Effect of boundary conditions on earth pressure reduction using EPS Geofoam

T. N. Dave i) and S. M. Dasaka ii)

i) Assistant Professor, Department of Civil Engineering, Pandit Deendayal Petroleum University, Gandhinagar – 382007, India.
ii) Associate Professor, Department of Civil Engineering, Indian Institute of Technology Bombay, Powai, Mumbai – 400076, India.

ABSTRACT

This paper presents results of small scale physical model tests on an instrumented rigid retaining wall subjected to 1-D shaking and effectiveness of EPS (expanded polystyrene) geofoam to reduce seismic earth pressures. Two different boundary conditions viz., retaining wall with and without hinge at the base were considered during experiments. Initial application of 50 kPa static surcharge, followed by seismic load in the form of a stepped sinusoidal acceleration in the range of 0 to 0.7 g was applied in increments of 0.045 g, each increment being applied for 5 seconds at 3 Hz frequency. The seismic earth pressure distribution was observed nearly hydrostatic in the case of retaining wall with hinge, without geofoam inclusion. Whereas, for the retaining wall without hinge, the observed seismic earth pressure distribution was curvilinear with maximum pressures in the upper half of the retaining wall.

Provision of 10D (10 kg/m²) EPS geofoam reduced the total lateral force on the retaining wall by about 23% and 28%, for retaining wall with and without hinge, respectively. It was observed that, boundary conditions are mainly influenced the earth pressure distribution in both the cases, with and without geofoam provision.

Keywords: seismic loading, earth pressure reduction, EPS geofoam, boundary conditions

1. INTRODUCTION

Earth-retaining structures are integrally designed to withstand lateral pressures due to backfill, surcharge load from adjacent structures and traffic and earthquake loads. The cost of these structures is directly proportional to the earth pressures they are subjected to. Under severe earthquake loading, larger forces act on these walls compared to that of static active or at-rest conditions. Researchers are constantly working for a viable solution to reduce the earth pressures exerted on retaining walls, which would eventually reduce the construction cost of the wall, and post-construction maintenance cost. Technique of providing compressible inclusion at the backfill-wall interface came into existence to minimize earth pressures on retaining walls. Previous research studies indicated that provision of a compressible inclusion behind a rigid, non-yielding/limited yielding or yielding wall would reduce earth pressure by imparting controlled yielding in the backfill material and contribute to the economical design of the wall. Deformations in the backfill soil mobilize a greater portion of the available shear strength of the material and decrease the unbalanced lateral forces acting on the retaining structure.

2 LITERATURE REVIEW

Among all the methods, provision of a compressible inclusion in the form of Expanded Polystyrene (EPS) geofoam at the wall-backfill interface proved successful because of ease in construction and predictable stress-strain characteristics of the inclusion. In the past, studies were conducted with materials such as glass-fiber insulation (Rehnman and Broms, 1972) and cardboard (Edgar et al., 1989) for similar applications. However, they were not successful, as their stress-strain behavior was unpredictable and uncontrollable. On the other hand, Expanded Polystyrene (EPS) geofoam is considered as a suitable material as it fulfills the required stress-strain behavior and has smaller stiffness than any other geofoam materials. Additionally, Horvath (1997) documented 30 years of proven durability of EPS geofoam in several geotechnical applications.

Experimental investigations on the concept of reduction of seismic load on the retaining wall in the presence of geofoam inclusion were performed by several researchers on reduced scale models tested on shaking table (Hazarika et al. 2002, Bathurst et al. 2006, Zarnani and Bathurst, 2007). Hazarika et al. (2002) showed reduction in the peak lateral loads in the range of 30% to 60% compared to that on an identical structure but with no compressible inclusion. Zarnani and Bathurst (2007) noticed that the magnitude of the dynamic lateral earth force was reduced with decreasing geofoam modulus. Horvath (2010)
highlighted compressive stiffness as the single most important behavioural characteristic of any compressible inclusion influencing the reduction. Athanasopoulos et al. (2012) observed that EPS of 20 kg/m$^3$ density and relative thickness ($t/h$) of 15% to 20% can reduce the seismic pressure by up to 20%, and the seismic displacement of the wall by up to 50%, depending on shaking intensity and height of the wall. Moreover, through small scale model experiments, Dave et al. (2013) and Dasaka et al. (2014) highlighted that provision of EPS geofoam mitigates the seismic earth pressures on rigid, non-yielding wall as well as gravity retaining wall, respectively.

The available literature highlighted that though, the behavior of EPS geofoam and its influence on the earth pressure reduction under seismic loading are studied, the effect of boundary condition of retaining wall on earth pressure distribution with and without EPS geofoam under combined surcharge and seismic loading is not fully understood. Hence, the present study is aimed at understanding the effect of boundary condition on the magnitude and distribution of earth pressure through experimental investigations on small scale models tested at the 1-D shaking table facility.

3 EXPERIMENTAL PROGRAM

3.1 Materials used in the present study

In the present study, Indian Standard (I.S.) Sand of Grade III was used as backfill soil, and based on results of particle size distribution (Fig. 1), it was classified as SP according to the Unified Soil Classification System (USCS). Physical properties of backfill material are presented in Table 1. Angle of internal friction obtained by conducting the direct shear test was 39°. Further, EPS geofoam of density 10 kg/m$^3$ was used as inclusion between the retaining wall and backfill. Uniaxial compression tests were carried out on EPS samples at an axial strain rate of 10%/minute, and yield strength of the EPS geofoam was found as 29.3 kPa, as shown in Fig. 2.

| Property          | Grade III |
|-------------------|-----------|
| $G_s$             | 2.65      |
| $C_u$             | 1.42      |
| $C_c$             | 0.93      |
| $\gamma_{\text{min}}$ (kN/m$^3$) | 14.58 (ASTM D4254-00) |
| $\gamma_{\text{max}}$ (kN/m$^3$) | 17.10 (Pluviator) |
| $\gamma_{\text{backfill}}$ (kN/m$^3$) | 16.3 (RD – 68%) |

3.2 Details of experimental model study

The physical tests described in this paper were carried out on 1.2 m × 1.2 m shaking table located at the Indian Institute of Technology Bombay. The table had 10 kN payload capacity and was driven by a 100 kN capacity Schenk hydraulic actuator with ancillary controller. The table was driven in the horizontal direction only, as it was noted that the horizontal component of seismic induced dynamic earth loading is typically the most important loading of the application under investigation. The table can excite the rated payload at frequencies up to 50 Hz and ± 5g. The maximum displacement of the table was ± 125 mm. The instrumented retaining wall models were built in a stiff, strong box (1200 mm long, 310 mm wide and 700 m high) and bolted to the steel platform of the shaking table. Detailed diagram and pictorial view of experimental setup are illustrated in Fig. 3 and 4. The model retaining wall was placed at a distance of 0.10 m from one of the ends, allowing 1.1 m as backfill length behind the retaining wall. A 15 mm thick stainless steel plate was used as a model retaining wall and was instrumented with 7 diaphragm type earth pressure...
cells, attached flush with the surface of the wall. The wall was restrained laterally using three universal load cells rigidly connected to the other side of the retaining wall at 125, 325 and 555 mm elevations; however the bottom end of the wall was either hinged or free to rotate about the base.

![Fig. 3. Detailed diagram of the experimental setup](image)

![Fig. 4. Pictorial view of experimental setup](image)

One long side of strong box was made-up of Plexiglas and other sides of stainless steel. The inside surface of the Plexiglas was covered by 120 mm wide and 60 mm thick greased polyethylene sheet with an overlap of 10 mm with each other. The combination of friction-reducing membrane and rigid lateral bracing was adopted to ensure that the test models were subjected to plane strain boundary conditions. A plywood sheet was bolted to the bottom of strong box, and a layer of sand was epoxied to the top surface of plywood to create a rough surface, so as to simulate backfill continuity in vertical direction. A series of experiments were carried out without geofoam and with geofoam inclusion at the wall-backfill interface. In all experiments, the sand was backfilled at 68% relative density using portable travelling pluviator (Dave and Dasaka, 2012) and top surface was manually leveled. The actual relative densities achieved in each test during the backfilling were monitored by collecting samples in small cups of known volume placed at different locations. Previous studies of the authors highlighted that an EPS panel of density of 10D (10 kg/m$^3$) and 75 mm thickness ($t/H = 0.125$) helps in maximum reduction in earth pressure. Hence, the EPS panel of 10 kg/m$^3$ density and dimensions of 700 mm × 300 mm and 75 mm thickness, prepared using a hot-wire cutter, was pasted to retaining wall using ABRO tape to have proper contact of an EPS panel with retaining wall during the test. In order to apply uniformly distributed surcharge on the backfill, a rubber bellow was placed over an 8 mm thick rubber sheet laid on the surface of the backfill. Specially designed neoprene rubber bellow of 250 kPa capacity with non-return pneumatic valve was connected to a compressor to apply regulated pressure. A steel plate of 10 mm thickness with attachments to measure surface settlement was placed between rubber bellow and rubber sheet and a steel plate of 10 mm thickness was placed on the rubber bellow such that when inflated with compressed air, the plate moved upwards to mobilize reaction from frame, which was rigidly connected to the tank, thereby transferring pressure to the sand fill.

Three LVDTs were used to measure vertical settlement on top of the backfill at 150 mm, 450 mm and 750 mm from the retaining wall. The LVDTs were firmly mounted on the reaction frame with magnetic stand and were rested on angles welded on steel plate. Four accelerometers (PCB Piezotronics) were used to obtain acceleration-time excitation history. Out of these, three were embedded in backfill at 100 mm, 300 mm and 500 mm from the bottom and one accelerometer was mounted directly on the shaking table to record the input base acceleration-time excitation history, as shown in Fig. 3.

![Fig. 5. Positioning of Accelerometer in the backfill](image)

The accelerometers were attached to mounting blocks before placing them at desired locations, to ensure that the devices remained level and moved in phase with the surrounding sand during shaking, as shown in Fig. 5. All the instruments were monitored by
a separate high speed data acquisition system (MGC plus—HBM Inc. and Catman professional software). Data from a total of 17 instruments were recorded at a speed of about 100 Hz in order to prevent aliasing and to capture peak response values. After the model preparation was completed, surcharge pressure was applied in increments of 10 kPa up to 50 kPa and corresponding magnitude and distribution of earth pressures were monitored. Further, under maintained surcharge pressure, the models were excited using a displacement-time history selected to match a target stepped-amplitude sinusoidal accelerogram with a frequency of 3 Hz, as shown in Fig. 6.

The above frequency was adopted, as frequencies of 2–3 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). This simple base excitation record was more aggressive than an equivalent true earthquake record with the same predominant frequency and amplitude (Bathurst and Hatami, 1998, Matsuo et al., 1998). 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).

4 RESULTS AND DISCUSSION

Experimental evaluation of earth pressure due to static surcharge only and combined sustained static - seismic loading were carried out for model tests without and with geofoam inclusion, to observe the effect of boundary conditions. Model tests on instrumented retaining wall when the wall was hinged at the base and when the wall was not hinged at the base are compared. For the wall hinged at the base the observed earth pressure distribution was approximately triangular in shape, as shown in Fig. 8. Just above the base of the wall, lower earth pressures were observed, this may be due to arching of backfill soil. Experimental evaluation of seismic earth pressure on retaining wall by application of seismic acceleration revealed a reduction in the earth pressure in top 1/3 portion of the wall, while the increase for remaining wall height, as shown in Fig. 8.

During seismic loading, top portion of the wall might have moved sufficiently away to achieve an active condition, showing reduction in pressure in the top portion of the wall. The increase in total lateral
thrust was negligible for 0.18g (about 2.36%), however, after 0.36g, increase in earth pressure was observed throughout the wall height. The total lateral thrust increased with increase in seismic acceleration and the maximum increase in total lateral thrust was observed to be of 23% at 0.7g. The maximum increase in lateral pressure of 49.5% was observed at about 0.35h from bottom. The observed reduction may be due to sufficient lateral movement of retaining wall, and subsequent mobilization of backfill strength and reduction in effect of surcharge load due to wall movement, as shown in Fig. 8.

As shown in Fig. 9, for retaining wall free at the base and without geofoam, application of seismic acceleration caused an increase in earth pressures, with maximum pressures at about h/3 from top of wall. Though, pressures near the top of the wall reduced with an increase in seismic acceleration, lateral thrust on the retaining wall is increased by about 29.64% under seismic acceleration of 0.7g. Maximum earth pressure is found to increase by 17.62% at 0.7g. As the wall was free to rotate about its base during seismic loading, the wall might have moved towards backfill causing increase in pressures at about 0.4 h from the top, with increase in seismic acceleration.

For retaining wall hinged at the base, the earth pressure distribution with geofoam inclusion is presented in Fig. 10. The measured total thrust under 50 kPa surcharge pressure was 23.2% less than that on wall without geofoam inclusion. Reduction in total lateral thrust under surcharge loading is attributed to compression of geofoam and associated backfill strength mobilization which resulted in settlement of backfill. As during surcharge load application phase, compression of geofoam had reached its elastic limit, hence a further reduction in earth pressure was negligible during the seismic loading phase.

The maximum reduction in total lateral thrust under combined loading is 26.9%, corresponding to the applied seismic acceleration of 0.36g. At the seismic acceleration of 0.7g, the reduction in maximum total lateral thrust was about 23%. Experiments with geofoam inclusion showed a 54% increase in maximum lateral thrust under seismic loading, though it was 9.75% lower than the corresponding lateral thrust in the absence of geofoam inclusion. The maximum lateral pressure was reduced by 54% due to geofoam inclusion at location h/3 from base of wall.

Fig. 9. Earth pressure under combined sustained static and seismic loading without geofoam – Wall not hinged

Fig. 10. Earth pressure under combined sustained static and seismic loading with geofoam – Wall hinged at the base

Fig. 11 presents earth pressures under combined loading on retaining wall with 10D geofoam inclusion when the wall was free at the base.

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Fig. 11 presents earth pressures under combined loading on retaining wall with 10D geofoam inclusion when the wall was free at the base.
static pressures on the rest of the wall. For seismic acceleration of 0.7g, lateral thrust was reduced by 28.25\% compared to the case of retaining wall without geofoam. Though, provision of EPS geofoam at backfill-wall interface showed significant reduction in static and seismic loads in both the cases, due to small scale model studies and associated boundary conditions, the observed reduction in magnitude of earth pressure was less than that noted from a numerical study on a 6 m high wall carried out by the authors.

5 CONCLUSIONS
Following are the major conclusions derived from the present study:

- Maximum earth pressure was observed to act at h/3 from the base of the wall and h/3 from the top of the wall for the cases when wall was hinged at the base and wall was free at the base, respectively.
- In both the cases, the increase in total lateral thrust was found negligible up to 0.18g seismic acceleration. However, after 0.36g, increase in earth pressure and total lateral thrust were observed throughout the wall height.
- The maximum reduction in total lateral thrust under combined sustained static and seismic loading by provision of 10D geofoam were observed as 26.9\% and 28.25\% at 0.36g seismic acceleration for the cases when wall hinged at the base and wall free at the base, respectively.
- Under the seismic acceleration of 0.7g, lateral thrust on the retaining wall increased by 23\% and 29.64\% for the cases when wall hinged at the base and wall free at the base, respectively.
- Boundary conditions mainly influence the earth pressure distribution in both the cases but not the lateral thrust.

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