Performance of Mechanically Stabilized Earth Structures in Seismic Conditions

Atanu Adhikari and Deepak Manjunath

Abstract Mechanically Stabilized Earth (MSE) or Reinforced Soil structures are composite structures consisting of alternating layers of compacted backfill and soil reinforcement elements that are fixed to a facing. The stability of MSE structures is derived from the interaction between the backfill and soil reinforcements, involving friction and tension. The facing is relatively thin and is intended to perform the primary function of preventing erosion of the structural backfill. The significant relative cost saving that can be realized when this system is used compared to traditional RCC retaining structures, combined with ease of construction has resulted in widespread adoption of this technology in India and around the world. MSE structures have been found to perform satisfactorily when subjected to seismic loading conditions provided that recommended practices are adopted during their construction. This paper presents case studies of superior performance of MSE structures when subjected to seismic loading both during and after completion of construction including a case study on the behaviour of MSE structures founded on soft silt deposit in seismically active hilly terrain in the stretch from Quazigund to Baramulla where an earthquake measuring 5.4 on the Richter scale occurred during construction of the structure.

Keywords Reinforced earth · MSE wall · Mononabe-Okabe · Pseudo-static seismic loading

1 Introduction

One of the fundamental characteristics of earthquake resistant structures is the ability to dissipate energy induced due to earthquake loading by means of deformation within serviceability limits. Such structures are constructed with materials

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that can resist shear and tension, with simple, regular shaped individual members joined to form a continuous system that is capable of redistributing the earthquake forces. Mechanically Stabilized Earth (MSE) structures possess all these properties. Mechanically Stabilized Earth (MSE) or Reinforced Soil structures are composite structures consisting of alternating layers of compacted backfill and soil reinforcement elements that are fixed to a facing. The stability of MSE structures is derived from the interaction between the backfill and soil reinforcements, involving friction and tension. The facing is relatively thin and is intended to perform the primary function of preventing erosion of the structural backfill. The significant relative cost saving that can be realized when this system is used compared to traditional RCC retaining structures, combined with ease of construction has resulted in widespread adoption of this technology in India and around the world.

2 Experimental Models and Structures

Over the years, the response of MSE structures to seismic loading has been extensively studied by means of three types of experimental models and structures [6], namely:

1. Scale Models
2. ½ Scale Models and
3. Full Scale structures.

2.1 Scale Models

Initial studies pertaining to seismic response of MSE structures were conducted on scale models of MSE structures on which seismic loading was induced by means of vibrating tables (Fig. 1).

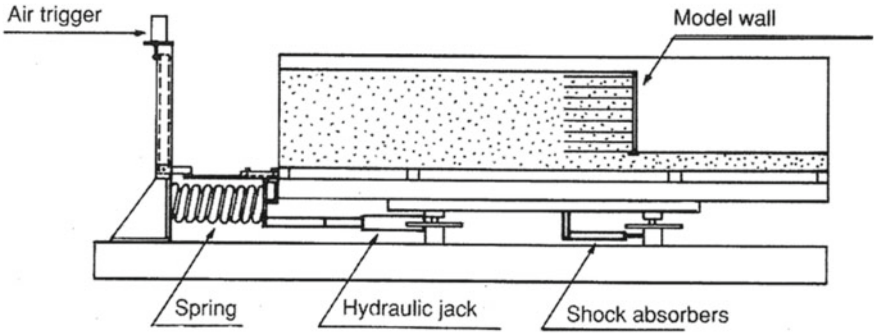

Fig. 1 Scale model on vibrating table [6]

However, drawing inferences and conclusions from such studies was a risky proposition due to inability of such models to represent behaviour of actual full size structures, specifically with respect to replicating adherence conditions, ductility of the reinforcements, the proportions of the structure, the period of vibration and so on. Moreover, it was difficult to observe the mode of reinforcement failure i.e. rupture or pull out [6].

2.2 ½ Scale Models

The short comings of scale models were addressed in the form of half scale models conceptualized by Professor Chida. These half scale models were placed on a vibrating table inside a box arrangement. This arrangement was instrumented with accelerometers and extensometers to record measurements during the experiments (Fig. 2). In this set up, earthquake loading was simulated through of a range of frequencies and accelerations that were induced by the vibrating table. Analysis of measurements recorded during experiments conducted using this set up, indicated a relatively even increase of tension in the reinforcements with increase in the induced acceleration. However, the rigidity of the frame was observed to influence the results at high frequencies [6].

2.3 Full Scale Structures

The propagation of significant vibrations through the reinforced soil mass, their effect on tension and adherence of reinforcements and the actual period of the vibration of the structures was studied by experiments conducted on full scale structures. Through these experiments, it was inferred that while seismic loading influences vertical stress, it did not have an effect on friction and thereby did not have an effect on adherence of the reinforcements [6].

3 Analysis of Experimental Data

At the request of Reinforced Earth Group, a critical analysis of all previous studies was conducted by the late Professor H.B. Seed [6]. Based on the experimental data, he drew the following conclusions:

1. The fundamental period of vibration of a structure is a function of its height and is only a fraction of a second. The maximum acceleration is nearly equivalent to the acceleration at ground level.

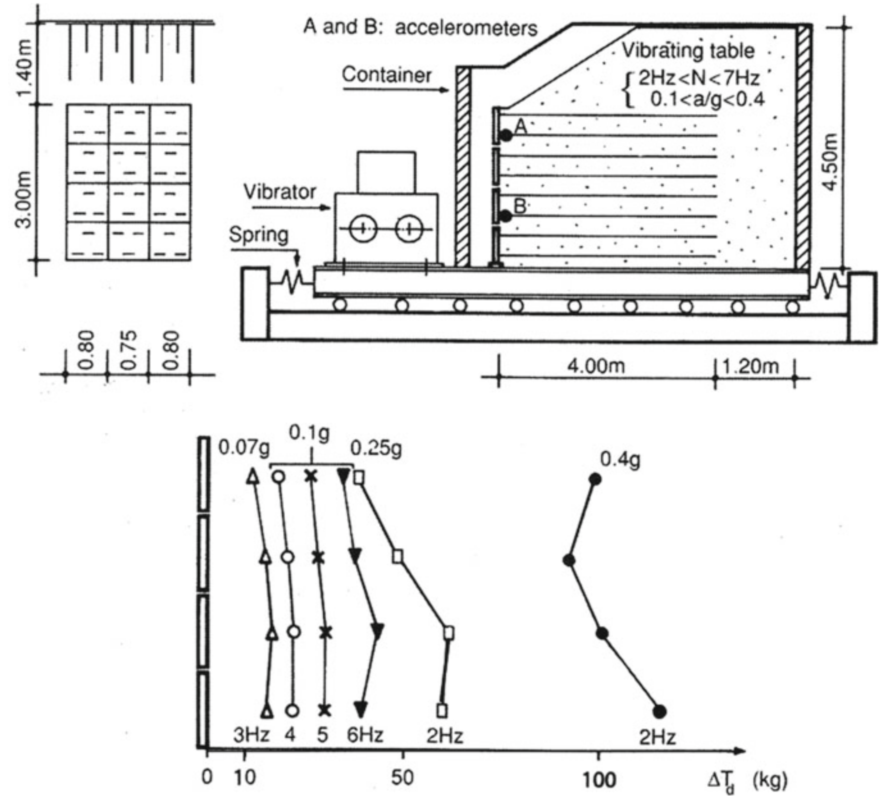

Fig. 2 ½ Scale model developed by Professor Chida and distribution of dynamic tension increments [6]

2. The excess dynamic tensile load that is developed in the reinforcements due to acceleration induced by seismic loading is practically constant throughout the height of a standard structure.
3. There is no residual deformation when MSE structures are subjected to accelerations up to 0.3 g

In addition, Professor Seed recommended that certain assumptions, like the width of the active zone, should be verified by other means, such as finite element method analysis.

4 Finite Element Analysis

When MSE structures using linear inextensible reinforcements were analyzed by finite elements method, the following inferences were drawn [6]:

1. The horizontal acceleration generally increases from the base to the top of the wall. While the average value is close to the input acceleration when the structure is founded on rock, the average acceleration transmitted to the structure is noticeably reduced when the structure is founded on less firm ground.
2. There is no residual deformation and a maximum elastic deformation of 13 mm results at the top of a 10 m tall MSE structure when it is subjected to seismic loading that induces an input acceleration of 0.4 g.
3. When compared with static loading, the location of the maximum tension line in the reinforcements doesn't change when MSE structures are subjected to seismic loading, even at high input accelerations.
4. When the reinforcements are evenly distributed in the structure, this internal dynamic force resulting due to seismic loading is equally distributed at all levels of reinforcements. The distribution is proportional to the shear resistance of the resistive zone, and hence is a function of the adherence length of the reinforcements.
5. When the reinforcements are unevenly distributed, the dynamic force is also distributed in proportion to the reinforcement density with the more heavily reinforced sections resisting more force.

5 Design Approach

Finite Element analyses have been adopted to analyse the behaviour of reinforced soil walls under static and seismic loading [1, 4, 9]. The design standards to be followed for design of reinforced soil walls and slopes in India find mention in Clause 3100 of Ministry of Road Transport & Highways (MoRTH) Specifications for Road & Bridge Works (5th Revision) as well as IRC:SP 102–2014. MoRTH Clause 3100 [10] allows for design to be done as per BS 8006:2010 [2] as well as FHWA-NHI-10–024 [3]. Since BS 8006:2010 does not cover the design checks to be carried out in seismic condition, the general design approach involves conducting the design checks for static case as per BS 8006 while the design checks for seismic case are carried out as per the Mononobe-Okabe pseudo-static approach presented in FHWA-NHI-10–024. MSE structures designed by adopting this design approach have been found to perform satisfactorily when subjected to seismic loading conditions provided that recommended practices are adopted during their construction.

6 Performance of MSE Structures Subjected to Seismic Loading

This section presents case studies to illustrate the performance of MSE structures subjected to seismic loading.

6.1 MSE Walls for Quazigund to Baramulla Rail Over Bridge Project

During the construction of eight Rail Over Bridge (ROB) approaches using MSE walls in the Quazigund to Baramulla project, the site experienced an earthquake of magnitude about 7.0 on Richter scale with epicenter about 150 km away from the site, in Pakistan. By means of extensive soil investigation, the foundation soil for most locations was found to be characterized by filled-up soil of 1–2 m followed by layers of fine grained clayey silt of low/ medium plasticity upto 15–20 m depth. In some locations sand was encountered at 16 m depth. Clayey silt upto 15 m depth was composed of 3–5% of sand, 80–95% of silt and 2–7% of clay. The SPT-N value was found to vary from 1–9 upto a depth range of 6–10 m.

MSE walls using discrete cruciform panels and high adherence steel strip reinforcement were adopted for the construction of the ROB approaches. The static design of the MSE structures was carried out as per BS 8006, 1995 and the seismic design was carried out as per AFNOR NF P 94–220, July 1992. The backfill used was well-graded riverbed material with engineering properties that conformed to the mechanical, physical and hydraulic and electrochemical criteria defined in the technical specifications. The foundation soil was reinforced with high tenacity polyester Geogrids as transition course to improve bearing capacity and to achieve global stability.

For reinforced soil walls upto a height of 4 m, no ground treatment was proposed. Walls exceeding 4 m height, the ground was proposed to be treated with one or two layers of high strength PET geogrid, which, were extended 3 m on both sides beyond the structure width depending on detailed analysis. Structures whose height exceeded 4 m were constructed in two or three stages with waiting period designed to dissipate excess pore pressures developed at the end of each stage of construction [5].

6.1.1 Seismic Event During Construction

The Kashmir earthquake (also known as the South Asia earthquake or the Great Pakistan earthquake) of 2005, was a major earhquake whose epicenter was located in the Pakistan administered Kashmir occurred at 08:50:38 h. Pakistan standard time (03:50:38 UTC) on 8th Oct. 2005. It registered 7.6 on the richer scale making it a major earthquake similar in intensity to the 1935 Quetta earthquake, the 2001 Gujarat earthquake, and the 1906 San Francisco earthquake. The equivalent magnitude of tremor on Richter scale at site was 5.4.

All the MSE walls on Baramula—Quazigund section experienced the impact of this earthquake. The constructed height of the wall was 6 m at the time of the seismic event. While many residential structures in the vicinity collapsed or were damaged due to earthquake, no damage was observed in the MSE walls (Fig. 3).

Fig. 3 (Top) Damage sustained by buildings in Uri 30 km from site and (Bottom) MSE approach wall for Bridge No. 127 after the earthquake [5]

The vertical alignment, individual panel joints, vertical and horizontal gap between the panels were found to be intact. No bulging, differential movement between the panels, or any damage in the panels was observed after the earthquake.

6.2 Performance of MSE Walls During the Northridge, Kobe and Izmit Earthquakes

6.2.1 Northridge Earthquake

23 MSE Wall structures measuring 5–10 m in height and located between 13–83 km from the epicentre were subjected to seismic loading during the 1994 Northridge earthquake. The earthquake subjected the structures to horizontal accelerations varying between 0.07–0.91 g and vertical accelerations varying between 0.04–0.62 g [7]. While the buildings and other structures in the vicinity of the MSE structures were severely damaged during the earthquake, the only damage observed in the MSE

walls was minor spalling of the concrete panels. It is of high importance to note that while over 75% of the MSE wall structures were designed using lesser horizontal ground accelerations than actually occurred, over 50% of the MSE wall structures were designed by not considering any horizontal ground accelerations at all [8].

6.2.2 Kobe Earthquake

Over 120 MSE wall structures ranging in height from 5 m to over 10 m were inspected after the 1995 Kobe earthquake. While the structures were designed using ground accelerations ranging from 0.15–0.2 g, the actual ground acceleration during the earthquake was 0.27 g. While ground deformation was observed next to 22 structures, 10 structures exhibited minor cracking of the concrete panels with 3 structures exhibiting significant lateral movement. While deformations recorded in walls at Awaji Island and Hosiga-oka Park varied between 4–113 mm, all the structures were recorded to remain functional after the earthquake [8].

6.2.3 Izmit Earthquake

One bridge and ramp structure located in Arifiye, in close proximity to the epicentre, was inspected after the 1999 Izmit earthquake. The differential settlements that were initiated by the seismic event caused panels to separate by as much as 75 mm at some locations. However, while the bridge collapsed, it was observed that the bridge approach MSE ramp walls remained stable and only sustained nominal damage. This is noteworthy, especially considering that the MSE walls were subjected to a ground accelearation of 0.4 g while they were actually designed considering a ground acceleration of 0.1 g only [8].

7 Conclusions

This paper presents inferences drawn from experiments that were conducted to study response of MSE structures to seismic loading. Selected case studies from around the world have been presented to support the conclusion that MSE structures remain structurally stable after experiencing significant seismic loading. MSE walls being flexible in nature, can be constructed over very soft soil where the expected settlement is very large and in areas prone to high seismic activity. Special arrangements like provision of slip joints are very important to ensure that MSE structures can accommodate large differential settlements.

References

1. Bathurst RJ, Hatami K (1998) Seismic response analysis of a geosynthetic reinforced soil retaining wall. Geosynth Int 5(1–2):127–166
2. BS 8006–1 (2010) Code of practice for strengthened/reinforced soils and other fills. BSI Standards Publication, London, UK
3. FHWA-NHI-10–024 (2009) Design and construction of mechanically stabilized earth walls and reinforced soil slopes. US Department of Transportation, Federal Highway Administration, Virginia, USA
4. Karpurapu R, Bathurst RJ (1995) Behavior of geosynthetic reinforced soil retaining walls using the finite element method. Comp Geotech 17(3):279–299
5. Mahajan P, Biwas S, Adhikari A (2008) Behaviour of reinforced earth structures founded on soft silt deposit in seismically active hilly terrains. In: Proceedings of the new horizons in earth reinforcement—otani, Miyata & Mukunoki, Taylor & Francis Group, London, pp 797–802
6. Reinforced Earth Management Services Sdn Bhd, Reinforced earth structures in seismic regions, Kuala Lumpur, Malaysia
7. Sandri D (1994) Retaining wall stand up to the northridge earthquake. Geotechnical Fabrics Report 12(4):30–31
8. Sankey JE, Segrestin P, Evaluation of seismic performance in Mechanically stabilized earth structures. https://www.tierra-armada.cl/descargas/Evaluation-of-Seismic-Performance-in-Mechanically-Stabilized-Earth.pdf
9. Segrestin P, Bastick MJ (1998) Seismic design of reinforced earth retaining walls—the contribution of finite element analysis. In: Yamanouchi T, Miura N, Ochiai H (eds) Proceedings of the international geotechnical symposium on theory and practice of earth reinforcement, Balkema, Rotterdam, pp 577–582
10. Specifications for road and bridge works (2013) Ministry of Road Transport & Highways, New Delhi, India