SEISMIC ISOLATION OF EARTH RETAINING WALLS USING EPS COMPRESSIBLE INCLUSIONS – RESULTS FROM CENTRIFUGE TESTING

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ABSTRACT

An experimental program involving centrifuge testing on model retaining walls under horizontal cyclic shaking is currently under way at the RPI centrifuge facilities. Fully instrumented rigid retaining walls with a prototype height of 4m, supporting cohesionless backfill, and seismically isolated with EPS compressible inclusions, are subjected to horizontal sinusoidal shaking of varying intensity. The lateral earth pressures on the wall as well as the accelerations throughout the model are recorded. Test results from both, isolated and non-isolated walls are compared to study the isolation efficiency of the compressible inclusions. The experimental results are also compared to results from previous numerical analyses and conclusions are drawn on the effectiveness of this isolation method.

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Introduction and Motivation

Earth retaining structures constitute an important component of many civil engineering works. These structures may be of a number of types (e.g. reinforced concrete retaining walls -gravity or cantilevered-, bridge abutments or basement walls) and they are designed to safely resist the lateral pressures exerted by earth masses. In earthquake prone areas an earth retaining structure must be designed to be able to withstand the seismic earth pressures in addition to the static ones. The provisions of current seismic codes for estimating the earth thrust due to the design earthquake are based mainly on the Mononobe-Okabe method and their use results in a significant increase of earth pressures under strong earthquake motions (Towhata, 2008). Poor design in such cases may lead into serious damage or even collapse of the retaining structure, with catastrophic consequences to important infrastructure works. On the other hand, the appropriate design against the increased lateral -static plus dynamic loading results in a significant increase in the construction cost. Despite the fact that the validity of current seismic code provisions and the applicability of assumptions made by analytical solutions to practical retaining walls has recently been questioned (Lew et al., 2010; Nakamura 2006; Al Atik and Sitar, 2008), the design and dimensioning of such walls is still, and probably will continue to be for some time in the future, based on the existing codes. Furthermore, recent research results from large scale shake table tests have shown that for high ground accelerations, significant earth pressure thrusts are measured on the retaining structures (Wilson and Elgamal, 2010). For these reasons, a method for the seismic earth pressure reduction (or isolation) would be particularly welcome by the civil engineering profession and construction industry (for both new and existing structures).

In the last decade a new method for the isolation of retaining structures against lateral seismic earth pressures has been proposed (Horvath, 1995; Inglis et al., 1996; Pelekis et al. 2000; Hazarika and Okuzono, 2004; Hazarika, 2005, Athanasopoulos et al., 2007, Zarnani and Bathurst, 2009). In this method a layer of EPS geofoam (playing the role of a compressible inclusion) is placed between the back face of the wall and the backfill material (Fig. 1). During earthquake loading the backfill seismic pressures are first applied to the EPS layer. This layer acts as a buffer (due to its greater compressibility) absorbing the major part of the thrust and transferring only a portion of it to the retaining structure. To date, research in this direction has primarily focused on shaking table testing of small scale physical models (Zarnani and Bathurst 2009) and numerical analysis (e.g. Inglis et al., 1996, Athanasopoulos et al., 2007). Small scale shaking table tests have certain limitations due to boundary effects and scale effects, and numerical analysis is typically limited due to assumptions for the soil stress-strain response, etc. To develop a robust methodology for the seismic isolation and/or seismic retrofit of earth retaining structures, results from numerical analysis need to be validated through physical testing, such as centrifuge testing, because the scaling and boundary conditions allow for correct modeling of the soil behavior, and lateral earth pressures can be estimated correctly.

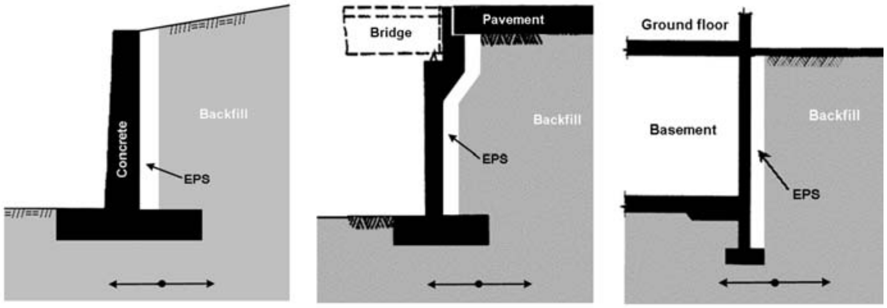

Figure 1: Isolation against the seismic lateral thrust on earth retaining structures by an EPS geofoam compressible inclusion.

Centrifuge testing is ideally suited and provides a great opportunity for modeling earth retaining structures because the scaling and boundary conditions allow for correct modeling of the soil behavior, and lateral earth pressures can be estimated correctly. Centrifuge testing is also relatively inexpensive and reproducible, and therefore a parametric study can be performed to identify the parameters mostly affecting the isolation efficiency of the EPS inclusions. This paper presents the first prototype scale (full scale) data with respect to seismic isolation of earth retaining structures. This research also presents an opportunity to redefine the role of physical testing in the development of new understanding of dynamic soil-structure interaction problems.

Literature Review/Background

Previous research on the effectiveness of EPS in providing isolation against the active earthquake lateral thrust, has focused almost entirely, on the case of non-yielding earth retaining walls. The concept was first proposed by Horvath (1995) and evolved as an extension of the initial use of compressible inclusions for reducing the static lateral earth thrust against non-yielding walls (e.g. Partos and Kazaniwsky, 1987; McGown et al., 1988; Karpurapu and Bathurst, 1992; Tsukamoto et al., 2002; Horvath, 2004). The studies on the effectiveness of EPS compressible inclusions as a seismic isolator of non-yielding walls against earth thrust have followed two directions: (a) numerical analyses using limit static approach and finite element difference programs (e.g. Inglis et al., 1996, Athanasopoulos et al., 2007) and (b) shaking table tests on small scale physical models (e.g. Hazarika and Okuzono, 2004; Zarnani and Bathurst, 2009). The soil behavior in the numerical analyses was assumed to be either elasto-plastic or equivalent linear. The EPS geofoam, based on experimental data, was assumed to be either a purely cohesive material or an equivalent linear material. Based on the results of extensive parametric analyses, the isolation efficiency with respect to earth pressures, A_p, (i.e. the ratio of the reduction of seismic thrust increment due to the isolation, to the value of seismic thrust increment without the isolation) of EPS compressible inclusions in the case of non-yielding walls was found to depend on the following parameters: 1) cross-section shape of compressible inclusion, 2) material density of EPS geofoam, 3) normalized thickness of compressible inclusion, 4) relative excitation frequency, 5) shaking intensity and 6) wall height and flexibility.

Physical testing can help verify the numerical analyses and validate their results. A common limitation with physical testing for most geotechnical engineering applications is the large scale of most structures, including retaining walls that are of interest to this project. Centrifuge testing offers an invaluable opportunity to perform physical testing on smaller scale model without boundary effect problems. In centrifuge testing the weight of natural material is artificially increased (utilizing the centrifuge forces), thus making the behavior of the small scale model to duplicate the behavior of the prototype structure. It is emphasized that the centrifuge tests provide results representative of the actual field conditions, in contrast to the small scale (1 g) shaking table tests in which the response depends on the scale of the model. Dynamic centrifuge testing has become an invaluable tool to understanding geotechnical earthquake engineering problems that would have been otherwise very hard to study. Advantages of dynamic centrifuge modeling have been discussed by many researchers such as Kutter (1995) and Dobry and Liu (1994). These advantages include a) use of small-scale models to accurately simulate prototypes with realistic soil stress states and depths, b) repeatability of results for like models, c) direct observation of modes of failures and deformations, d) efficient and cost-effective solution compared to full-scale testing, e) ability to apply earthquake motions with a wide range of magnitudes and frequency contents; and f) evaluation of empirical methods and validation of numerical modeling techniques (Al-Atik and Sitar, 2008).

Centrifuge Testing

To validate the seismic isolation efficiency of EPS-Geofoam compressible inclusions for retaining walls two centrifuge experiments were performed on the dynamic centrifuge at the Center for Earthquake Engineering Simulation (CEES) at Rensselaer Polytechnic Institute (RPI) in Troy, NY (Fig. 2). The centrifuge has a nominal radius of 2.7 m, a maximum payload of 1.5 tons, and an available bucket area of 1 m^2. The centrifuge capacity in terms of the maximum acceleration multiplied by

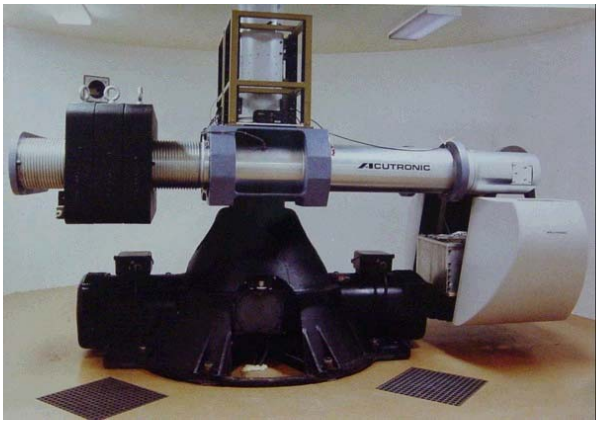

Figure 2: Centrifuge facility at RPI, NY (http://nees.rpi.edu/equipment/centrifuge/)

the maximum payload is 150 g-tonne. The 1D shaking table has a maximum payload mass of 250 kg and a maximum centrifugal acceleration of 100 g.

Model Construction and Instrumentation

The two models were constructed in the large rectangular rigid container with internal dimensions of 0.88 m long x 0.39 m wide x approximately 0.36 m deep. It was suggested that a rigid container be used for this experiment because the relative density of the sand used in the model is proposed to be 71% which is dense enough that very little movement of the sand is expected. Since the sand will not be moving, a laminar container is not necessary for this experiment and the switch from a laminar container to a rigid container will simplify the data analysis. The rigid container is also larger than the laminar container allowing for more space inside the model.

The first experiment was performed on a uniform density sand model. The model configuration is shown in Figure 3 in profile and plan views. In prototype scale, the first model consists of two cantilever flexible retaining walls of approximately 4m height and spanning the width of the container. The structures were designed to have the stiffness, mass and natural frequency of typical reinforced concrete structures. They sit on approximately 3.5 m of dry medium-dense sand (D_r = 71%) and the backfill soils consists of dry medium-dense sand (D_r = 71%). Both structures have stiff mat foundations.

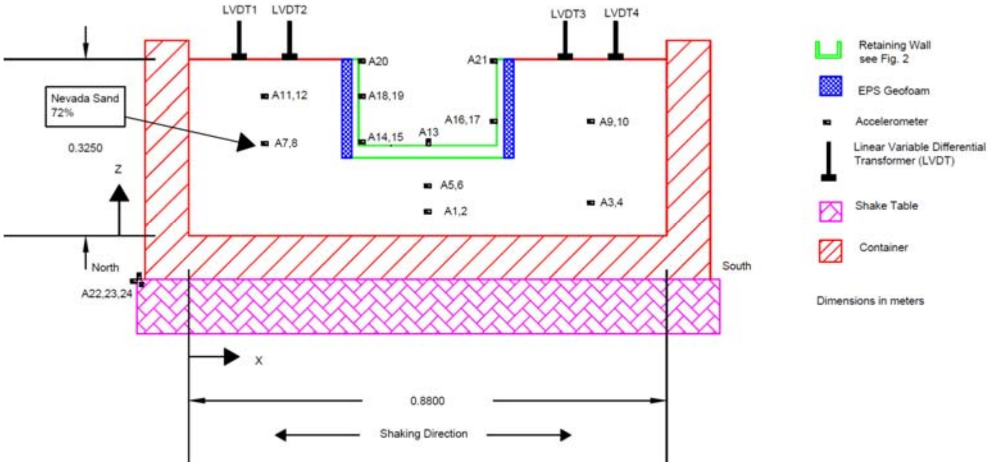

Figure 3: Model cross-section and instrumentation layout for the wall with the EPS inclusion.

The second centrifuge experiment was performed using the same configuration as described above. The only difference is the presence of the EPS-geofoam compressible inclusion between the retaining walls and the backfill soil. The thickness of the EPS inclusion is 10% of the wall height (normalized EPS thickness, t_r =10%) and equal to 40 cm in prototype scale.

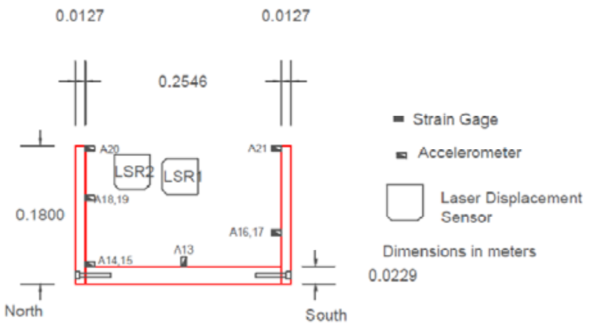

Figure 4: Retaining wall cross-section and instrumentation layout.

The sand used in the two centrifuge models was fine, uniform, angular Nevada sand. It has a mean grain size of 0.14 - 0.17 mm, a coefficient of uniformity of 1.67, a specific gravity of 2.67 and less than 5% fines (Kammerer et al. 2000). The model flexible retaining walls were constructed of an aluminum plate. The U-shaped cantilever structures were constructed using three plates in a tunnel-like configuration as can be seen in Figure 4. The two wall plates were bolted to the base plate and spanned the width of the container.

The model was constructed in several lifts of the dry Nevada sand. The size of the lifts corresponded to the vertical spacing of the instruments that had to be placed and the sand was placed at 71% relative density by pluviation. RPI has several different size pluviators that are available to use and by using the correct drop height, a relative density of 71% was reached. A vacuum device was used to smooth the surface of each lift so that instruments could be placed in the proper location. The sequence of the model construction consisted of placing first the foundation sand in several lifts, then placing the U-shaped retaining walls and then placing the backfill sand behind both of the walls. To minimize friction between the walls and the rigid container and to prevent sand from flowing through, a layer of grease and Teflon was placed at the end of each retaining wall. Figure 5(a) shows a step during the model construction.

Figure 5: Model preparation. (a) The backfill soil is placed behind the walls. (b) The tactile pressure pads have already been attached to the walls.

The two models used to perform the two centrifuge test were heavily instrumented to collect the necessary accurate and reliable measurements of accelerations, displacements, strains and earth pressures. The accelerometers manufactured by PCB Piezotronics were used to record horizontal accelerations, and are calibrated by RPI every 6 months. The accelerometers are 0.28 in x 0.49 in. and measure acceleration in one direction. They were mounted on the retaining wall using adhesive or mounted inside the model and held in place by the surrounding sand and a small strip of wax circling the accelerometer to make sure it did not slip. Three accelerometers were mounted to the shake table in the horizontal, vertical, and transverse directions to record the input acceleration time-history.

Lateral earth pressures acting on the retaining walls were recorded using tactile pressure sensors (Fig. 5b). The pressure sensors that are compatible with the software at RPI are made by Tekscan. High speed tactile pressure sensor pads were used. The tactile pressure measurement system is an extremely thin (~0.1 mm), flexible tactile force sensor that is placed between two mating surfaces to measure the contact pressure (Palmer et al., 2009). The measured forces can be presented either statically or dynamically and the information can be seen as graphically informative 2D or 3D display. These tactile pressure sensors are especially useful in the measurement of lateral pressure on the wall and values of the lateral pressure coefficient before and after shaking. These sensors were calibrated before the production tests for a range of expected pressure during a spin in the centrifuge. Strain gages were placed in a vertical array on both retaining walls to measure the wall deformation during the shaking event. This will allow for an indirect computation of the stress on the retaining wall and compare with the measurements from the tactile pressure sensors. The strain gages were attached to the wall by adhesive and connecting wires were soldered onto each gage.

Laser sensors were used to measure horizontal and vertical movement of the retaining walls. The laser displacement sensors are manufactured by Keyence and have dimensions of 2 in. x 2 in. x ½ in. They are calibrated by RPI every 6 months. The sensors have a range of plus or minus 4 inches but also have a minimum spacing distance between each sensor. The laser sensors were mounted onto the container but not to the retaining wall in order to measure the movement of the retaining wall. L-brackets that can be clamped to the container and to which the laser sensors can be fitted were used. Settlement of the surface of the backfill sand in the model was measured using LVDTs.

A high speed camera was also used during the production test to monitor the model during the spin and shaking motion and verify that no instruments are moving during the production test. Table xx shows the instrumentation inventory. The layout of the instrumentation is shown in Figures 3 and 4. The data acquisition (DAQ) infrastructure at RPI was used to record data during all stages of the centrifuge tests.

Both centrifuge model tests (i.e. without and with the EPS layer) were conducted at 22.2g, and then shaken with a harmonic, sinusoidal motion of varying amplitudes and frequencies. The motion was applied parallel to the long sides of the container and orthogonal to the retaining walls. A total of 10 input motions for each model were used with amplitudes equal to 0.05g, 0.1g, 0.2g, 0.3g and 0.35g at frequencies of both 2Hz and 3Hz. The reason for not shaking the model with a higher input acceleration was that the model was very heavy and during the shaking of the model at higher intensities the shaker's natural frequency interfered with the input signal.

Centrifuge Test Results

The main objective for performing the centrifuge tests is to better understand the seismic isolation efficiency of EPS-Geofoam compressible inclusions for retaining walls and validate preliminary results from numerical analyses. Due to space limitation in this paper, the authors will focus on the results based on data collected from the tactile pressure sensor pads. Figure 6(a) shows the static lateral earth pressure distribution as recorded by the tactile pressure sensors (two locations along the tactile pads are shown, i.e. 12 and 24) and as computed using at-rest and fully mobilized Rankine active lateral pressure coefficients (Ka and Ko respectively) for the model without the EPS inclusion. As can be observed there is good agreement between the measured and computed values, with the measured values closer to Ko conditions since the walls do not displace enough to fully mobilize active conditions. The tactile pressure pads have a height of 2m, and therefore cover the middle 2m of the retaining wall.

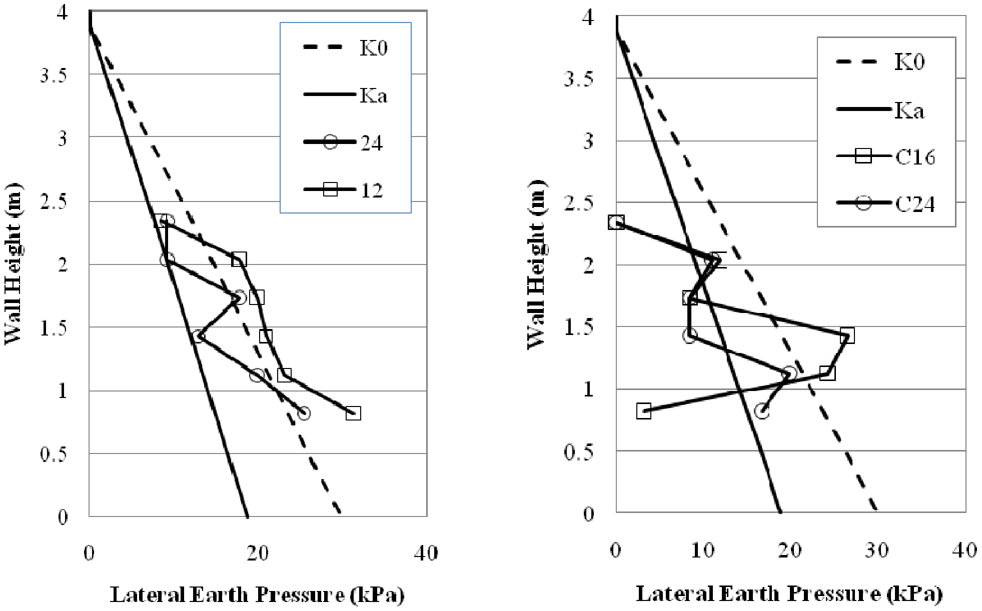

Figure 6: Static Lateral Earth Pressures for the two centrifuge models: a) without EPS, b) with t_r = 10% EPS.

Figure 6(b) shows the same results for the model with the EPS layer. Due to the presence of the EPS, the static lateral pressures are somewhat reduced, since the soil is able to deform the EPS more and therefore mobilize active pressures to a greater degree. The reduction varies along the height of the wall between 5% and 30%. These results and the good agreement with analytical methods increase our confidence on the tactile pressure sensor pads measurements. The top row of the pressure pad stopped working properly during the spin up and this is the reason their value is so low.

Figure 7 shows the variation of the total lateral earth pressure distribution with time for half a loading cycle for an input acceleration of 0.2g at a frequency of 2Hz. The total lateral earth pressures at certain times become greater than the static pressures, particularly near the mid-height of the wall. For the case with the EPS a reduction of the total lateral pressures is observed as well as smaller variation of the earth pressures during the half cycle of loading. The reduction varies along the height of the wall from 5% to 50% near the mid-height of the wall. With respect to the total earth thrust, P_{AE}, the reduction observed in these tests was equal to 27.7% on average across the entire tactile pressure pad.

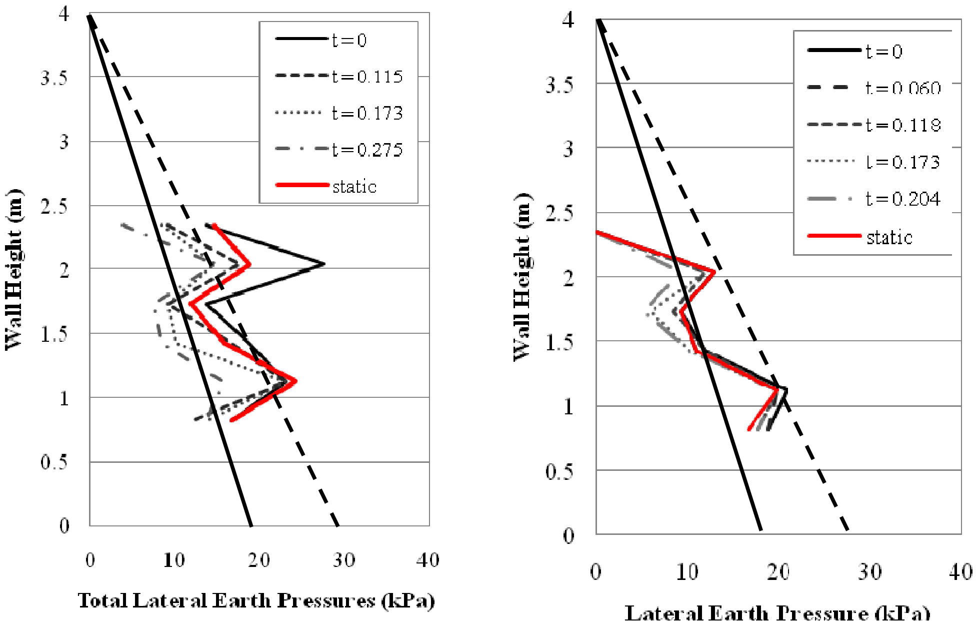

Figure 7: Total lateral earth pressures for an input acceleration 0.2g at a frequency of 2Hz: a) without EPS, b) with EPS.

These results compare well with results from finite element numerical analyses of similar non-yielding retaining walls isolated using EPS with a normalized thickness equal to 10% (Athanasopoulos, et al., 2007).

Conclusions

Earth retaining structures constitute an important component of many civil engineering works. These structures are designed to safely resist the lateral pressures exerted by earth masses. In earthquake prone areas an earth retaining structure must be designed to be able to withstand the seismic earth pressures in addition to the static ones. In the last decade a new method for the isolation of retaining structures against lateral seismic earth pressures has been proposed, where a layer of EPS geofoam (playing the role of a compressible inclusion) is placed between the back face of the wall and the backfill material and acts as a buffer.

Two centrifuge tests were performed on 4.0m tall retaining wall models founded and backfilled with dry, medium dense, Nevada sand. The models were shaken with a range of sinusoidal motions. These tests have given the first ever set of data for this type of project. Preliminary results and processing of the data from the centrifuge tests indicate that the EPS-geofoam layer that was included in the second model acted as a buffer and helped reduce the seismic pressures that were applied on the retaining wall. The isolation efficiency of a t_r=10% inclusion of EPS was found to vary between 10% and 50% along the height of the wall for an input motion of 0.2g at a frequency of 2Hz. These results are in good agreement with previously performed numerical analyses for similar walls and soil conditions. These centrifuge tests will also provide us with high quality data that can be used towards a better understanding of the seismic response and performance of earth retaining structures in general.

References

1. Al Atik, L., and Sitar, N. (2008) Dynamic centrifuge study of seismically induced lateral earth pressures on retaining structures. Proc. of the 4th Decennial Geotechnical Earthquake Engineering and Soil Dynamics Conference.
2. Athanasopoulos, G.A., Nikolopoulou, C.P., Xenaki, V.C. and Stathopoulou, V.D., (2007), “Reducing the Seismic Earth Pressure on Retaining Walls by EPS Geofoam Buffers – Numerical Parametric Study”, Proceedings of 2007 Geosynthetics Conference (in CD), Washington D.C., USA, 15pp.
3. Dobry, R, and Liu, L.(1994) “Centrifuge Modeling of Soil Liquefaction,” Proceedings of the Tenth World Conference on earthquake Engineering, Balkema, Rotterdam, 6801-6809.
4. Hazarika, H. and Okuzono, S., (2004), ‘’Modeling the Behavior of a Hybrid Interactive System Involving Soil, Structure and EPS Geofoam’’, Soils and Foundations, Japanese Geotechnical Society, October 2004, Vol. 44, No. 5, pp. 149-162
5. Horvath, J. S., (2004), “Geofoam Compressible Inclusions: The New Frontier in Earth Retaining Structures”, Geotechnical Engineering for Transportation Projects, Proceedings of Geo-Trans 2004, ASCE Geotechnical Special Publication No. 126, July 27-31, 2004, Los Angeles, California, M. K. Yegian and E. Kavazanjian Eds., Vol. 2, pp. 1925-1934
6. Inglis, D., Macleod, G., Naesgaard, E. and Zergoun, M., (1996), ‘’Basement Wall with Seismic Earth Pressure and Novel Expanded Polystyrene Foam Buffer Layer’’, Proceedings of 10th Annual Symposium of the Vancouver Geotechnical Society, Vancouver, B.C., 18p.
7. Kammerer, AM, Wu, J, Pestana, JM, Riemer, M, and Seed, RB. (2000) “Cyclic Simple Shear Testing of Nevada Sand for PEER Center Project 2051999,” Geotechnical Engineering Report No. UCB/GT/00-01, University of California, Berkeley, CA.
8. Karpurapu, R. and Bathurst, R. J., (1992), “Numerical Investigation of Controlled Yielding of Soil-Retaining Wall Structures”, Geotextiles and Geomembranes, Vol.11, No. 2, pp. 115-131
9. Kutter, BL. (1995) “Recent Advances in Centrifuge Modeling of Seismic Shaking,” Proceedings., St. Louis, Vol. II, 927-941.
10. Lew, M., Sitar, N., and Atik, L. (2010) “Seismic Earth Pressures: Fact or Fiction?”, Proc. Of the Earth retention Conf., Bellevue, Washington, August 2010, ASCE GSP 208, pp. 656-673
11. McGown, A., Andrawes, K. Z. and Murray, R. T., (1988), “Controlled Yielding of the Lateral Boundaries of Soil Retaining Structures”, In Proceedings of the ASCE Symposium on Geosynthetics for Soil Improvement,1988, ed. R.D. Holtz, Nashville, TN, USA, pp. 193-211
12. Nakamura, S. (2006) Re-examination of Mononobe-Okabe theory of gravity retaining walls using centrifuge model tests. Soils and Foundations 46 (2):135-146.

13. Ossa, A. and Romo, M.P. (2011) Dynamic characterization of EPS geofoam, Geotextiles and Geomembranes, No.29, pp. 40-50
14. Palmer, M.C., O'Rourke, T.D., Olson, N.A., Abdoun, T., and Ha, D. (2009), "*Tactile Pressure Sensors for Soil-Structure Interaction Assessment*", ASCE J. Geotechnical and Geoenvironmental Engineering, Vol. 135, Issue 11, November, pp. 1638-1645.
15. Partos, A. M. and Kazaniwsky, P. M., (1987), "Geoboard Reduces Lateral Earth Pressures", In Proceedings of Geosynthetics '87, New Orleans, USA, February 1987
16. Pelekis, P. C., Xenaki, V. C. and Athanasopoulos, G. A., (2000), "Use of EPS Geofoam for Seismic Isolation of Earth Retaining Structures: Results of a FEM Study", Proceedings of the 2nd European Geosynthetics Conference, EuroGeo 2000, Bologna, Italy, October 2000, A. Cancelli, D. Cazzuffi and C. Soccodato Eds., Vol. 2, pp. 843-846
17. Towhata, I. (2008) Geotechnical Earthquake Engineering, Springer ed.
18. Trandafir, A.C., Bartlett, S.F., and Lingwall, B.N. (2010) Behavior of EPS-geofoam in stress-controlled cyclic uniaxial tests" Geotextiles and Geomembranes, No. 28, pp. 514-524
19. Tsukamoto, Y., Ishihara, K., Kon, H. and Masuo, T., (2002), "Use of Compressible Expanded Polystyrene Blocks and Geogrids for Retaining Wall Structures", Soils and Foundations, Japanese Geotechnical Society, Vol. 42, No. 4, August 2002, pp. 2
20. Wilson, P., and Elgamal, A. (2010) Large-Scale Passive Earth Pressure Load-Displacement Tests and Numerical Simulation, ASCE Journal of Geotechnical and Geoenvironmental Engineering, Vol. 134, pp.1634-1643
21. Zarnani, S., and Bathurst, J. (2008), "Numerical Modeling of EPS Seismic Buffer Shaking Table Tests", Geotextiles and Geomembranes 26 (2008), 371-383.
22. Zarnani, S., and Bathurst, R. J. (2007), "Experimental Investigation of EPS Geofoam Seismic Buffers Using Shaking Table Tests", Geosynthetics International, 2007, 14, No. 3.
23. Zarnani, S., and Bathurst, R.J. (2009), "Numerical Parametric Study of Expanded Polystyrene (EPS) Geofoam Seismic Buffers", Canadian Geotechnical Journal, Vol. 46, pp. 318-338.

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