Displacement based seismic assessment of cantilever retaining walls

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Abstract

Present study deals with displacement based seismic assessment of cantilever retaining walls. Experimental investigations and nonlinear finite element (FE) analyses have been carried out in order to understand seismic behavior of cantilever retaining walls. A scaled down model of cantilever retaining wall was used for shaking table experiment. Earthquake induced retaining wall displacements, free vibration response of retaining wall and seismic pressure behind retaining wall were investigated based on experimental and numerical results. It was observed that seismic performance of cantilever retaining wall is highly influenced by backfill soil. Retaining wall displacement and settlement of backfill soil is mainly dependent on the severity of seismic shaking.

Keywords: retaining wall, shaking table experiment, displacement, seismic, performance, scaled model.

Introduction

Earth retaining structures plays a key role in modern infrastructure system, i.e. retaining walls, sheet pile walls, basement walls and bridge abutments. Realistic and accurate assessment of earthquake induced structural actions is a prime concern for safe and effective design of earth retaining structures. The present study deals with displacement based seismic assessment of earth retaining structures. Pluck tests have been performed on scaled down models, for understanding the effect of seismic actions on earth retaining structures. Shaking table facility at The University of Melbourne has been used for pluck tests. Frequency domain analyses have also been performed for understanding free vibration response of scaled down model. The capability of finite element (FE) software Abaqus was also examined for replication of experimental results. Pressure distribution behind the fixed end wall was also studied. A nonlinear pressure distribution was observed behind the retaining wall, small duration of peak pressure was also observed. Detachment of wall from backfill soil and excessive settlement of backfill soil was observed in all cases.

Literature review

Seismic response of earth retaining structures have been studied by many researchers. Newmark (1965) studied seismic behavior of dams and embankments and established a relationship to estimate the earthquake induced slip in dams and embankments. Richard and Elms (1979) studied seismic displacement of gravity retaining walls and proposed a design procedure for retaining walls. Whitmen and liao (1985) modified the work of Newmark (1965) and Richard and Elms (1979) and developed design charts for estimation of earthquake induced retaining wall displacement. The studies carried by Newmark (1965), Richard and Elms (1979) and Whitmen and liao (1985) assumed a rigid backfill behind the retaining walls, which is a major limitation of their work. Earthquake loading generates inertial forces in earth retaining structures and backfill soil. Due to these inertial forces an additional thrust starts acting behind the earth retaining structure, which is known as dynamic earth pressure (Seed and Whitman 1970, Siddharthan et al. 1994). The design manuals recommend to use the Mononobe-Okabe (MO) method proposed by Mononobe and Matsuo (1929) to predict seismic pressure behind retaining walls (AASTHO guide specifications for LFRD seismic bridge design 2011, Eurocode 8. 2008, AS 5100.2. 2017). However, the validity of MO method has been challenged by many researchers (Sherif and Fang 1984; Psarropoulos et al. 2005; Yazdani et al. 2013). Experimental investigations have been performed on full scale and scaled down models for understanding the effects of earthquake actions (mainly dynamics pressure) on retaining walls (Sherif and Fang 1984, Simonelli et al. 2000, Latha and Krishna 2006, Oldecop and Zabala 1996, Mikola and Sitar 2013). However, these studies did not include the role of backfill soil on displacement behavior of retaining walls and time dependent pressure behind the retaining walls. Therefore, a schematic experimental and numerical study is required in order to understand the effect of seismic actions on earth retaining structures.

Research methodology

The present study deals with experimental and numerical investigations of seismic response of fixed end retaining walls. A series of pluck tests have been carried out on scaled model for understanding the displacement demand of retaining wall and pressure distribution behind retaining wall. Frequency domain analyses have also been performed on experimental results to understand the free vibration response of retaining wall, and to estimate the natural period of retaining wall. The capability of FE software Abaqus was also verified for replication of experimental results. Non-linear time history FE analyses have been carried out in dynamic explicit module of

Abaqus, which is very popular for large deformation numerical analysis (Abaqus/Explicit User's Manual, version 6.13. 2013).

Shaking table experiment on scale down retaining wall model

Experiment set up and scaled model construction

Shaking table experiments have been performed on scale down retaining wall models; to understand the seismic displacement and distribution of seismic pressure on earth retaining structures. All experiments have been performed on a 10 scale down model. Aluminum retaining wall has been chosen for shaking table experiments. Figure 1 shows the details of scaled model. Scaled height and thickness of Aluminum wall is 0.4 m and 4 mm respectively, which represents a 4 m high and 40 mm thick prototype retaining wall. Width of scaled wall is 0.4 m. Base of scaled retaining wall is fixed with the help of steel angle sections. Selection of retaining wall material (aluminum) and boundary condition (fixed base) is made for achieving a deflection pattern of retaining wall and backfill soil induced pressure effects on wall deformation. The total length of scaled model is 1.7 m, which is decided based on observations with lesser length models for minimizing the pulse reflection. A rectangular wooden frame is used for retention of backfill soil. High density foam of 20 mm thickness is applied at the end of wooden frame for minimizing wave reflection. Sand paper is applied on wall at wall and backfill interface, and base of frame for generation of friction between wall and backfill soil.

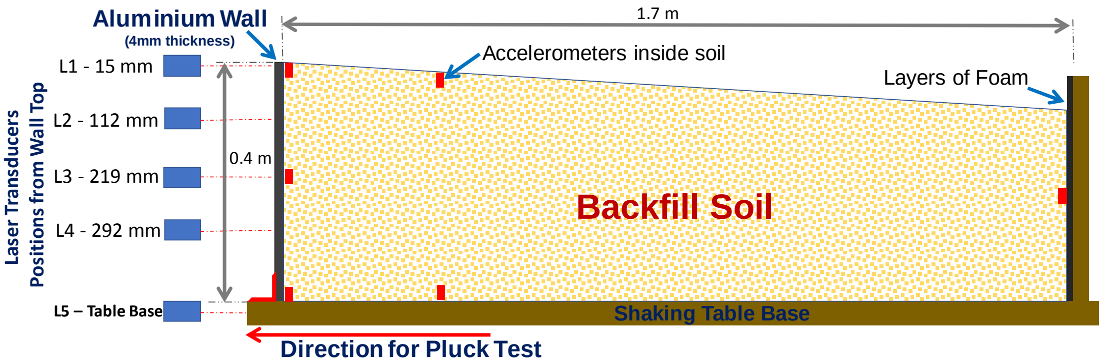


Figure 1 Details of scaled down retaining wall model.

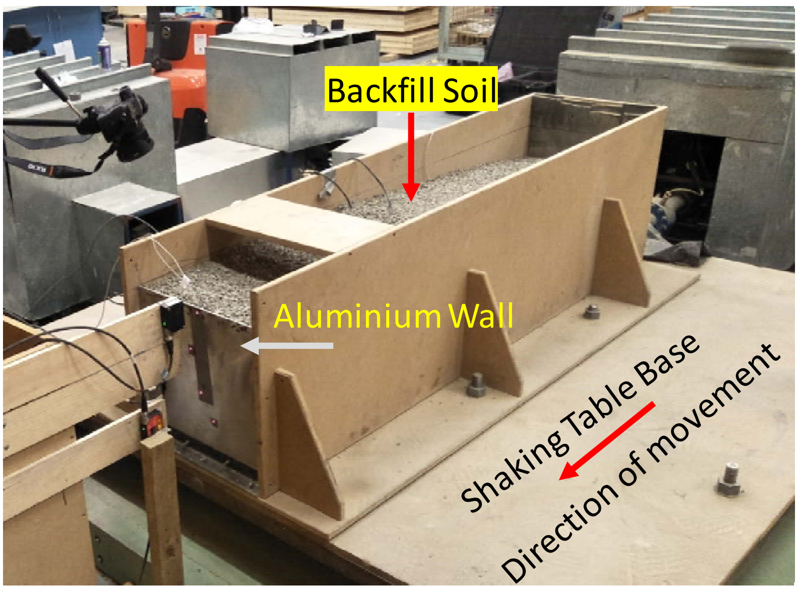


Figure 2 Experimental setup at The University of Melbourne.

Backfill construction and geotechnical testing of soil
Crushed rock with a maximum particle size of 7 mm has been chosen as backfill soil material. In order to obtain engineering properties of backfill soil, different geotechnical experiments have been carried out at geotechnical engineering laboratory, The University of Melbourne. Consolidated-Drained (CD) triaxial tests have been performed to investigate the constitutive behavior of backfill soil (D7181-11. 2011). Based on the results of CD tests, angle of internal friction of crushed rock is 44°. The target density 1700 kg/m^3 was decided for backfill soil construction and CD tests. Backfill is constructed in layers using dry pluviation method, the layer thickness is kept 100 mm; in order to control the density. Backfill soil is pluviated from a fixed height of 250 mm for equal distribution of backfill soil (Vogelsang et al. 2013). The constrained modulus of backfill soil is investigated based on its load deformation response against different confinements. One dimensional compression test has been performed for finding load deformation response of backfill soil at different confinements, based on experimental results the constrained modulus of crushed rock is 2.06 MPa for 6.6 kPa confinement. Similar values of constrained modulus has been reported by Kim and Santamarina (2008). Figure 2 shows the scaled down retaining model and backfill soil; placed on shaking table at The University of Melbourne.

Pluck test and instrumentation details
A series of pluck tests with varying amplitude has been carried out on scaled down retaining wall model. Shaking table facility has been used for generation of pluck test pulses at the base of scaled down model. Figure 3 shows the pluses used for pluck tests and movement direction of shaking table. Laser transducers and accelerometers have been used for capturing deformation and accelerations of scaled down retaining wall, figure 1 and 2 shows the positions of laser transducers and accelerometers. High speed camera has also been used for capturing the movement of retaining wall and backfill soil in slow motion.

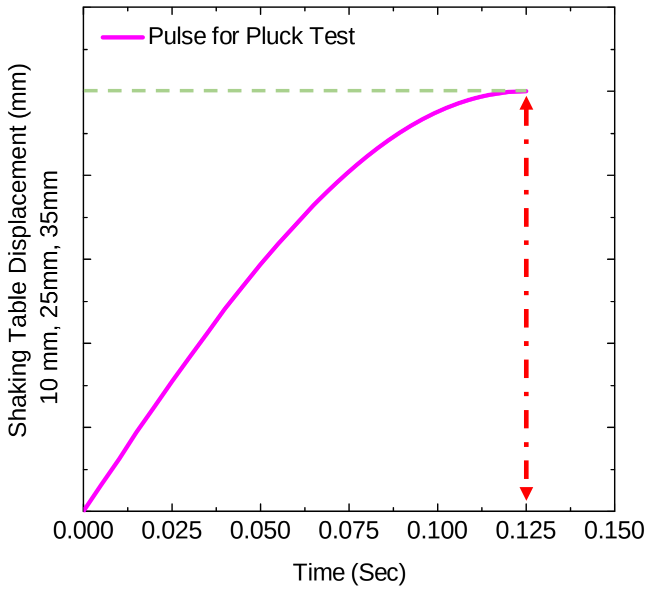


Figure 3 Pulse used for pluck test.

Free vibration response of retaining wall (frequency domain analysis)
Free vibration response of wall soil system has been studied with the help of pluck tests. Frequency domain analyses have been performed on post pulse; displacement and acceleration data obtained from laser transducers and accelerometers respectively. Based on frequency domain analyses of pluck test, the natural frequency of retaining

wall is 18 Hz (first mode). It should be noted here that analytical natural frequency of backfill soil column of 0.4 m height is 15 Hz (first mode). This gives an additional weightage to the accuracy of experimental results.

Non-linear finite element modelling of shaking table experiment

Two dimensional (2-D) non-linear plain strain FE analyses of pluck tests have been carried out in FE software Abaqus. The capability of FE software has been verified in order to achieve an accurate and reliable numerical solution. Figure (4) shows the FE mesh and cartesian co-ordinate system of FE model. Plastic properties have been assigned to aluminum wall and backfill soil using von-Mises and Drucker-Prager plasticity models respectively. The elastic modulus of aluminum wall and steel (base and angle) is considered as 70 and 200 Gpa. The interface between retaining wall & backfill soil, base & backfill soil, and foam (back side) & backfill soil has been modeled with frictional contact in tangential direction and hard contact in normal direction. The coefficient of friction has been chosen as 0.56 for wall & backfill soil, 0.2 for foam & backfill soil. The friction coefficient between the backfill soil and model base is highly depending on the amplitude and frequency of applied loading (Hashemnia and Pourandi 2018), therefore calibrations has been performed for finding the friction coefficient between the base and backfill soil. The non-linear FE analyses in Abaqus have been carried out in dynamic explicit scheme, which is highly suitable for large deformation problems (Abaqus/Explicit User's Manual, version 6.13. 2013). Fixity has been modelled between wall base & steel angle, model base & steel angle, foam & back side wall, and foam & base. The base of FE model is free to displace in horizontal ("*x*") direction and restrained in vertical ("*y*") direction. Initial equilibrium was also stabilized in soil by adding geostatic stresses in the soil domain. The FE model is meshed with 4 node bilinear two-dimensional elements with reduced integration and hourglass control technique (CPE4R).

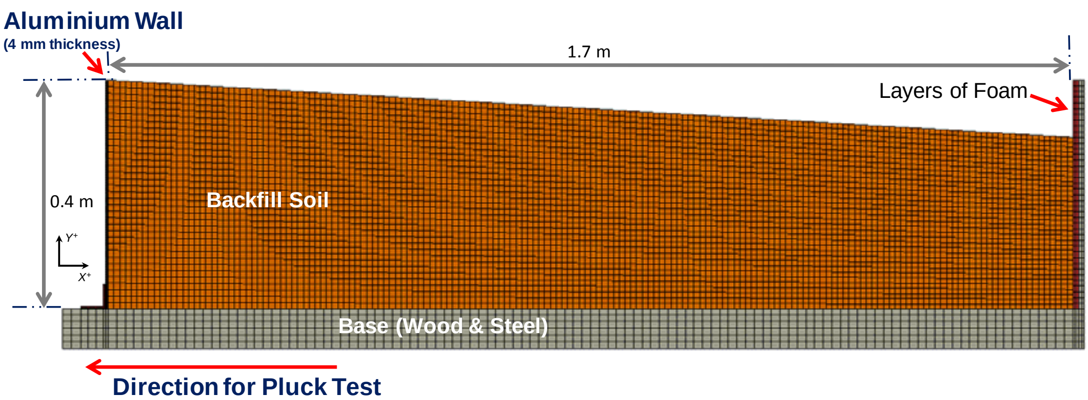
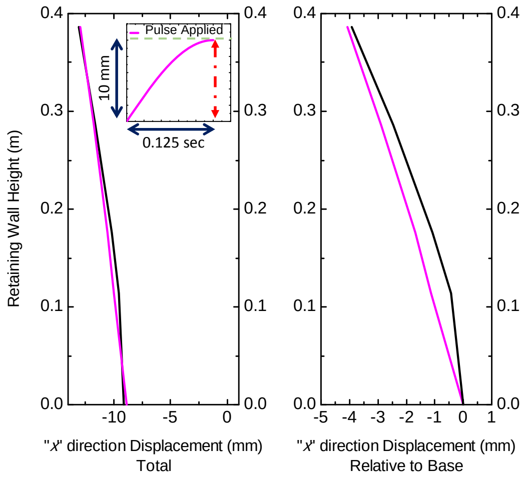


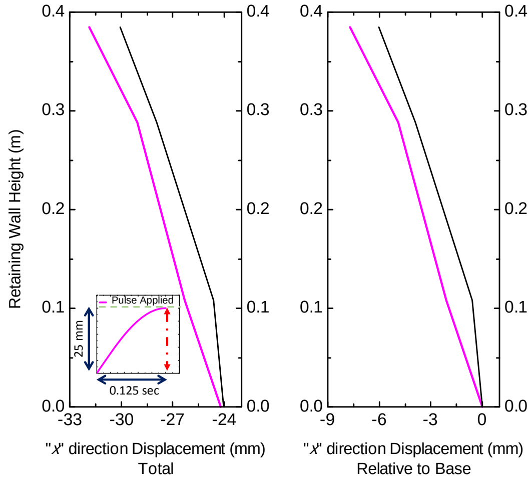
Figure 4 FE model of retaining wall in Abaqus.

Validation of FE model with shaking table experiment

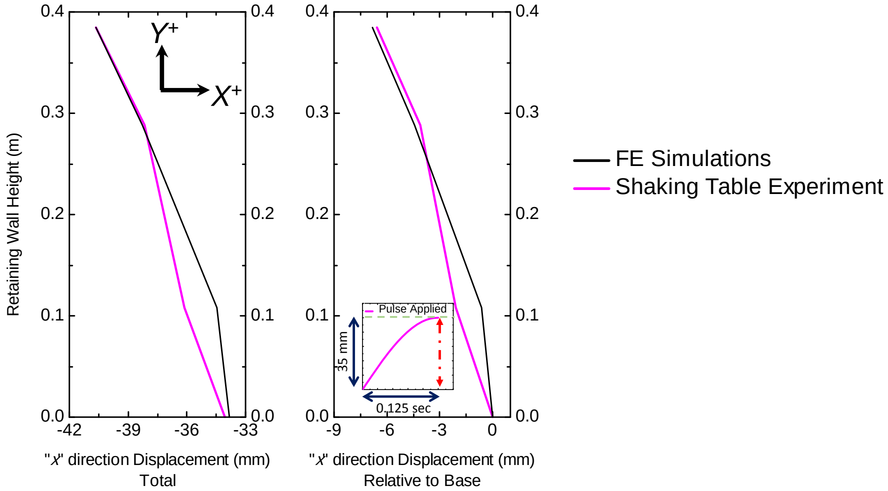
Figure 5 shows comparison of maximum displacement (along the wall height) between experiment results and Abaqus for 10mm, 25mm and 35mm amplitude pluck tests. A good agreement was observed between experiment and Abaqus results. Figure 5 also shows the comparison of relative displacement (along the wall height) between experiment results and Abaqus for 10mm, 25mm and 35mm amplitude pluck tests, a good agreement was observed between Abaqus and experimental results. It should be noted here that experiment has been performed with crushed rock type backfill soil, which has a high discrete nature. However, the present FE investigation is performed with continuum element modelling for simplicity and less computational cost. Therefore, authors recommend FE software calibration with experimental data for every soil structure interaction problem. Natural period of retaining wall observed from shaking table experiment is also matched with FE investigations. Therefore, it can be concluded that Abaqus is able to replicate the realistic nonlinear seismic response of shaking table experiment.



(a) "*x*" direction displacement along the wall height (bottom to top) for 10 mm amplitude pluck test.



(b) "*x*" direction displacement along the wall height (bottom to top) for 25 mm amplitude pluck test.



(c) "*x*" direction displacement along the wall height (bottom to top) for different pluck tests.

Figure 5 Comparison of absolute and relative displacements, captured during shaking table experiment and computed using FE simulations.

Discussions on displacement behavior of retaining wall

Displacement of retaining wall and wall soil separation

Figure 5 shows the peak retaining wall displacements along the wall height for three different pluck tests (10, 25 and 35mm amplitude). The higher displacement at wall top has been observed in all cases. During the experiments and FE simulations separation of wall from backfill soil has been observed in all cases, it was observed that backfill soil is subjected to higher inertial forces due to which it is not moving immediately with retaining wall which creates a separation between retaining wall and backfill soil due to this the dynamic pressure reduced during the initial phase of loading (wall backfill separation phase). It should be noted here that current practices do not includes the wall backfill separation phase, in seismic design of retaining wall, which leads to an uneconomical design of retaining wall as higher dynamic earth pressure is considered into the design.

Figure 6 shows horizontal acceleration response spectrum (5% damping considered) for free vibration period (post pulse duration), observed during shaking table experiment. Increment in horizontal acceleration has been observed with increasing wall height, which is responsible for higher displacement at retaining wall top. The horizontal acceleration also raised with increasing pluck test amplitude.

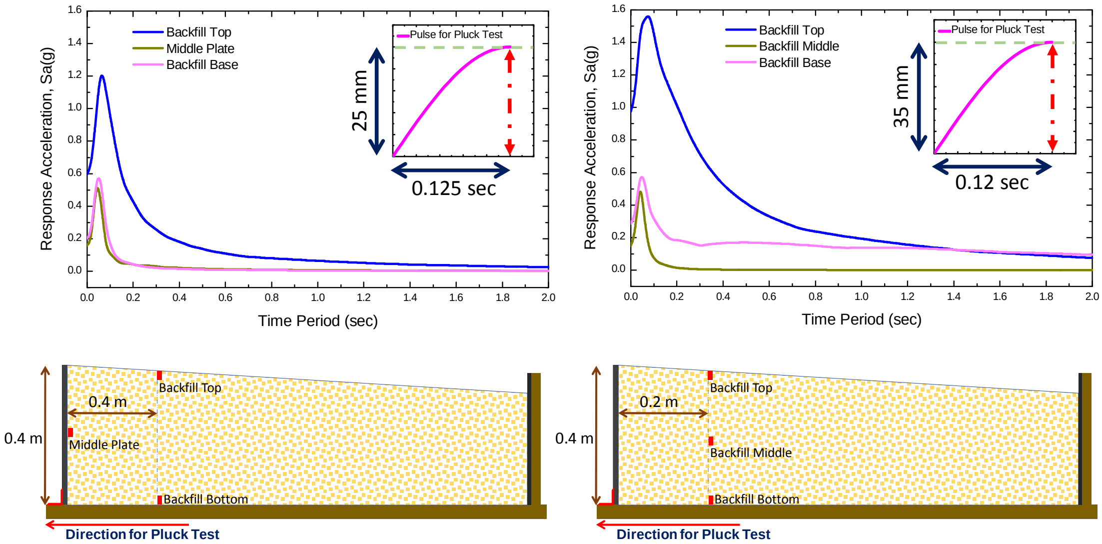


Figure 6 Horizontal spectral acceleration for 25mm and 35 mm amplitude pluck test.

Discussion on dynamic pressure

Figure 7 shows dynamic pressure distribution along the wall height based on FE simulations of pluck tests for 10 mm and 35 mm amplitude. Non-linear dynamic pressure distribution has been observed along the wall height. Amplitude of dynamic pressure raised with increasing pluck test amplitude. Dynamic pressure behind the retaining wall is also calculated using MO equation with a reduced peak acceleration coefficient (50% and 65%) as suggested by AASTHO guide specifications for LFRD seismic bridge design (2011). It is clear from figure 7 that dynamic pressure based on non-linear FE simulations is high compared to dynamic pressure calculated using MO equation. Moreover, MO equation gives a linear pressure distribution along the wall height. It should be notated here that similar nonlinear distribution of dynamic earth pressure has been observed by Sherif and Fang (1984). Therefore, the validity of MO equation is doubtful for predicting the seismic pressure demand of retaining walls. Moreover, the duration of peak pressure is very small, therefore using the same seismic pressure distribution into the design calculations leads to an uneconomical seismic design of earth retaining structures.

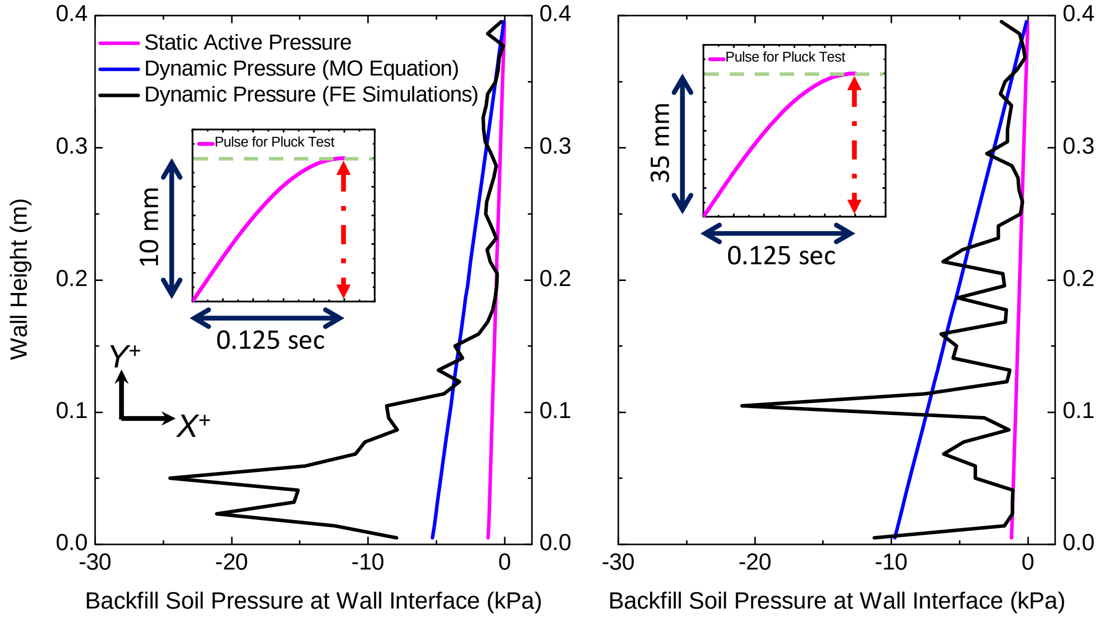


Figure 7 Backfill soil pressure behind the retaining wall.

Conclusions

Experimental and FE investigations have been performed in order to understand the seismic behavior of earth retaining structures. Shaking table experiments has been performed on scaled down fixed end cantilever retaining wall model. Free vibration response of retaining wall-backfill soil system has been studied based on experimental results. FE simulations have also been performed for ensuring the capability of FE software for replication of experimental results. Following conclusions have been made based on present study:

- Wall soil separation has been observed during all pluck tests. The wall soil separation should be considered into the seismic design of retaining wall.
- Displacement demand of retaining wall depends on the amount of ground shaking and inertia of backfill soil.
- The horizontal thrust raised toward the top of backfill soil, which is responsible for higher displacement of retaining wall at top and settlement of backfill soil. Non-linear dynamic pressure distribution along the retaining wall height has been observed.
- The FE software can simulate the seismic behavior of earth retaining structures. However, calibration of FE software should be performed against experimental data.

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