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SEISMIC LOAD ATTENUATION USING EPS GEOFOAM BUFFERS IN RIGID WALL APPLICATIONS

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ABSTRACT

The paper briefly describes a series of reduced-scale shaking table tests that were carried out at RMC to demonstrate that expanded polystyrene (EPS) geofoam materials can be used as seismic buffers to attenuate earthquake-induced dynamic forces developed against rigid retaining wall structures. Two numerical modelling approaches are described that were used to predict the results of the physical experiments. The methods are based on: 1) a simple displacement block wedge approach, and; 2) a FLAC code. Both numerical approaches are shown to capture the peak dynamic-force time response of the seismic buffer wall models. Finally, the FLAC model is scaled up to prototype scale and example results presented to show that the use of EPS geofoam inclusions against rigid wall structures can be expected to significantly reduce earthquake-induced dynamic earth forces compared to the unmodified wall case.

Introduction

The concept of reducing the magnitude of earth pressures against rigid wall structures by placing a compressible vertical inclusion between the rigid wall and the retained soil has been proposed by a number of researchers for the case of static load conditions. The first reported field application of this technique was described by Partos and Kazaniwsky (1987). They used a prefabricated expanded polystyrene beaded drainage board 250 mm thick that was placed between a 10 m-high non-yielding basement wall and a granular backfill. McGown et al. (1988) carried out laboratory experiments on 1 m-high wall models constructed using horizontally compressible platens to measure the effect of wall material compressibility on the magnitude of earth pressures and wall deformations. Karpurapu and Bathurst (1992) carried out a numerical parametric study using a FEM code that was first verified against the physical test results reported by McGown and Andrawes (1987) and McGown et al. (1988). Karpurapu and Bathurst then used the numerical code to develop a series of design charts to select the thickness and elastic modulus of the compressible inclusion to minimize end-of-construction earth pressures against non-yielding retaining walls constructed to different heights and with a range of granular backfill materials compacted to different densities. The results of the previous work cited here supports the concept that a suitably selected vertical inclusion will allow sufficient lateral expansion of soil (controlled yielding) such

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that the retained soil is at or close to active failure and hence the earth pressures against the rigid structure are (according to classical earth pressure theory) at a minimum value.

Today the product of choice for the vertical compressible inclusion material is block-molded low-density expanded polystyrene (EPS), which is classified as a geofoam material in modern geosynthetics terminology (Horvath 1995). The concept of static earth pressure reduction using a geofoam inclusion can be extended to the case of seismic-induced dynamic force attenuation. Specifically, a properly selected EPS geofoam material could be used to reduce the potentially larger earth forces that may develop during earthquakes. In this paper, we refer to the compressible material as a seismic buffer.

The first application of this technology in North America for seismic design was reported by Inglis et al. (1996). Panels of EPS from 450 to 610 mm thick were placed against rigid basement walls up to 9 m in height at a site in Vancouver, British Columbia. Analyses using program FLAC (Itasca 1996) showed that a 50% reduction in lateral loads could be expected during a seismic event compared to a rigid wall solution.

This paper first briefly describes an experimental test program that was carried out at the Royal Military College of Canada to demonstrate proof of concept using the results of reduced-scale shaking table tests on rigid walls constructed with and without EPS geofoam seismic buffers. A simple displacement model was also developed to simulate the shaking table experimental results. Next, a numerical FLAC model is described that was used to simulate the experimental shaking table tests carried out at RMC. The paper shows that the results of both numerical models were in generally good agreement with experimental measurements. Finally, the FLAC numerical model used to simulate the shaking table tests is scaled up to investigate the simulated earthquake response of prototype-scale rigid walls with and without a seismic buffer.

Experimental Investigation

The experimental program was used to investigate the influence of geofoam compressibility (modulus) on the magnitude of load developed against non-yielding wall models 1 m high, by 1.4 m wide and retaining a granular soil extending 2 m behind the compressible layer. The models were constructed on a shaking table at RMC.

Reduced-Scale Shaking Table Experiment Design

A total of seven different tests were carried out. An example configuration showing the arrangement of the non-yielding wall, geofoam seismic buffer, retained soil and instrumentation is illustrated in Fig. 1. Wall 1 (control) was constructed without a seismic buffer. In all other walls the geofoam buffer was kept at a constant thickness of 0.15 m. The density of EPS geofoam is a key material property defining the compressive behaviour of geofoam. There are many proposed relationships in the literature to correlate the initial elastic tangent Young's modulus of EPS geofoam with density. A summary of these correlations for non-elasticized geofoam has been reported by Zarnani and Bathurst (2007). Elasticized EPS is manufactured by applying a load-unload cycle after manufacture. This gives the EPS linear elastic behaviour up to about 10% strain under compression and linear (proportional) behaviour up to about 40%, compared to about 1% strain for the non-elasticized material. However, the elasticized EPS geofoam has a lower elastic modulus compared to the non-elasticized material with the same density. Table 1 lists the properties of the EPS geofoam material used in the shaking table experimental tests. Due to page limitations only the experimental results for Walls 1, 2, 3 and 7 are presented in this paper. It should be noted that Walls 2 and 3 were constructed with unmodified EPS geofoam. The density and stiffness of the seismic buffer was artificially reduced by mechanically removing EPS material in Wall 7. Readers are directed to the papers by Bathurst et al. (2007a) and Zarnani and Bathurst (2007) for additional details on the experimental design and test results.

An artificial sintered synthetic olivine material (JetMag 30-60) was used as the retained soil in the experimental shaking table tests. This material was selected because it is silica free and thus avoided the health danger of silica dust generation during material handling in an enclosed laboratory environment. Backfill soil properties are summarized in Table 2. All tests in the current investigation were performed with the same volume and placement technique to ensure a consistent retained soil mass. A 6 mm-thick aluminium plate with aluminium stiffeners was used to construct a stiff bulkhead (rigid wall) in all tests. The aluminium bulkhead was supported laterally by four load cells rigidly braced to the shaking table platform. The bulkhead (and seismic buffer) was seated on an instrumented footing supported by three frictionless linear bearings. The linear bearings were seated on five load cells. The footing arrangement allowed the vertical and horizontal load measurements at the wall boundaries to be fully decoupled. The boundary conditions for the rigid wall prevented wall rotation and vertical and horizontal displacements. Four displacement potentiometers were used to measure lateral deformations at the geofoam-soil interface. An accelerometer was also mounted directly on the shaking table to record the input base acceleration-time excitation history. Four other accelerometers were embedded in the backfill soil at the locations shown in Fig. 1.

The same stepped-amplitude sinusoidal record with a frequency of 5 Hz was used as the horizontal base excitation history in all tests. Fig. 2 illustrates the measured table accelerogram filtered to 12 Hz and with linear baseline correction. A 5 Hz frequency (i.e. 0.2 s period) at 1/6 model scale corresponds to 2 Hz (i.e. 0.5 s period) at prototype scale according to the scaling laws proposed by Iai (1989). Frequencies of 2 to 3 Hz are representative of typical predominant frequencies of medium to high frequency earthquakes (Bathurst and Hatami 1998), and fall within the expected earthquake parameters for North American seismic design (AASHTO 2002). The displacement amplitude (i.e. actuator stroke) was increased at 5-second intervals up to a peak base acceleration amplitude in excess of 0.8g and the test terminated. This simple base excitation record is more aggressive than an equivalent true earthquake record with the same predominant frequency and amplitude. However, it allowed all walls to be excited in the same controlled manner and this allowed valid quantitative comparisons to be made between different wall configurations. Finally, it should be noted that the models were only excited in the horizontal cross-plane direction to be consistent with the critical orientation typically assumed for seismic design of earth retaining walls (AASHTO 2002).

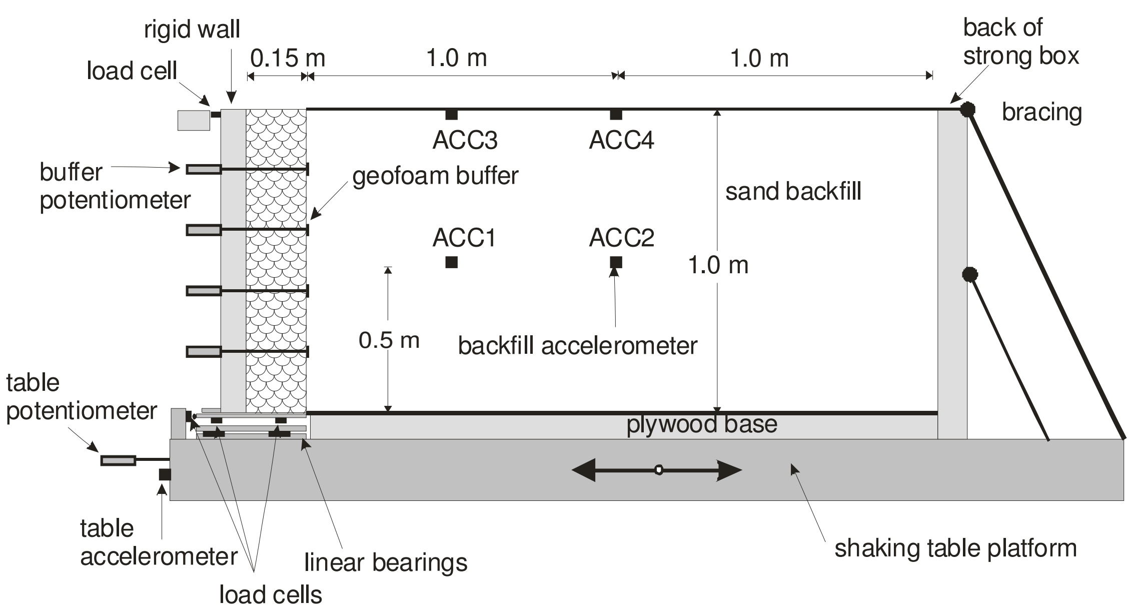

Figure 1. Example shaking table test configuration and instrumentation.

Table 1. EPS geofoam buffer properties.

Wall #	Bulk density (kg/m^3)	Initial tangent Young's modulus (MPa)	Thickness (m)	Type (ASTM C 578)
1	Control structure (rigid wall with no seismic buffer)			
2	16	$4.8^{\#}$ $(5.08 \pm 1.89)^{\ddagger}$	0.15	I
3	12	$3.2^{\#}$ $(3.31 \pm 1.48)^{\ddagger}$	0.15	XI
4	14	$1.3^{\#}$	0.15	Elasticized
5	$6^{\dagger}$ (50% removed by cutting strips)	$0.53^{\#}$	0.15	XI
6	$6^{\dagger}$ (50% removed by coring)	$0.6^{\#}$	0.15	XI
7	$1.32^{\dagger}$ (89% removed by coring)	$0.38^{\#}$	0.15	XI

Notes: † density of intact EPS geofoam = 12 kg/m^3; $^{\#}$ average back-calculated values from cyclic stress-strain measurements during experiments; ‡ average modulus and standard deviation using published correlations with density (Bathurst et al. 2007a)

Table 2. Backfill soil properties.

Property	Value
Density	15.5 Mg/m^3
Peak angle of friction	51º
Residual friction angle	46º
Cohesion	0
Relative density	86%
Dilation angle	15º

Experimental Results

Selected test results are presented here to demonstrate the essential performance features of the test walls. The principal measure of the relative influence of the seismic buffer on system response was the lateral wall force-base acceleration history recorded at end of construction (initial static loading condition) and during subsequent excitation (Fig. 3). As may be expected, the largest earth forces were recorded for the control wall (Wall 1 with no seismic buffer) and the lowest earth forces were recorded for the structure with the lowest bulk density geofoam buffer (Wall 7). For clarity, horizontal wall force histories with respect to peak base acceleration at each stepped amplitude level are plotted in Fig. 3 for Walls 1, 2, 3 and 7 only. The reduction in total lateral earth load for walls with seismic buffers is 11%, 15% and 40% of the value for the control wall for Walls 2, 3 and 7, respectively at peak acceleration of 0.75g.

Numerical Investigations

Displacement Model

Bathurst et al. (2007b) proposed a simple one-block model for calculating the dynamic response analysis of seismic buffer retaining walls (Fig. 4). The soil wedge is modeled as a rigid block under plane strain conditions. The seismic buffer is located between the rigid retaining wall and soil. A linear failure plane is assumed to propagate through the backfill soil from the heel of the buffer at an angle to the horizontal that

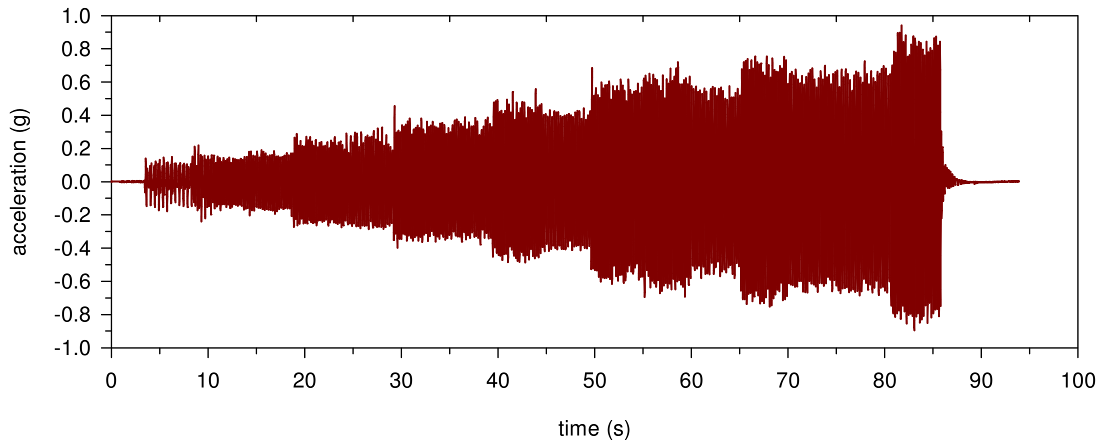

Figure 2. Example measured stepped-amplitude sinusoidal base excitation record – filtered to 12 Hz and linear baseline corrected.

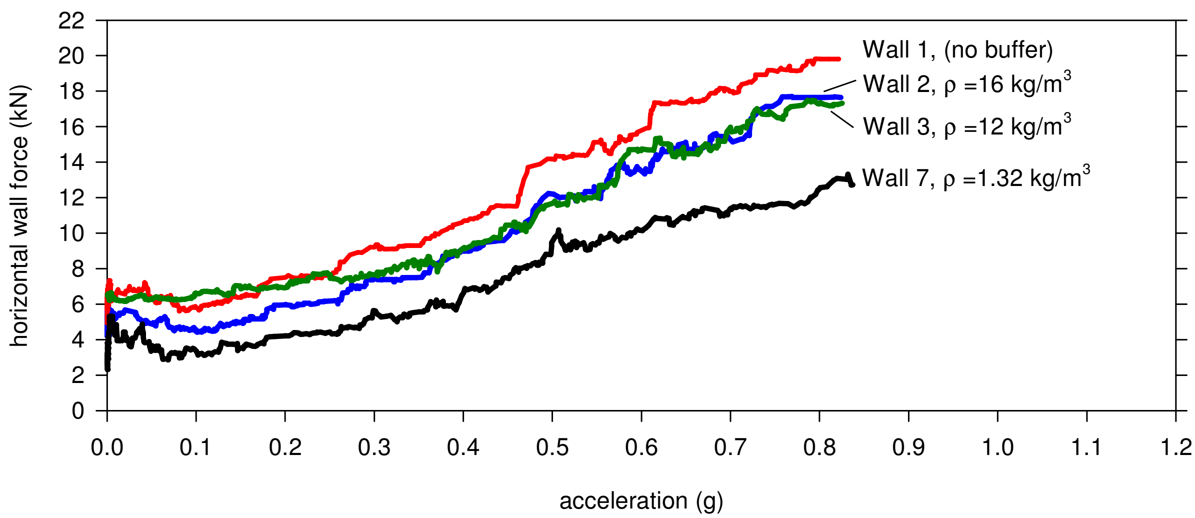

Figure 3. Horizontal wall forces recorded at peak base acceleration amplitude levels for Walls 1, 2, 3 and 7.

decreases with increasing magnitude of peak input acceleration. The forces at the wedge boundaries are computed using linear spring models. The compression-only force developed at the boundary between the soil wedge and geofoam buffer is computed using a single linear compression-only spring. The linear normal spring acting at the soil-soil wedge boundary permits tension and compression but was observed to develop only compressive forces during computation cycles. The shear springs at block boundaries are modeled as stress-dependent linear-slip elements to permit plastic sliding. The solution scheme is based on an explicit time-marching finite difference approach, which is commonly used for the solution of discrete element problems. The approach was modified to consider the compressible geofoam-soil boundary condition and changes in geometry of the soil wedge (block). At each time step, the numerical scheme involves the solution of the equations of motion for the block followed by calculation of the forces.

Computed load-time responses for two test cases presented earlier using the displacement model are presented in Figs. 5a and 5b. For clarity only the peak values from the load-time records for each numerical simulation are plotted in the figures. The datum for the plots is the end of construction. Hence,

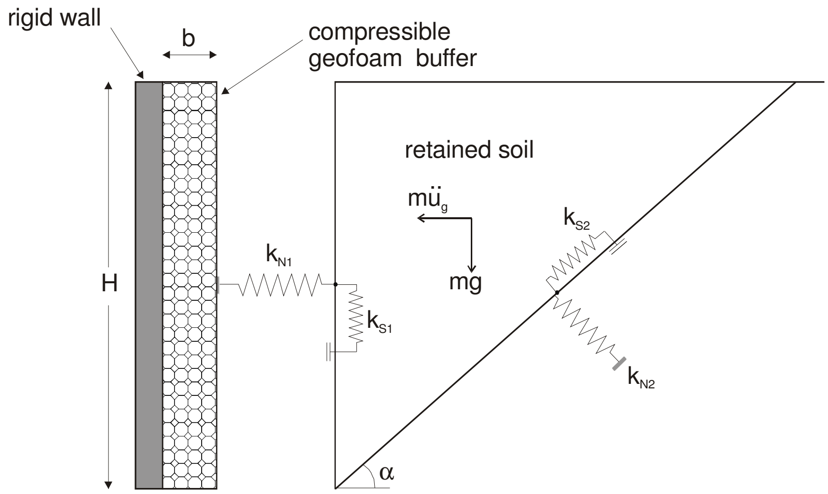

Figure 4. Single block displacement model.

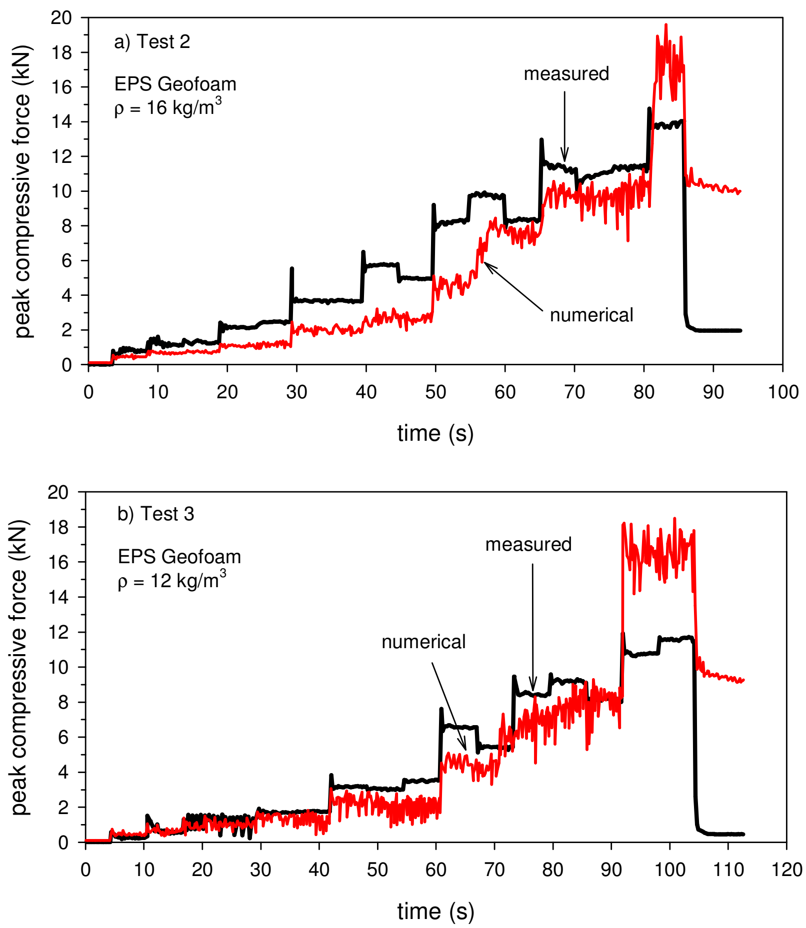

Figure 5. Wall force - time histories from physical tests and simple displacement numerical model.

these values are the result of dynamic loading only. The peak dynamic horizontal forces from the physical tests were computed from the sum of readings from the horizontal load cells mounted against the back of the walls. There is generally good agreement between the physical and numerical models for the configurations up to peak base input acceleration of about 0.7g. At higher accelerations there are likely more complex system responses that cannot be captured by the simple displacement model employed. For example, there are likely higher wall deformation modes at higher levels of base excitation. The poor predictions at peak base excitation levels likely led to the overestimation of buffer compression and loads at the end of the tests when the walls were returned to the static condition. Nevertheless, the trends in the measured data for the two walls with respect to buffer force are generally captured by the numerical model up to about 0.7g, and in many instances there is good quantitative agreement.

FLAC Simulation of Reduced-Scale Models with Seismic Buffers

Numerical simulations of the RMC reduced-scale models were also carried out using the program FLAC (Itasca 2005). The FLAC numerical grid for the simulation of the geofoam buffer tests is shown in Fig. 6. The height and width of the numerical grid and thickness of the geofoam were selected to match the physical tests.

The backfill soil was modeled as a purely frictional, elastic-plastic material with Mohr-Coulomb failure criterion. This model allows elastic behaviour up to yield (Mohr-Coulomb yield point defined by the friction angle), and plastic flow at post-yield under constant stress. The geofoam buffer material was modeled as a linear elastic, purely cohesive material. While a more advanced non-linear strain hardening model could have been implemented in the FLAC code, the simple constitutive model adopted here was judged to be sufficient since the measured compressive strains in the physical models were less than the elastic strain limit of 1% determined from rapid uniaxial compression tests reported by the manufacturer.

A no-slip boundary at the bottom of the sand backfill was assumed to simulate the rough boundary in the physical tests (i.e. a layer of sand was epoxied to the bottom of the strong box container). A slip and separation interface between the buffer and the soil was specified. This interface allowed the soil and buffer to separate with no tensile stress. The base and the two vertical boundaries of the models were excited using the measured base input acceleration record for each test during the experimental program.

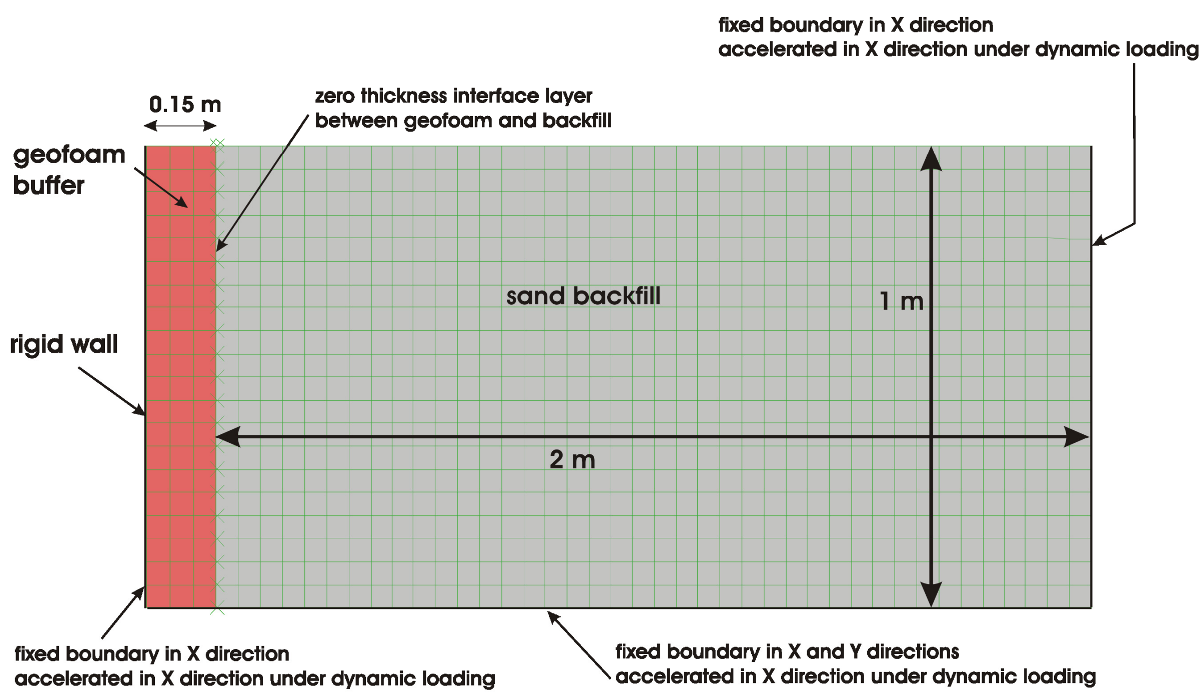

Figure 6. FLAC numerical grid showing geofoam buffer, sand backfill and boundary conditions.

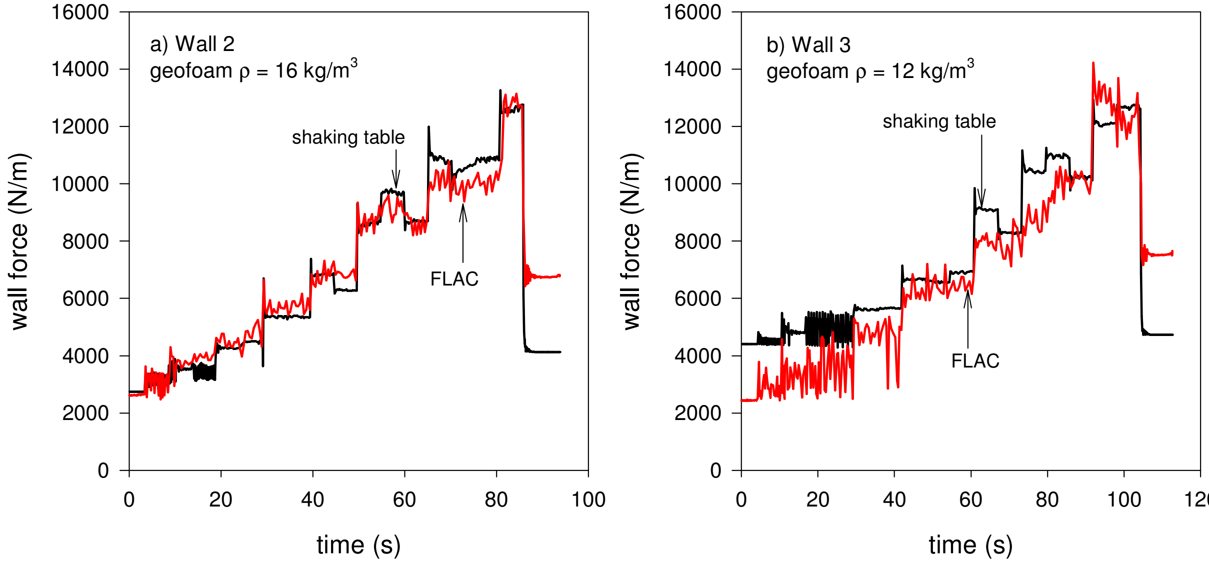

Figure 7. Wall force - time histories from physical tests and FLAC numerical simulations.

The horizontal input acceleration was actually applied using an equivalent velocity record (i.e. integrated acceleration record) with base line correction to ensure zero displacement at the base at the end of shaking.

The numerical results of interest are the peak magnitudes of horizontal force developed at end of construction and during base excitation. Maximum wall force versus time histories for two physical tests and numerical simulations are presented in Fig. 7. The vertical axis in the plots corresponds to the total horizontal earth force acting against the rigid wall per unit width of wall. The figures show that there is reasonably good agreement between measured and predicted results. There is a noticeable discrepancy between results at the beginning of the test for Wall 3. This is believed to be due to locked-in initial horizontal stresses that may have developed as a result of the gentle initial vibro-compaction technique that was used to densify the soil during placement of the sand layers in the strong box.

FLAC Simulation of Prototype-Scale Walls with Seismic Buffers

The reduced-scale FLAC numerical model that was verified against the shaking table experimental tests described above was modified to investigate the response of seismic buffer systems under simulated earthquake loading. The height of the wall was increased to 5 m and the length of the backfill soil was increased to 15 m in order to minimize far-field boundary effects on the models. The geofoam seismic buffer thickness was scaled up to 0.8 m. An example variable base input excitation record with a constant frequency of 1.5 Hz is shown in Fig. 8. The plot shows a maximum horizontal acceleration of 0.4g after 4.5 seconds. In this numerical study four different combinations of excitation record with frequencies of 1.5 and 3 Hz, and peak acceleration of 0.3 and 0.4 g were applied to the model. The minimum value for the natural frequency of the prototype-scale model was estimated to be about 3.7 Hz, which is greater than the input frequency and hence resonance was not a possible complication. The same material constitutive models and model parameters used in the reduced-scale FLAC models were used for soil and geofoam in this study. However, the geofoam material was restricted to the non-elasticized material with density of 16 kg/m^3.

Fig. 9 illustrates the wall force variation with time for both the control case and the wall with an EPS seismic buffer. The variation in wall force follows the same waveform as the input base acceleration history. Superimposed on the response curves are the peak wall force values for both cases. Comparison

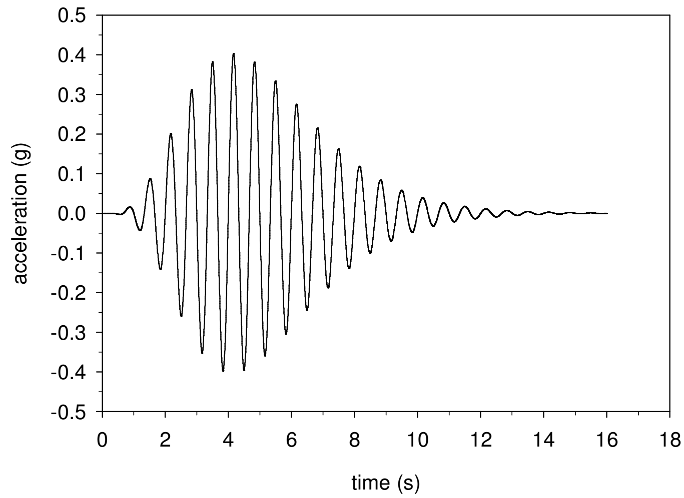

Figure 8. Example input acceleration history for prototype-scale FLAC model with frequency of 1.5 Hz and peak acceleration of 0.4g.

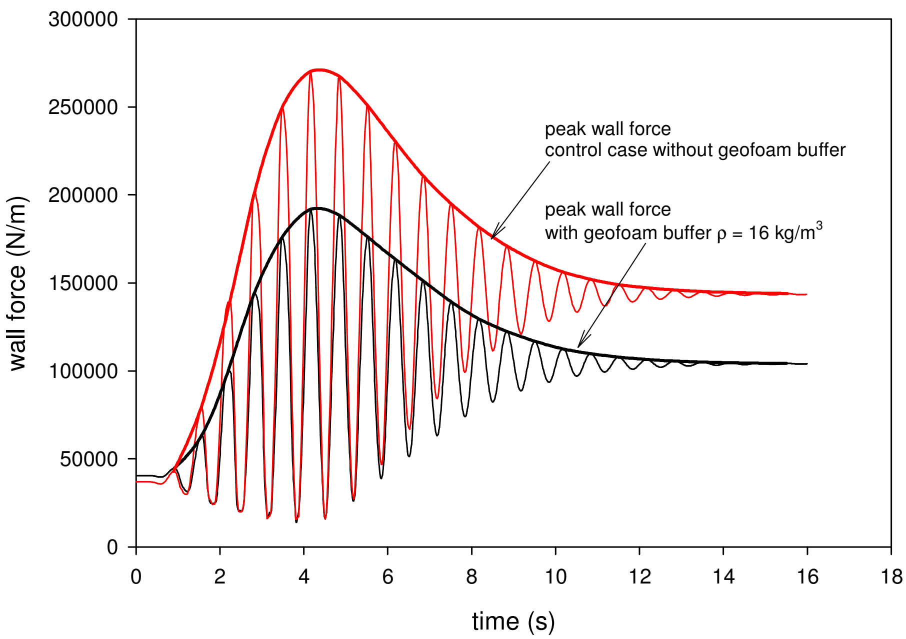

Figure 9. Horizontal wall force variation with time for prototype-scale control wall and wall with seismic buffer.

of the two data sets illustrates that there is a large reduction in the magnitude of horizontal wall force for the EPS geofoam seismic buffer configuration. The results for the four cases investigated showed that peak forces were reduced by 22% to 29% compared to the rigid control wall. Furthermore, as the frequency of base excitation increased the magnitude of force reduction decreased. However, the relative magnitudes of force reduction were essentially the same for simulations carried out with 0.3 or 0.4g peak acceleration and the same frequency.

Conclusions

In this paper the results of both physical experiments and numerical modelling are presented to demonstrate that a suitably selected vertical inclusion of compressible EPS placed against a rigid retaining wall can be used to attenuate dynamic earth forces due to earthquake. The physical shaking table test results showed that unmodified EPS materials reduced dynamic loads by up to 15%. Numerical modelling of prototype-scale systems showed that reductions as great as 30% are possible.

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