Displacement Based Estimate of Seismic Actions on Earth Retaining Structures

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Abstract

Present work deals with estimation of seismic actions on retaining walls. Shaking table experiments have been performed on scaled down retaining wall models to understand the effects of seismic actions on earth retaining structures. Detailed numerical investigations have also been performed on scaled down, prototype retaining wall models. Capability of finite element (FE) modelling approach is verified for replication of shaking table experiment results. Separation of retaining wall from the backfill has been observed during shaking table experiment and FE simulations. Earthquake induced displacement demand of retaining walls is mainly dependent on time dependent nature of backfill soil pressure and severity of earthquake ground shaking.

Keywords: Retaining wall, seismic design, displacement based design, shaking table test, scaled down model.

Introduction

Accurate assessment of seismic actions on earth retaining structures is prime concern of modern performance-based design. Present study deals with assessment of earthquake induced displacement of retaining walls. Shaking table experiments on scaled down retaining wall models have been carried out at The University of Melbourne, results of shaking table experiment were used to calibrate finite element (FE) model, detailed parametric investigations have been performed in order to understand displacement demand of retaining walls, role of backfill soil on seismic performance of retaining walls, time dependent nature of dynamic backfill soil pressure and amplification of horizontal acceleration. It was observed that FE software can accurately replicate seismic behaviour of earth retaining structures, earthquake induced displacement of retaining walls highly depends on severity of ground shaking, amplification of horizontal acceleration in backfill soil and time dependent nature of backfill soil pressure.

Literature review

Performance of earth retaining structures during past earthquakes have been examined by several researchers. ICSSC TR18 (1996), Koseki et al. (1995), Koseki (2002), Tatsuoka (1996) and Tatsuoka et al. (1997) studied performance of earth retaining structures during Kobe (1995) earthquake (PGA around 0.8g), damage of gravity type retaining walls was observed during Kobe earthquake, mainly due to overturning and excessive outward movement. However, reinforced concrete walls supported with pile foundation shown limited damage. In Chi-Chi earthquake of Taiwan (1999) collapse and major damage has been observed in unreinforced retaining walls, in case of conventional gravity type retaining walls excessive outward displacement (active displacement) and overturning has been observed by Shayo et al. (2009), Yazdani et al. (2013). Damage of several quay walls was reported by Matsuo and Ohara (1960) during Japanese earthquakes. Bridge abutments shown excessive rotation and sliding during 2008 Wenchuan earthquake, noticeable settlement of approach slab has also been observed (Qiang et al. 2009).

Present design guidelines recommend Mononobe-okabe (MO) equation for finding dynamic soil pressure on earth retaining structures (AASTHO guide specifications for LFRD seismic bridge design 2011, Eurocode 8. 2008, AS 5100.2. 2017). However, time dependent nature of dynamic soil pressure is not given by Mononobe-okabe equation. Displacement of free standing retaining wall can be predicted using Newmark sliding block method (Elms, 2000). However, estimation of earthquake induced displacement and rotation of earth retaining structures with constrained base and pile foundation supported is not presented in design standards. Bolton and Steedman (1982) performed experiments on scaled down model of fixed base cantilever retaining wall using centrifuge and reported nonlinear relative displacement of retaining wall. Mikola and Sitar (2013) studied seismic behavior of fixed end and basement walls with centrifuge experiments, and found that MO method gives conservative values of dynamic backfill pressure for non-displacing retaining walls, however, effects of different backfill soil type and displacement behaviour of fixed base earth retaining structures is not presented by them. Veletsos et al. (1997) and Psarropoulos et al. (2005) studied dynamic backfill pressure behind retaining wall by considering different wall flexibilities, they assumed perfect bonding between retaining wall and backfill soil. Alampalli (1990) developed a numerical program for finding earthquake induced displacement and rotation of retaining walls. Mikola and Sitar (2013) performed FE simulations for finding dynamics soil pressure and moment of retaining wall and basement wall models. Cakir (2013) studied earthquake response of retaining wall using finite element (FE) model and calibrated a two degree of freedom retaining wall model. Based on extensive literature review it was observed that seismic response of restrained earth retaining structures is highly influenced by backfill soil pressure, displacement and rotation of retaining wall, however, all these key issues are not addressed well in literature. Moreover, role of different backfill soil type and accurate validation of FE models with experiment data is not presented in literature. Therefore, a systematic experimental and numerical investigation is required in order to understand the role of (i) time dependent dynamic backfill soil pressure, (ii) amplification of horizontal acceleration, and (iii) earthquake induced displacement, on seismic behaviour of earth retaining structures.

Shaking table experiment at The University of Melbourne

In order to understand effects of earthquake actions on earth retaining structures; shaking table experiment on scaled down retaining wall model has been carried out. Scaled down retaining wall is fabricated with Aluminium sheet of 4 mm thickness, Aluminium has been chosen as retaining wall material so that deformation pattern of retaining wall can be observed. Crushed rock has been chosen as backfill soil material for easiness in backfill construction and characterization of backfill soil. Wooden container with smooth sides has been fabricated for retention of backfill soil. Sand paper has been applied at the base of wooden container to initiate friction between backfill soil (base side) and wooden container base. Several layers of high-density foam have been applied at backside of wooden container for minimizing boundary effects. Figure (1) shows photograph of scaled down retaining wall model placed on shaking table platform at The University of Melbourne.

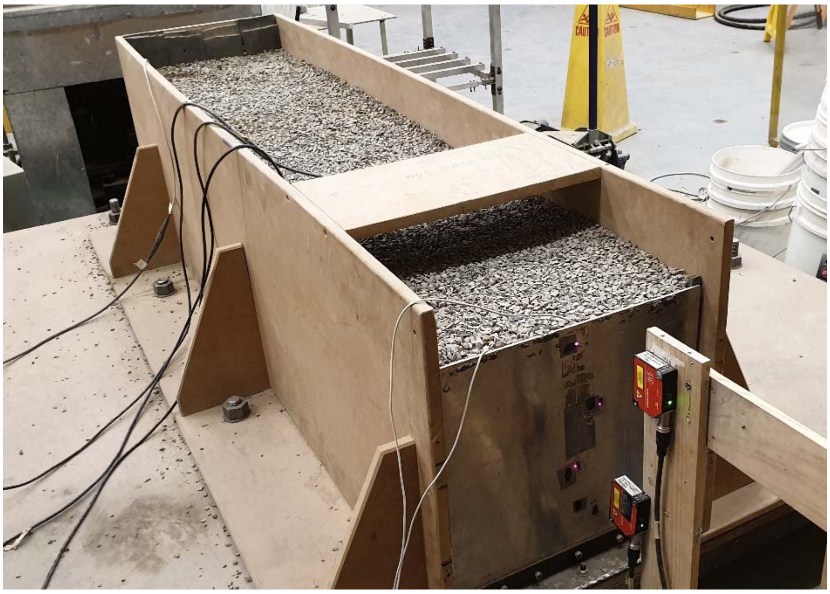

Figure (1) Shaking table experiment on scaled down retaining wall model at The University of Melbourne.

Instrument setup for shaking table experiment

Displacement of scaled down retaining wall model has been captured using laser transducers, three to four laser transducers were placed along retaining wall height for capturing retaining wall displacement. Uni-directional, bi-axial and tri-axial accelerometers were used for capturing acceleration. Accelerometers were placed inside backfill soil, and along retaining wall height. Figure (2) shows locations of laser transducers and accelerometers. High sampling frequency has been used for capturing displacement and acceleration to ensure accuracy of output data.

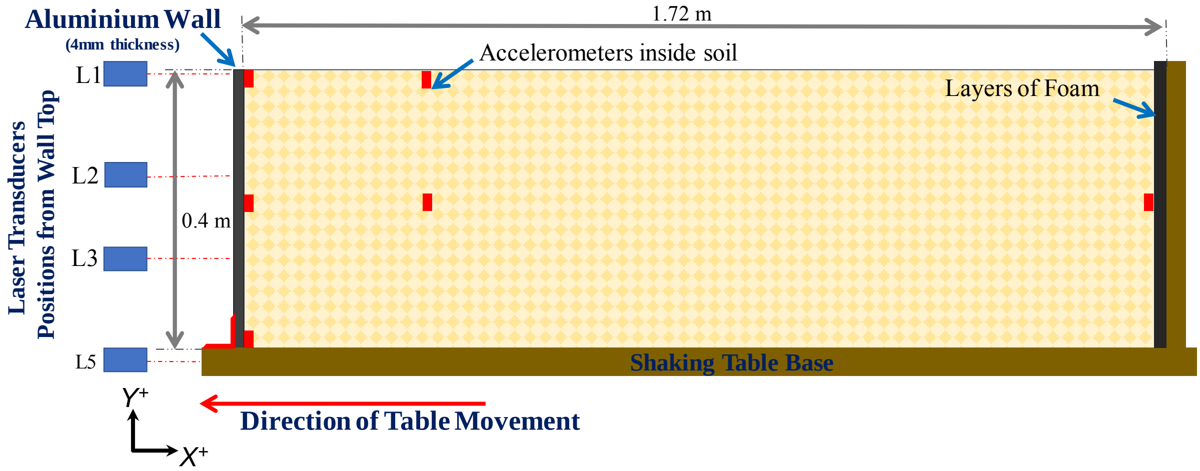

Figure (2) Details of instrumentation set up for shaking table experiment.

Pluck test on scaled down retaining wall model

Pluck tests have been performed on scaled down retaining wall model for understanding free vibration response of retaining wall and backfill soil. Frequency domain analyses have been performed on free vibration phase data for finding natural frequencies of scaled down retaining wall model. Based on free vibration analysis 1st natural frequency was observed as (19-20) Hz and second natural frequency was observed as (39-40) Hz, as shown in figure (3).

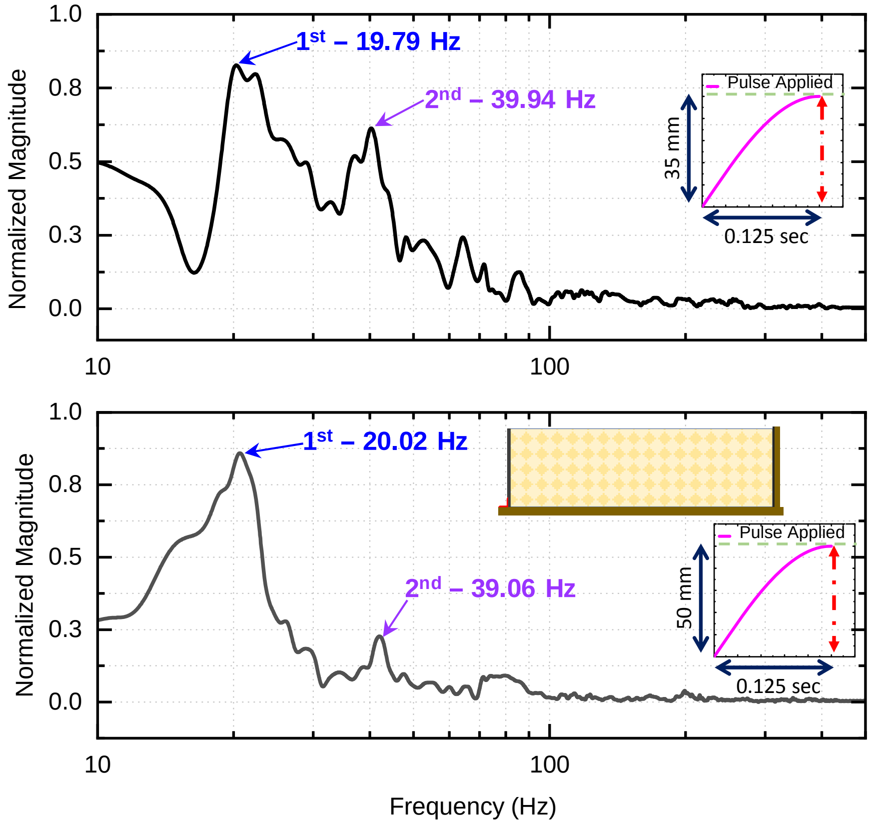

Figure (3) Natural frequencies of scaled down retaining wall model obtained for different pluck tests.

Shaking table experiment on scaled down retaining wall model using multiple pulse

Dynamic response of scaled down retaining wall model has been analysed using shaking table experiment. Choice of input motion is highly important for 1g shake table experiments in order to achieve accurate and realistic response of scaled down model (Yazdandoust, 2017). Therefore, different pulses have been selected as input base excitation for shaking table experiment. Figure (4) shows applied pulses on scaled down retaining wall model.

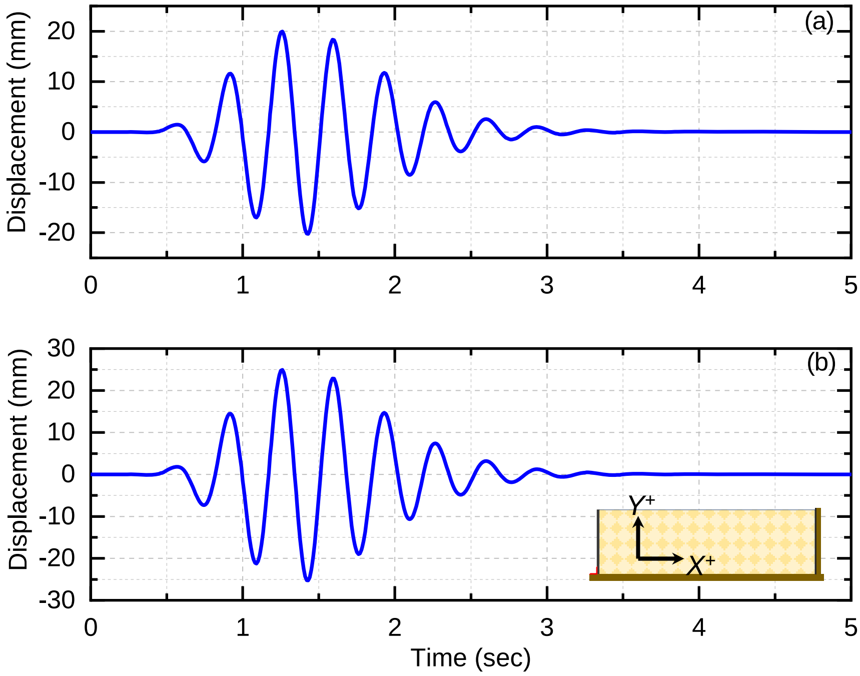

Figure (4) Pulses used for shaking table experiment.

Displacement response of scaled down retaining wall model

Figure (5) shows relative displacement at retaining wall top (relative to base) when subjected to multiple pulses base excitation. Residual displacement of retaining wall was observed for both pulses. Higher residual displacement was observed along increasing retaining wall height. It should be noted here that for both pulses, during active movement of shaking table (when wall move away from soil), active state relative displacement of retaining wall was observed. However, during passive movement of shaking table base, due to inertia of backfill soil; retaining wall maintains its active state residual displacement.

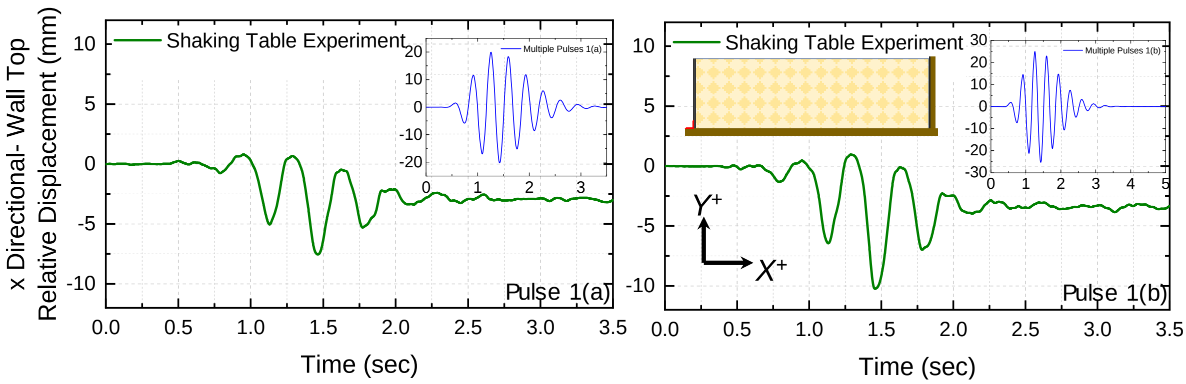

Figure (5) Displacement (Relative to base) at retaining wall top subjected to multiple pulses.

Acceleration response of scaled down retaining wall model

Figure (6) shows response spectral acceleration (RSA) at backfill soil base, middle and top. Amplification of horizontal acceleration was observed at backfill soil top, pulse with 20 mm maximum displacement shows 19 % amplification than base and pulse with 25 mm maximum displacement shows 23 % amplification than base. This observation emphasis bases for higher residual displacement towards retaining wall top and importance of understanding time dependent nature of dynamic backfill soil pressure.

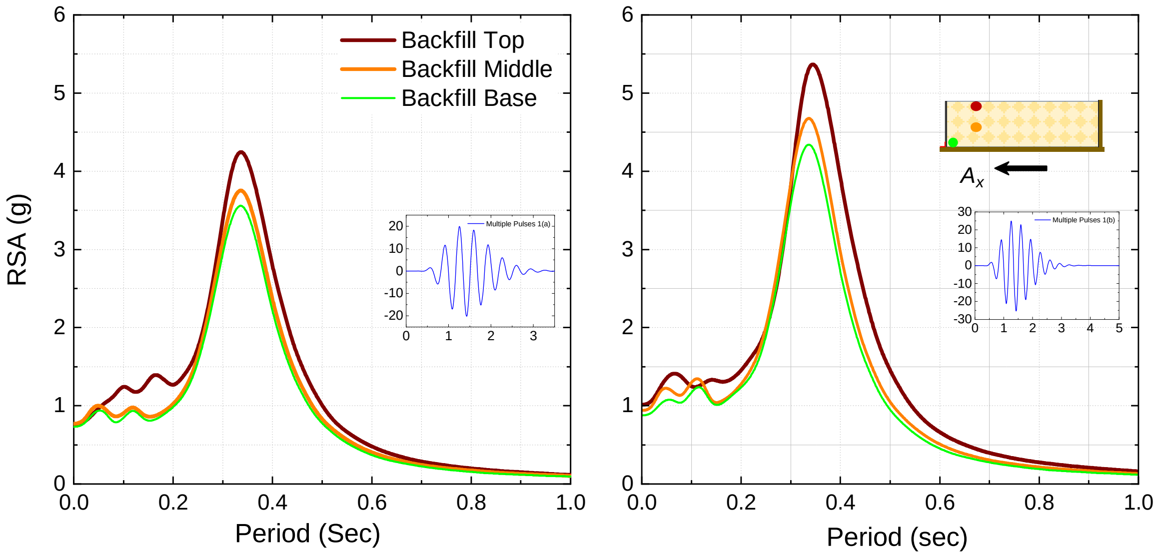

Figure (6) Response spectral acceleration (RSA) at backfill soil base, middle and top for different pulses.

Important observations from shaking table experiment

Shaking table experiments on scaled down retaining wall model were performed for understanding free vibration response of retaining wall soil system and seismic response of scaled down retaining wall model. Nonlinear displacement behaviour of flexible retaining wall was observed, amplification of horizontal acceleration towards backfill soil surface was also observed along with detachment of retaining wall from backfill soil. Shear wave velocity of backfill soil (crushed rock) was also obtained from acceleration captured at backfill soil base and surface.

Characterization of backfill soil

Sieve size analysis, one dimensional compression and consolidated drained (CD) triaxial tests have been performed on crushed rock (backfill soil type). Maximum density of crushed rock was estimated as 1790 kg/m^3. Sieve size analysis shows 6.5 mm particle size of crushed rock for 60% finer (D_{60}). Based on one dimensional compression test, constrained modulus of crushed rock was estimated as 15.52 MPa (for 68 kPa confinement) (Kim and Santamarina, 2008). Constitutive behaviour of crushed rock was studied with the help of consolidated drained triaxial tests; performed at 34, 68 and 136 kPa confinement, based on which angle of internal friction of crushed rock was estimated as 44^{o}.

Numerical simulations of seismic actions on earth retaining structures

Validation of finite element modelling approach

Capability of finite element (FE) modelling approach has been verified for replication of shaking table experiment results. Shaking table experiments were performed by applying multiple pulses (20 and 25 mm maximum amplitude) at the base of scaled down retaining wall. Figure (7) shows FE model of scaled down retaining wall and shaking table base. FE analysis were performed using FE simulation software Abaqus. Two dimensional (2D) plain strain analyses were performed using explicit solution scheme of Abaqus, which is suitable for nonlinear & large deformation analysis (Abaqus/Explicit User's Manual, 2013). Aluminium retaining wall is modelled as elastic material with young's modulus and density equal to 69 GPa and 2700 kg/m^3 respectively. Backfill soil (crushed rock) is modelled using mohr-coulomb plasticity model, hardening and softening of backfill soil is simulated based on approach suggested by Potts and Zdravkovic (1999). Damping in backfill soil has been modelling using Rayleigh damping model, shear wave velocity obtained during shaking table experiment was used for finding Rayleigh damping parameters. Frictional contact in tangential direction and hard contact in normal direction has been used for all interactions. Interaction between retaining wall and backfill soil, model back face and backfill soil has been modelled using a friction coefficient of 0.64. Calibration has been performed for modelling interaction between backfill soil base and model base, it was observed that friction coefficient has high dependence on amplitude and frequency of applied loading (Hashemnia and Pourandi 2018). Base of FE model is restrained in vertical direction but free to displacement in horizontal direction, displacement of shaking table base captured during shaking table experiment was applied at the base of FE model as input base displacement. Geostatic stresses were also defined in backfill soil, along with gravity loading to ensure equilibrium before starting of explicit step. Four node plain strain continuum elements were used to mesh FE model.

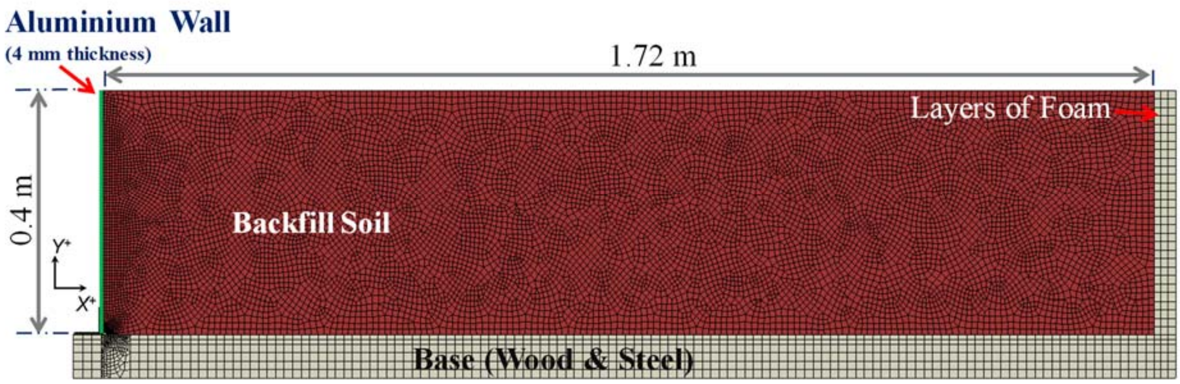

Figure (7) FE model of scaled down retaining wall (shaking table experiment).

Figure (8) shows comparison of relative displacement at retaining wall top obtained from shaking table experiment and FE simulations for 20 mm and 25 mm maximum amplitude pulses (left 20 mm and right 25 mm), a good agreement has been observed between shaking table experiment and FE simulation results, this validated capability of FE modelling approach for simulation of earthquake actions on earth retaining structures.

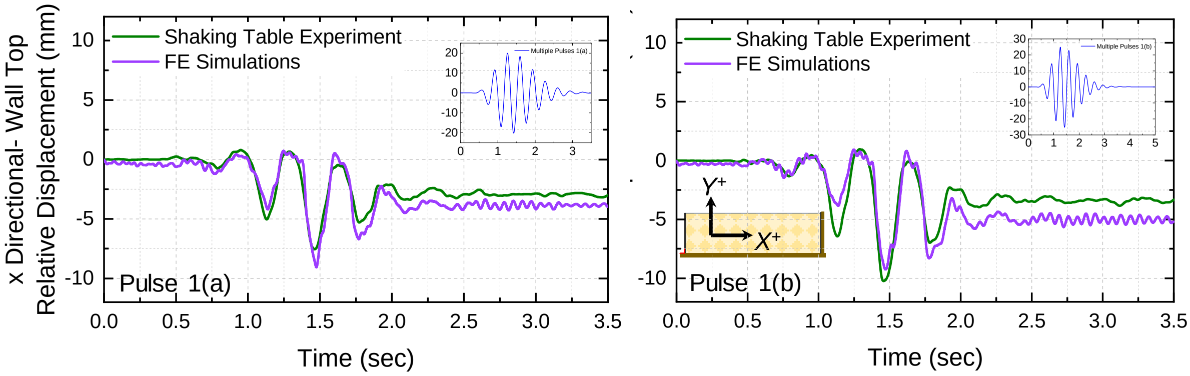

Figure (8) Comparison of displacements at retaining wall top (relative to base) obtained from shaking table experiment and FE simulations.

Finite Element (FE) modelling of prototype retaining wall

To study effects of seismic actions on earth retaining structures, a detailed and rigorous FE investigation is performed. Figure (9) shows FE model of prototype retaining wall considered in present study. Base below retaining wall and backfill soil is modelled as solid rock, retaining wall base is considered fully constrained with rock, this condition corresponds to earth retaining structures with fixity at their base, e.g., quay walls, basement walls, sheet pile walls, rock socketed walls. Structural design of reinforced concrete (RC) retaining wall was performed for overturning moment and factor of safety against overturning was obtained as 3.8. Designed reinforcement for retaining wall has a yield strength of 415 MPa, 25 mm diameter steel bar is used for main reinforcement bar and 16 mm diameter bar is used for secondary reinforcement bar, reinforcement and dimension details of prototype retaining wall is shown in figure (10b). Concrete of RC retaining wall (characteristic strength 40 MPa) is modelled using concrete damaged plasticity model and backfill soil is modelled using mohr-coulomb plasticity model respectively.

springs and dashpots were modelled at vertical boundaries to minimize boundary effects. Domain size study (without springs and dashpots) has also been performed by increasing backfill soil lengths until retaining wall displacement became constant, under highest considered earthquake (0.8g PGA). Similar analyses (with 0.8g PGA and 30 m long soil domain) were performed for retaining wall with springs and dashpots installed at vertical boundaries, which shown displacements like long soil domains. Figure (9) shows FE model of prototype retaining wall. Mesh convergence study has also been performed, fine mesh size was used at interface of backfill soil and retaining wall stem, retaining wall heel and backfill soil interface. Figure (10a) shows mesh near retaining wall stem and heel. Dimension details of retaining wall is shown in figure (10b).

Nonlinear time history analyses have been performed using Abaqus/Explicit solution scheme, friction between retaining wall and backfill soil, backfill soil base and rock has been modelled using frictional contact in tangential direction and hard contact in normal direction. Geostatic stresses and gravity have been applied in soil and rock to ensure equilibrium at starting of time history analysis. Bottom boundary of rock domain is restrained in vertical direction and free to displace in horizontal direction, boundaries of extreme left and right domains (separated by springs and dashpots) are restrained for horizontal and vertical movement. Earthquake time history has been applied at base of rock domain.

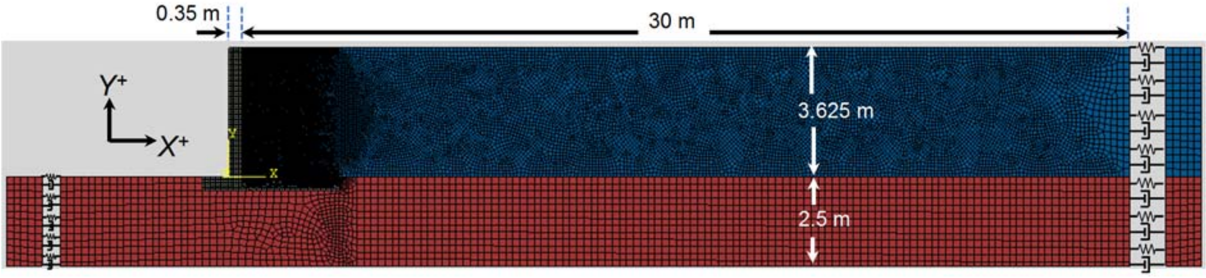

Figure (9) Finite element (FE) model of fixed base retaining wall model.

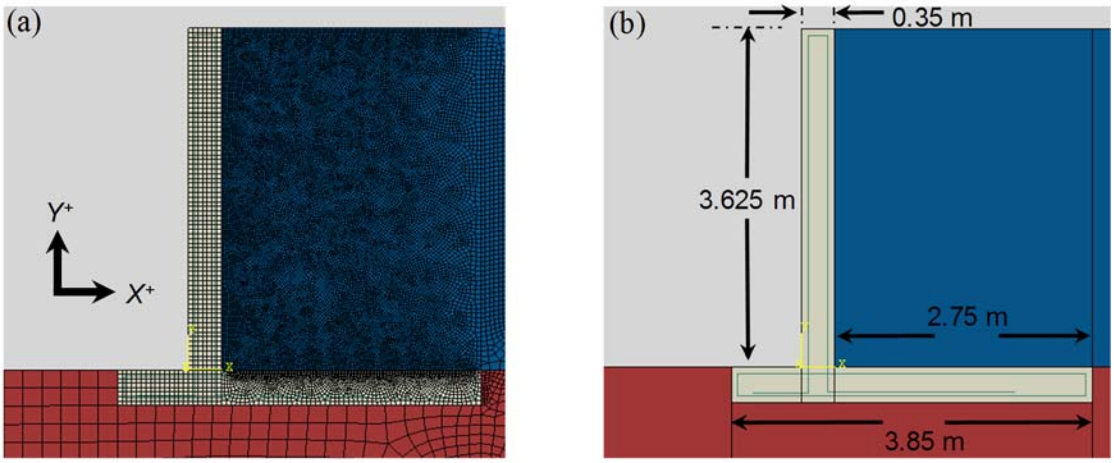

Figure (10) FE mesh of concrete retaining wall and backfill soil (left side), dimension details of retainining wall (right side).

Ground motion selection for nonlinear time history analysis

Selection of ground motion is an important task for nonlinear time history analyses, artificial accelerograms were obtained on rock outcrop; using program GENQKE (Lam, 1999). GENQKE program can generate artificial accelerograms assuming a seismic source model for different magnitude (M) and distance (R) combinations of interplate region, this kind of artificial accelerograms are proven very useful to study effects of earthquake actions on structures under low to moderate seismicity regions like Australia (Lumantarna et al. 2010, Shahi et al. 2017).

PEER ground motions data base was used for finding historical earthquake records for reverse fault type, on rock outcrop. PGA for all records is shown right side of figure (11).

Displacement response of retaining wall

Parametric FE investigations have been performed on prototype retaining wall model for different ground excitations. Figure (11a) shows displacement at retaining wall top (relative to base) for different artificial accelerograms. Higher relative displacement was observed at retaining wall top with increasing PGA. Permeant retaining wall displacement was observed in all cases. For artificial accelerograms (PGA from 0.66g, 0.72g and 0.74g) similar displacement of retaining wall was observed until 4 seconds, after which higher displacement for higher PGA was observed.

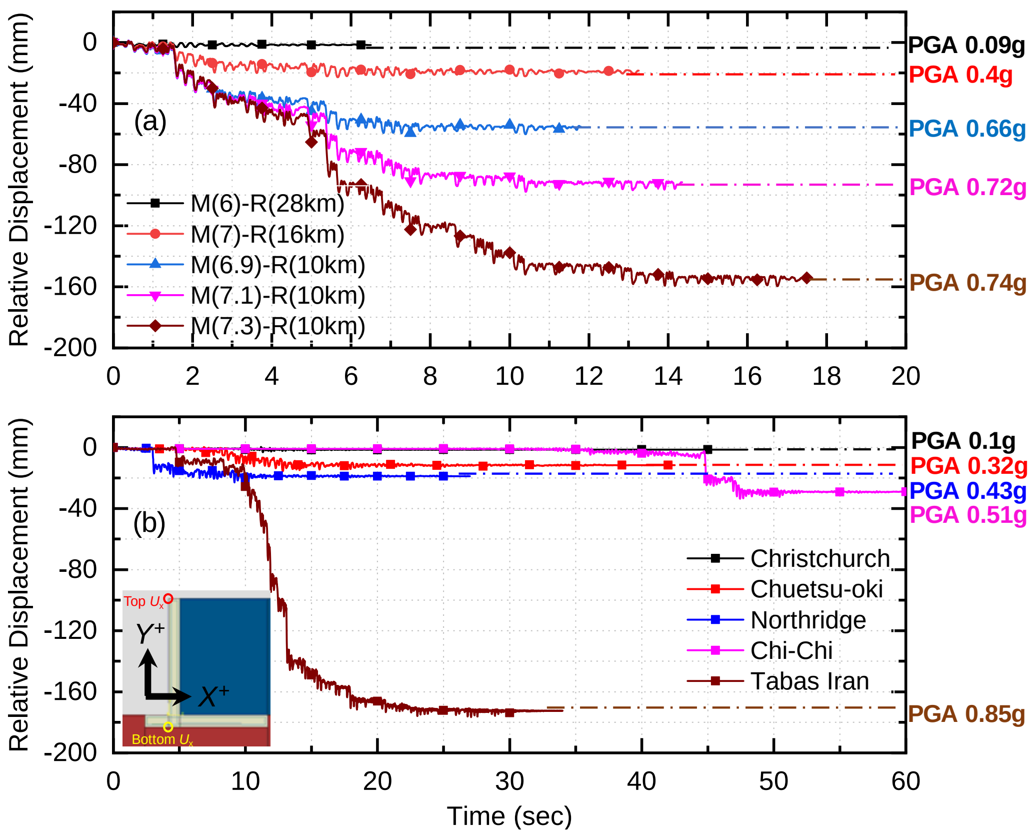

Figure (11) Displacement (relative to base) at retaining wall top, subjected to different ground accelerations.

Figure (11b) shows relative displacement at retaining wall top (relative to base) for different historical accelerograms. Permeant retaining wall displacement was observed for all cases (retaining wall subjected to historical accelerograms). It was observed that artificial and historical accelerograms of similar PGA generates similar permeant displacement at retaining wall top. It was also observed that for base restrained retaining wall backfill soil inertia plays an important role in active state displacement behaviour of retaining wall, similar behaviour was observed during shaking table experiment of scaled down retaining wall model, where active state displacement was permanent irrespective to base movement.

Amplification of horizontal acceleration

Amplification of horizontal acceleration was observed in all cases. Figure (12) shows RSA for horizontal acceleration at backfill soil base, middle and top (1.375 m from retaining wall stem). Higher amplification towards backfill soil top was observed for higher PGA. Amplification of horizontal acceleration at backfill soil top was observed up to 170 % and 220 % (of base acceleration) for PGA range between 0.08g -0.01g and 0.4-0.8 g, respectively. Immediate drop of horizontal acceleration/ amplification (after natural period) was observed for all cases. This observation supports importance of time dependent nature of backfill soil pressure into seismic design of earth retaining structures.

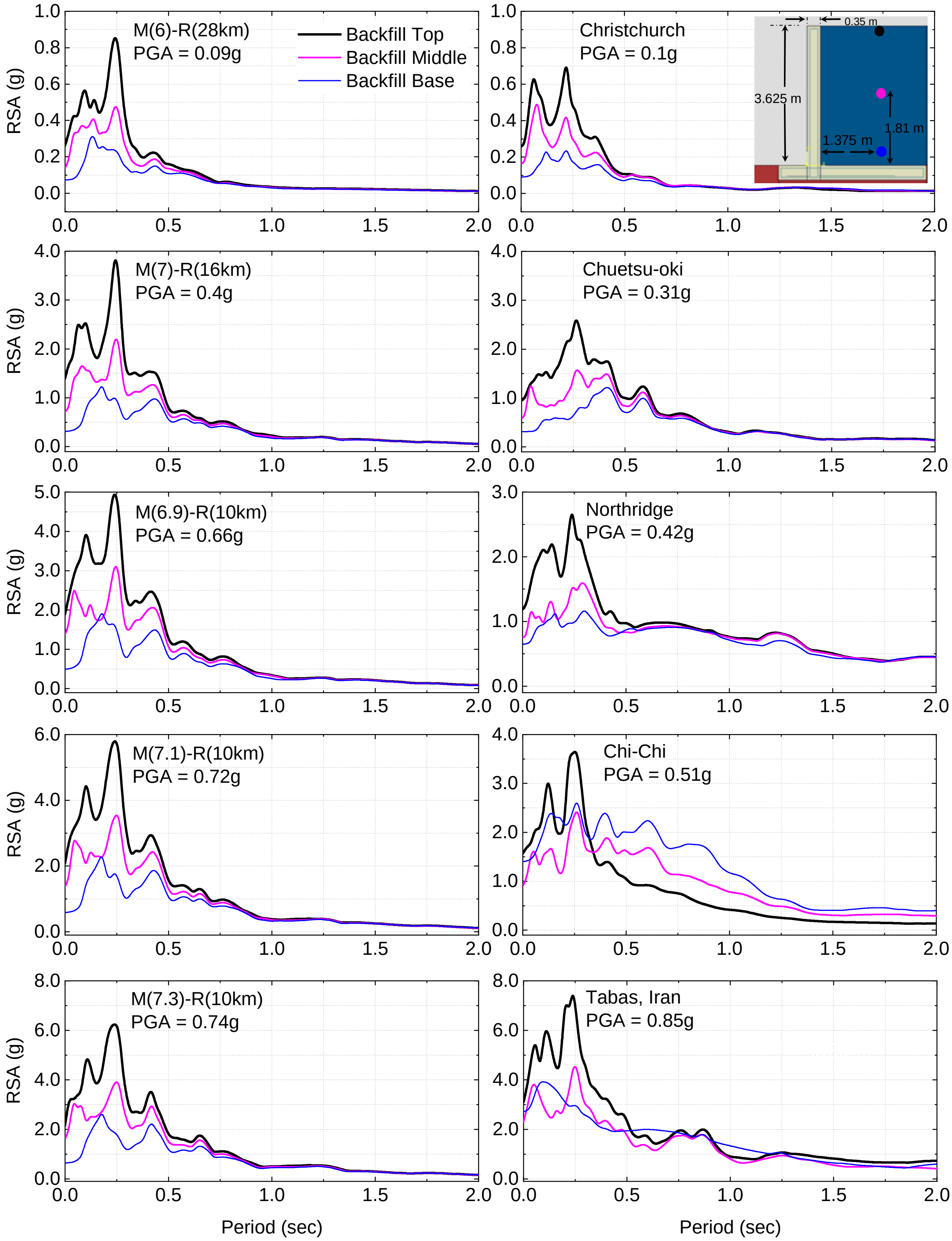

Figure (12) Response spectral acceleration at various backfill heights (1.375 m from retaining wall stem) for different ground accelerations.

Conclusions

Present study deals with assessment of earthquake induced displacement on earth retaining structures. Shaking table experiments have been performed on scaled down fixed base retaining wall model, amplification of horizontal accelerations and separation of retaining wall from backfill soil was observed during shaking table experiment. Pluck tests have also been carried out for understanding free vibration response of earth retaining structures. Learning and observations from shaking table experiments have been used for finite element modelling of prototype retaining wall model. FE model of prototype retaining wall was analysed against different ground accelerations. Permeant active state displacement of fixed base prototype retaining wall was observed for all cases. Higher active state displacement was observed at retaining wall top due to high inertia of backfill soil. High amplification of time dependent horizontal acceleration was observed along increasing backfill soil height (bottom to top).

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