Seismic Analysis of Reinforced Soil Retaining Walls

A. Murali Krishna and A. Bhattacharjee

1 Introduction

The reinforced soil walls offer a good solution to conventional earth retaining structures in terms of better utilisation of space, speed of construction and loading capacity. Reinforced soil walls are constructed using different reinforcing elements and wall facing systems. Satisfactory performances and failures of reinforced soil walls during earthquakes are reported by several researchers (Koseki et al. 2006; Koerner and Koerner 2013 etc.). Analysing the performance of retaining structures under static and seismic ground shaking conditions helps to understand better about their behaviour during earthquakes and to design these structures more seismic efficient. Thus, dynamic behaviour of reinforced soil retaining walls is of research interest to several researchers through different modes of studies like, physical model studies, analytical studies and numerical model studies (Cai and Bathurst 1995; Hatami and Bathurst 2000; Ling et al. 2004; Lee et al. 2010; Liu et al. 2011; Krishna and Latha 2012; Bhattacharjee and Krishna 2012, 2015a). This paper highlights the observations obtained from physical land numerical studies on reinforced soil walls subjected to dynamic excitations.

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2 Physical Model Studies

Physical model tests are very much essential when the prototype behaviour is very complicated to understand. The use of scaled models in geotechnical engineering offers the advantage of simulating complex systems under controlled conditions, and the opportunity to gain insight into the fundamental mechanisms operating in these systems.

Krishna and Latha (2007, 2009) conducted shaking table tests on wrap-faced- and rigid-faced reinforced soil walls to observe the seismic response. The wall models, tested on the shaking table, were of size 750 mm × 500 mm in plan area and 600 mm (H) deep. The models were constructed in flexible laminar container using four layers of geotextile reinforcement of length (L_{rein}) 420 mm (i.e. $0.7H$) wrapped around to form the facing. The models were constructed in equal lifts of sand filling by pulviation method. For rigid-faced walls, the facing was built from 12 hollow steel box sections and were bolted together with a vertical steel rod. The reinforcements at different vertical spacing were run through the bolts of the facing system to obtain a rigid connection between wall and reinforcements. The model walls were instrumented with displacement transducers, accelerometers and pressures cells. The details of the test configuration and location of various instrumentations (Krishna and Latha 2007) are shown in Figs. 1 and 2.

The models were subjected to sinusoidal motions at different base excitations. Typical response of model, tested for 20 cycles of 0.1 g acceleration (a) at 1 Hz frequency (f), in terms of horizontal displacements and accelerations at different elevations are shown in Figs. 3 and 4, respectively. The variation displacements of wall facing with frequency, no. of reinforcement layers, surcharge and base acceleration observed by Krishna and Latha (2007) and are shown in Fig. 5. From the figure it is observed that the wall face deformations are higher at low frequency shaking, low surcharge pressure, lesser reinforcing layers and high base acceleration. The model studies were also conducted by varying the relative density of backfill soil. Figure 6 shows the variation of displacements, acceleration amplification and horizontal pressure at different elevations for model with different relative density of backfill soil. The lateral deformation of facing decreases and

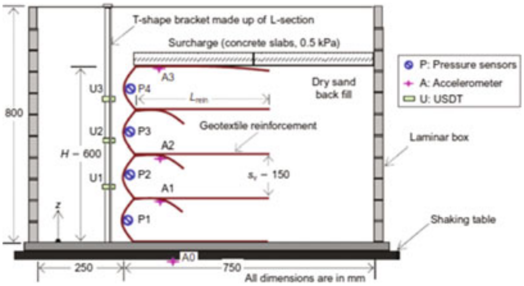
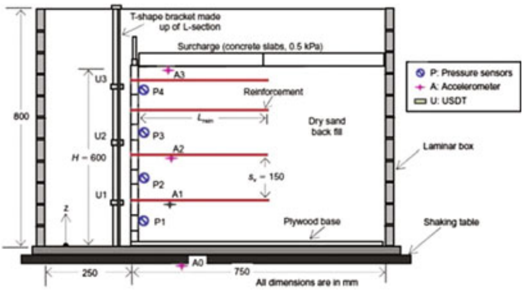


Fig. 1 Schematic diagram of wrap-faced wall configuration (after Krishna and Latha 2007)

Fig. 2 Schematic diagram of rigid-faced wall configuration (after Krishna and Latha 2009)



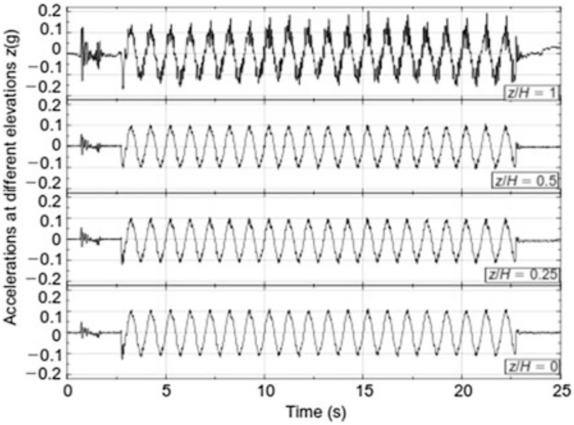
acceleration amplifications slightly increases with increase in relative density of backfill soil subjected to higher base excitation.

Krishna and Latha (2009) presented the seismic responses of rigid-faced reinforced soil walls with different reinforcement materials (Fig. 7) such as biaxial geogrid BX1 and BX2, uniaxial geogrid (UA), geonet and weak geotextile (WGT) having ultimate tensile strengths of 26.4, 46.6, 40, 7.6 and 0.4 kN/m respectively.

The inclusion of reinforcing material reduces the horizontal displacement to a considerable extent irrespective of reinforcement stiffness compared with unreinforced wall. More reduction of horizontal displacement for wall reinforced with biaxial geogrid compared to wall with weak geotextile. There is no significant variation in acceleration amplification for reinforced wall with different reinforcement stiffness.

Latha and Krishna (2008) compared horizontal displacements (Fig. 8) and acceleration responses (Fig. 9) of wrap-faced-, rigid-faced unreinforced and rigid-faced reinforced soil walls backfilled with sandy soil at different relative density (RD). The displacements reduce with increase in RD irrespective of facing type and reinforcement. The lateral deformation of wrap-faced wall is more than that of rigid-faced wall. During seismic excitation the soil within geotextile

Fig. 3 Accelerations at different elevations (after Krishna and Latha 2007)



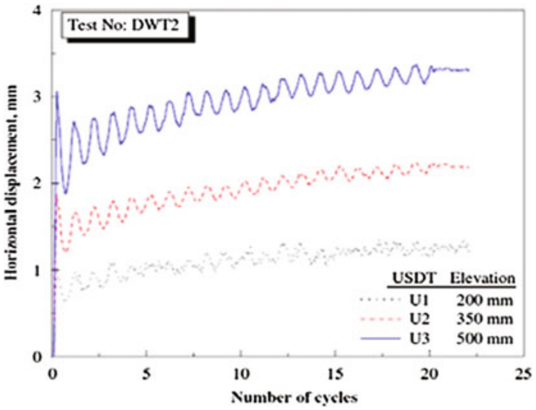


Fig. 4 Typical variation of horizontal displacements (after Latha and Krishna 2008)

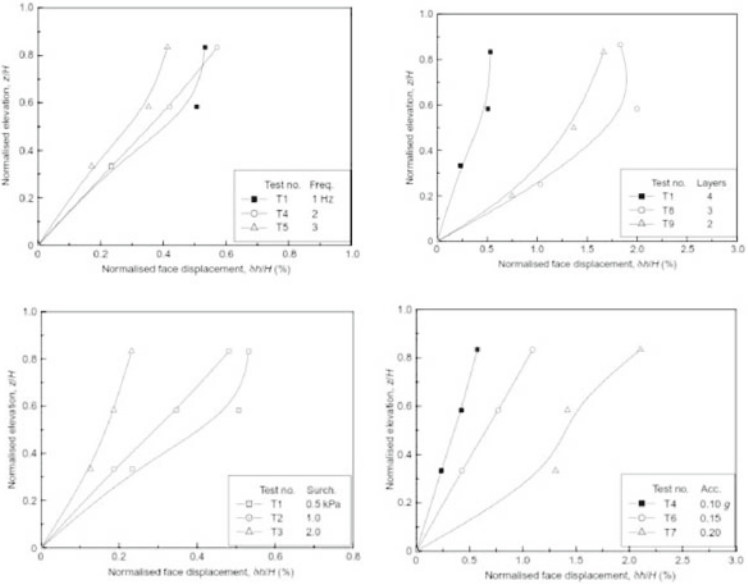


Fig. 5 Variation of horizontal displacement with **a** frequency **b** reinforcement layers **c** surcharge **d** base acceleration (after Krishna and Latha 2007)

wrapped layer settles, as a result face bulges out. But this phenomenon is absent in case of rigid-faced walls. The accelerations are amplified more on top of wall for all three types of wall. But there is no consistent trend in acceleration amplifications with change in relative density of backfill soil in all three types of walls.

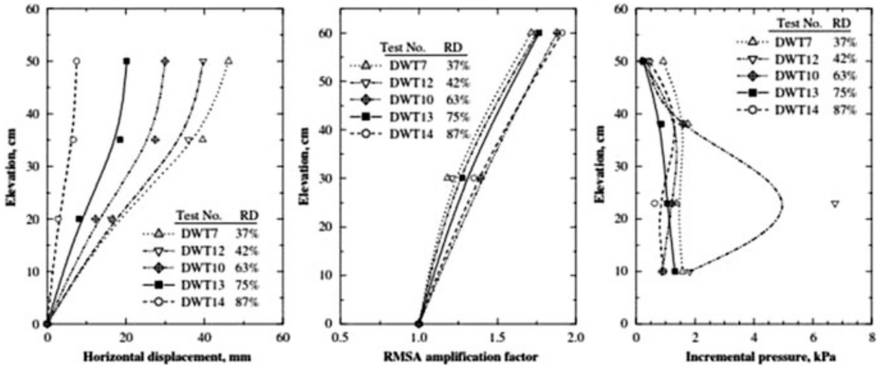


Fig. 6 Response of wrap-faced walls against higher base excitation (at end of 20 cycles of dynamic motion) **a** horizontal displacement **b** acceleration amplification and **c** incremental pressure (after Latha and Krishna 2008)

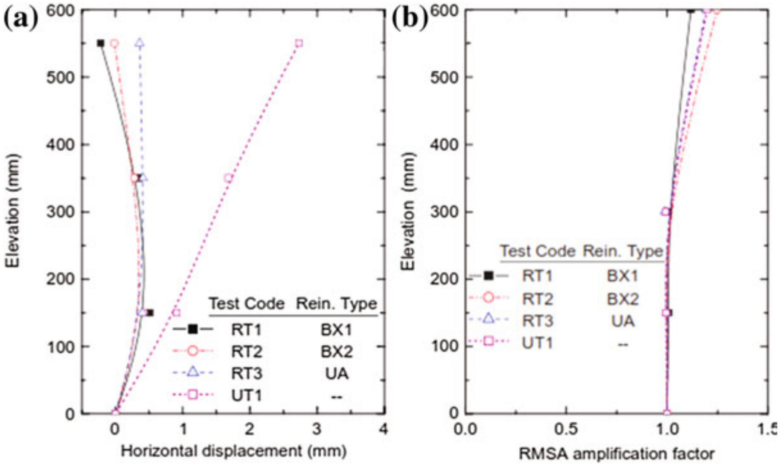


Fig. 7 Response of rigid-faced walls with different types of reinforcement after 20 cycles of 0.1 g at 2 Hz dynamic motion: **a** horizontal displacement **b** acceleration amplification (after Krishna and Latha 2009)

The maximum lateral displacements and maximum acceleration amplification for wrap-faced wall with relative density at smaller excitation (0.1 g, 1 Hz) and higher excitation (0.2 g, 3 Hz) is shown in Fig. 10. The variations of horizontal displacements are more for subjected to higher frequency than that of lower frequency. Small increases in acceleration amplification for wall with denser soil at higher excitation are observed.

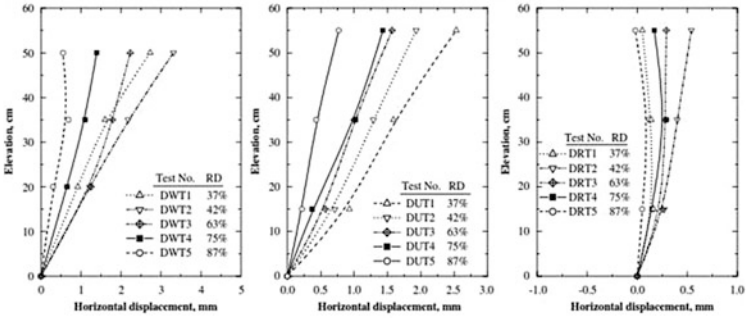


Fig. 8 Displacement profiles after 20 cycles of dynamic excitation for **a** wrap-faced **b** rigid-faced unreinforced **c** rigid-faced reinforced walls (after Latha and Krishna 2008)

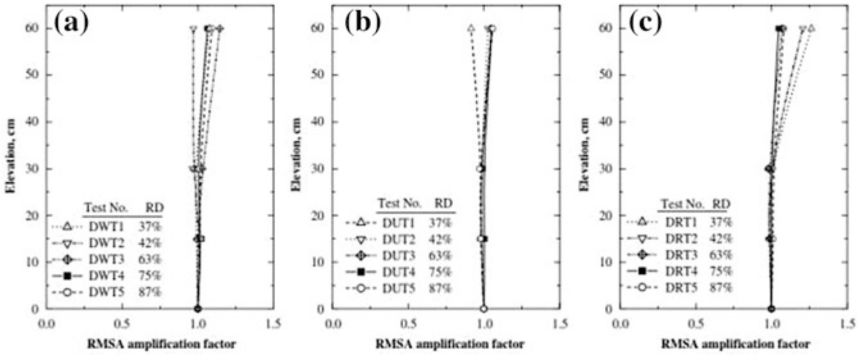


Fig. 9 Acceleration amplification after 20 cycles of sinusoidal dynamic excitation **a** wrap-faced **b** rigid-faced (after Latha and Krishna 2008)

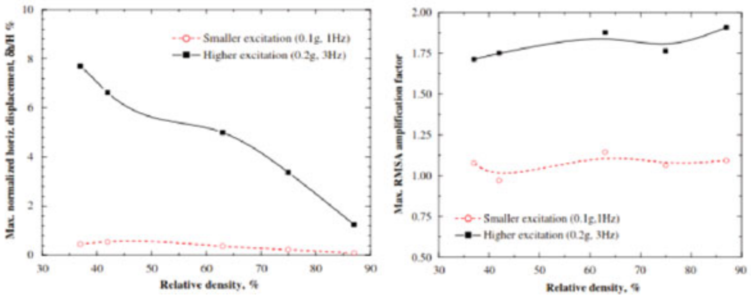


Fig. 10 Variation of **a** maximum displacement **b** maximum acceleration amplification with relative density for wrap-faced wall (after Latha and Krishna 2008)

3 Numerical Model Studies

Numerical models are particularly advantageous because of the difficulties associated with situations in which the prototype structures are too big to be tested; problems related to scaling, instrumentations; and, especially, repetition of model construction, etc. However, the key point to confirm the applicability of any numerical model is by its validation with the available prototype studies and/or small-scale laboratory model studies. The calibrated numerical model can then be used for extensive parametric studies. Krishna and Latha (2012) and Bhattacharjee and Krishna (2012, 2015a) developed numerical models and validated with the physical model tests results. The numerical model of wrap-faced wall was developed by using FLAC^{3D} and is shown in Fig. 11. The validated numerical models were further used to analyse the seismic performance of 6 m high prototype walls. The octahedral shear strains, horizontal and vertical displacements determined along the length of the wall and results are presented in Fig. 12. By comparing strain and displacements, it can be seen that the deformation of wrap-faced wall subjected to seismic excitation consists of three different modes: shear deformation zone within reinforced block, a zone of relative compaction at the end of reinforcement and a shear zone called compound deformation zone extending to the unreinforced backfill.

Bhattacharjee and Krishna (2015b) studied the effect of length of reinforcement on deformation behaviour. Figure 13 shows the comparison of octahedral shear strain in backfill soil with different reinforcement lengths after 20 cycles of dynamic excitation. The octahedral shear strains in soil decrease with increase in reinforcement lengths. The compound deformation zone length decreases with increase in reinforcement lengths. Figure 14 shows the comparison of octahedral shear strain in backfill soil with different number of reinforcing layers after 20 cycles of dynamic excitation. The increase in number of reinforcing layers reduce the soil strain within reinforced zone but do not effect length of compound deformation

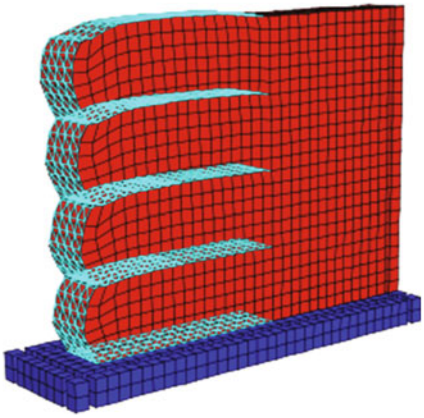


Fig. 11 Numerical model of wrap-faced reinforced soil wall (after Bhattacharjee and Krishna 2012)

Fig. 12 Octahedral shear strain, horizontal and vertical displacement along the length of backfill (a = 0.2 g, f = 5 Hz) (after Bhattacharjee and Krishna 2012)

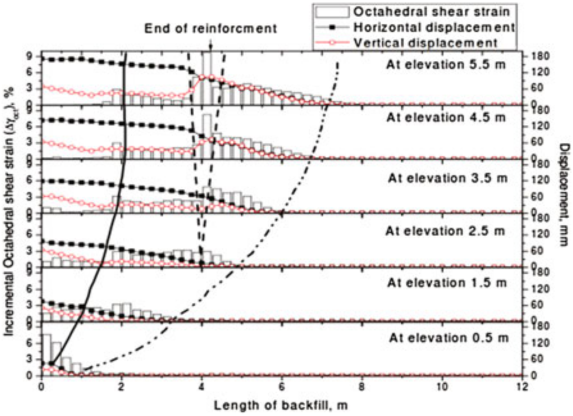
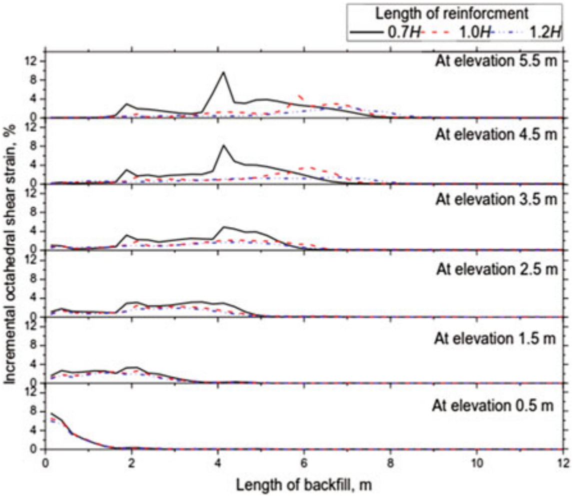


Fig. 13 Comparison of octahedral shear strain at backfill of wrap-faced wall with different reinforcement lengths after 20 cycles of dynamic excitation (a = 0.2 g, f = 5 Hz) (after Bhattacharjee and Krishna 2015b)



zone. So increase in number layers of reinforcements gives more stiffness to the reinforced soil. The study also reported that decrease in friction angles of backfill soil result in extension of the length of compound deformation zone deeper into unreinforced backfill soil.

The numerical model of rigid-faced wall developed by using FLAC^{3D} is shown in Fig. 15. The octahedral shear strains and displacements along the length of backfill between two layers of reinforcements are presented in Fig. 16. By comparing octahedral shear strain, horizontal and vertical displacements two deformation zones are identified. The first zone exists very close to the facing which can be considered as high strain zone and shows relative settlement near wall facing. The second zone is constant strain zone which extends beyond reinforced zone,

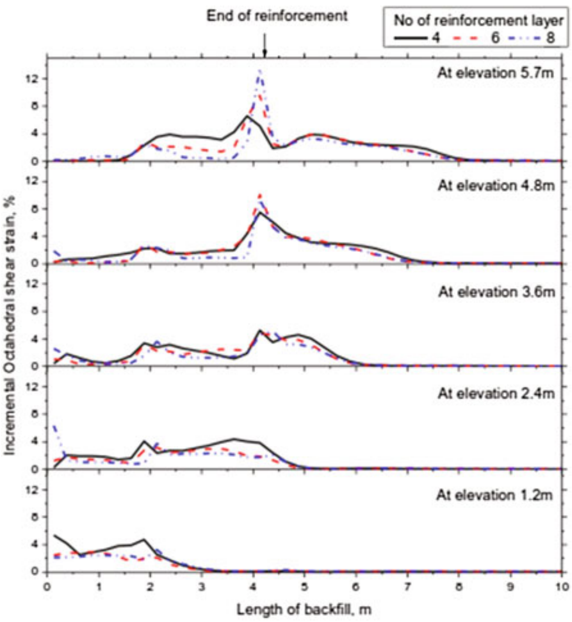


Fig. 14 Octahedral shear strains at backfill of wrap-faced walls with different reinforcing layers (a = 0.2 g, f = 5 Hz) (after Bhattacharjee and Krishna 2015b)

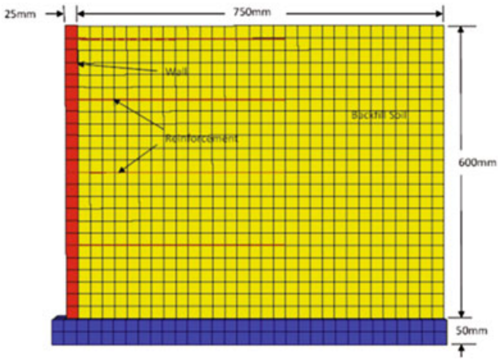


Fig. 15 Numerical model of rigid-faced reinforced soil wall (after Bhattacharjee and Krishna 2015a)

formed due to shear deformation within reinforced zone. This may result in some settlement near the facing and tension cracks in backfill soil.

Krishna and Bhattacharjee (2016) studied seismic behaviour of rigid-faced reinforced soil wall subjected to scaled earthquake ground motion. A full scale calibrated numerical model subjected to five-scaled earthquake ground motions with different predominant frequency ranging from 0.637 Hz for Loma Prieta EQ to 5.437 Hz for Parkfield EQ.

Figure 17 shows the base input ground motions for Loma Prieta and Parkfield EQ and their responses at top. The figure shows that amplitudes close to the fundamental frequency of the wall are amplified the most. Figure 18 shows the

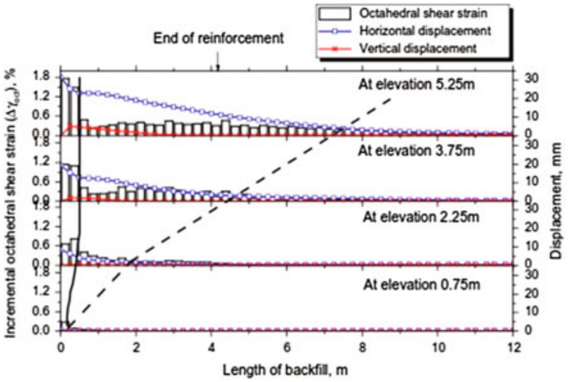


Fig. 16 Octahedral shear strain, horizontal and vertical displacements along length of backfill after 20 cycles of dynamic excitation (a = 0.2 g, f = 5 Hz) (Bhattacharjee and Krishna 2015a, b)

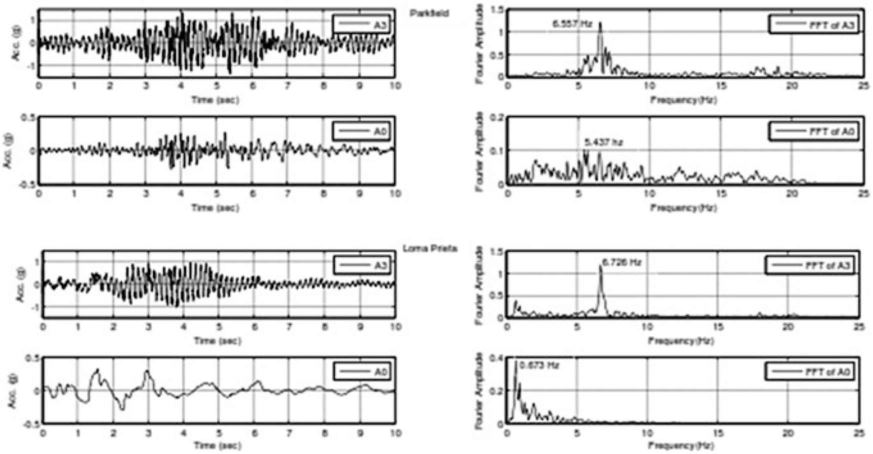


Fig. 17 Acceleration applied at the base of the model (A0) and acceleration recorded at the top of the backfill (A3) and corresponding FFT for Loma Prieta and Parkfield EQ (after Krishna and Bhattacharjee 2016)

variation in the form of horizontal displacement, acceleration amplification and horizontal pressure along the height of wall after different seismic excitations. It is observed from the figure that horizontal displacement and acceleration amplification are different for different earthquake excitations, but the horizontal pressures are nearly identical.

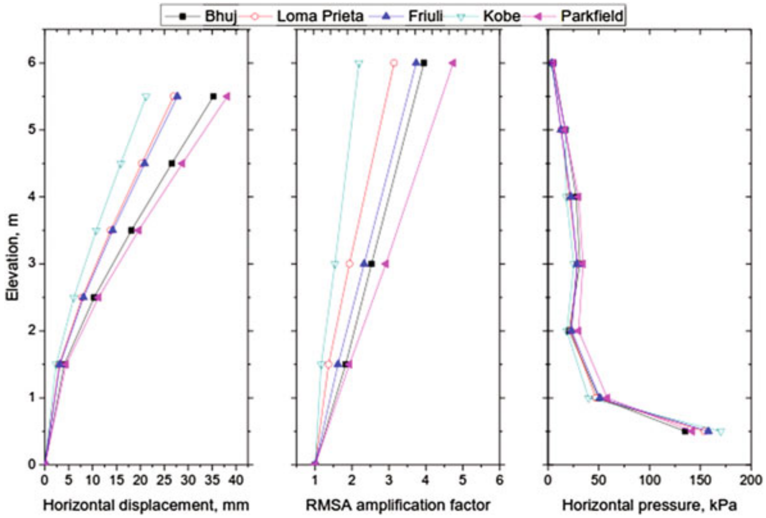


Fig. 18 Horizontal displacements, acceleration amplifications and horizontal pressures for wall subjected to different earthquake excitations (after Krishna and Bhattacharjee 2016)

Fig. 19 Octahedral shear strain along the length of backfill of rigid-faced wall subjected to Bhuj, Kobe and Parkfiled EQ

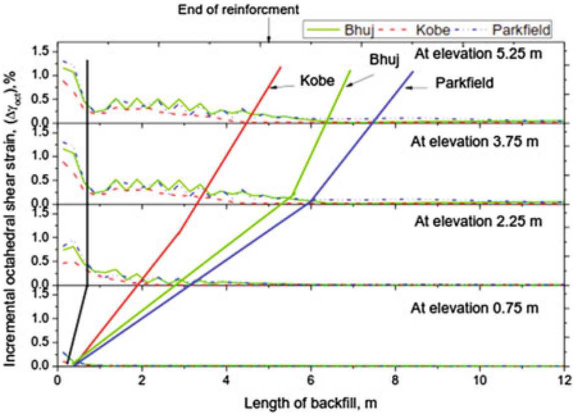


Figure 19 shows octahedral shear strain along length of backfill at different elevations subjected to Bhuj, Kobe and Parkfiled EQ. Two strained zones—a high strain zone near the facing and constant strain zone extended into the backfill are observed. The extent of high strained zone is same for all earthquakes but the extent three constant strained zones is different based on frequency content of scaled earthquakes.

4 Concluding Remarks

The paper discussed about the seismic analysis of wrap-faced- and rigid-faced reinforced soil retaining walls using physical and numerical model studies. Various parameters like backfill RD, reinforcement stiffness, number of layers, length of reinforcement, type of facing influence the wall performance in terms of horizontal displacements, acceleration amplifications, pressures and strains developed in soil and reinforcement. The formations of deformations zones within the wrap-faced- and rigid-faced walls are presented.

With the increasing use of reinforced soil retaining structures in the public infrastructure facilities in large extent; their seismic behaviour must be ensured which can be ascertained through different mode of studies. The insight obtained from the seismic analyses shall be incorporated in the design and construction of such important public infrastructures.

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