

Over a particular depth interval (a,b,...,f) or from the global velocity measurements (solid points) the data in Fig. 2 indicate that the shear wave velocity is approximately proportional to the fourth root of the vertical stress (slope ≈ 1/4 on log-log plot). The observation that shear wave velocity is constant with depth for global waves seems inconsistent. Vertical stress and density, however, vary with depth due to initial compaction and increased stress with depth. The velocity, $V_s = \sqrt{G_s / \rho}$, depends on density as well as shear modulus, and there are significant changes in density and spacing of accelerometers due to large volumetric strains in the shreds during the centrifuge spin-up that could contribute to the apparent inconsistency.

SHAKING TABLE RESULTS

Each model was subjected to a suite of sinusoidal and seismic-type shaking accelerations using the shaking table on the large centrifuge. The results from one seismic event in AES02, at 40 g with $a_{max,base} \approx 0.5$ g, are presented in Fig. 4. The data shown are in prototype units. Fig. 4a shows acceleration spectra at the base (in bold) and at the tops of intervals f and b (see Fig. 1). In Fig. 4b, the spectral ratios between the accelerometers in the shreds and the base motion are plotted.

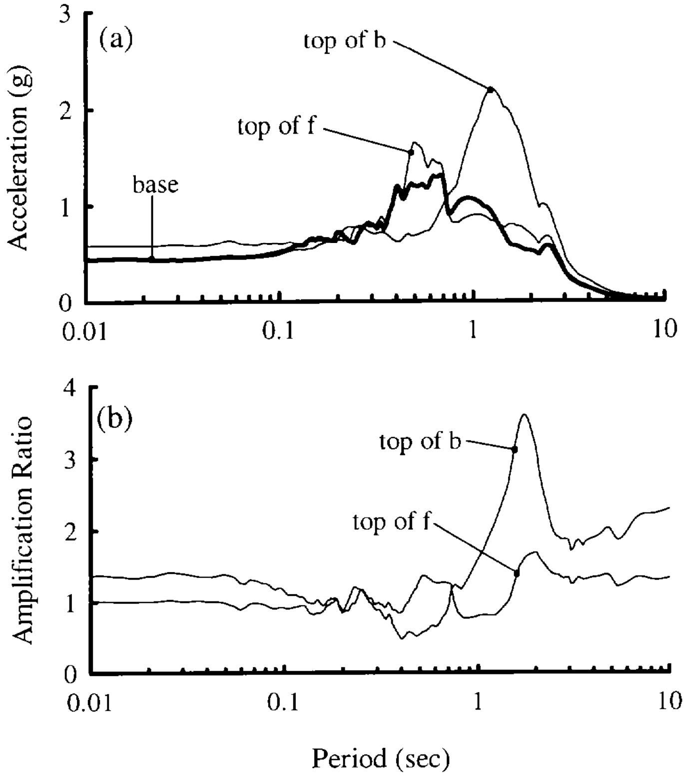

Fig. 4. Response of tire shreds to seismic input in AES02. (a) 5% damped response spectra and (b) ratio of shred motion to base motion

The natural frequency of the tire shreds appears to be around 1.7 s in this figure. All of the shaking events and their time histories are available in the data reports [Rosebrook et al. (2000 a, b)].

MODAL ANALYSES

Newcomb and Drescher (1994) have shown that the behavior of shredded tires in the field, for working loads after compaction and placement of overburden soils, can be approximated by an elastic model. In this project a simple two-dimensional finite element model was constructed of a bridge abutment with several potential tire shred backfill configurations. Modal analyses were used to study the effect of the tire shred regions. Fig. 5 illustrates a short abutment FEM example which includes three types of backfill; a 0.9-m thick horizontal layer of shreds on the bottom of the abutment, a 1-m wide vertical layer of shreds directly behind the abutment wall, and a 3.2-m thick horizontal layer of shreds above the lower layer. A 1-m thick layer of topsoil covers these layers.

In general, the analyses showed that the inclusion of shreds decreased the natural frequency of the abutment, as would be expected. However, the finite element analyses also showed that by varying the amount, location, and geometry of tire

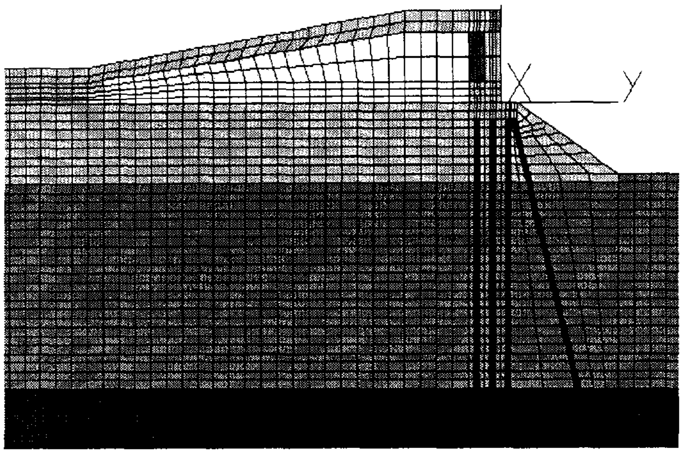

Fig. 5. Short abutment model for two dimensional FEM analysis. (partial mesh)

shreds fill sections, the dynamic characteristics of the abutment could be controlled in the design process.

CONCLUSIONS

The large centrifuge at UC Davis was used to investigate the dynamic behavior of tire shred material. The large container size and dynamic testing abilities of the centrifuge allowed the use of relatively large shreds under controlled conditions.

Small air-powered wave sources were developed to measure elastic wave propagation. The results from the small wave sources produced significant scatter, however, due to the relatively large sizes of the shreds as compared to the wave sources and instrumentation. Wave velocities from step displacement of the shaking table were more consistent, and the velocities were in the range of 35-50 m/sec.

The dynamic response of the tire shred profile was measured under a wide variation of excitation, from very small to very large shaking events. This data has been archived and is available to interested parties through the Center for Geotechnical Modeling at their web site, http://cgm.engr.ucdavis.edu.

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