

PAPER • OPEN ACCESS

Seismic Response of Mechanically Stabilised Earth Retaining Wall

To cite this article: M Joseph and S Banerjee 2021 *IOP Conf. Ser.: Earth Environ. Sci.* **727** 012017

View the [article online](#) for updates and enhancements.



The banner features a colorful striped border at the top. On the left, the ECS logo is displayed in a green circle. To its right, the text reads: "240th ECS Meeting", "Oct 10-14, 2021, Orlando, Florida", "Register early and save up to 20% on registration costs", "Early registration deadline Sep 13", and "REGISTER NOW" in orange. On the right side of the banner is a photograph of a diverse group of people in a professional setting, with a man in a white shirt and tie clapping and smiling.

ECS **240th ECS Meeting**
Oct 10-14, 2021, Orlando, Florida
**Register early and save
up to 20% on registration costs**
Early registration deadline Sep 13
REGISTER NOW

Seismic Response of Mechanically Stabilised Earth Retaining Wall

M Joseph¹ and S Banerjee²

¹ Ph. D Scholar, Indian Institute of Technology, Madras, India

² Associate Professor, Indian Institute of Technology, Madras, India

E-mail: ¹monicajoseph93@gmail.com, ²subhadeep@iitm.ac.in

Abstract. Mechanically Stabilised Earth retaining wall has become a premier choice of retaining wall design in places where seismic and high vibration loads are frequent. The wall displacement has to be monitored regularly for the safe and economic function of the structure. In the present paper, a numerical study on an MSE wall model under real records of earthquake loading condition using an explicit finite difference program has carried out. A parametric study to scrutinize the influence of strong-motion parameters such as peak ground acceleration and predominant frequency on the permanent displacement of the wall is accomplished. The influence of PGA and frequency of seismic excitation was visible in the results. At higher frequencies, the ground surface is disturbed severely leading to excessive heaving on the surface. The amplification of strong motion along the backfill is observed for low PGA motions, whereas, de-amplification is observed for high PGA motion.

1. Introduction

The earthquake triggered ground motion, causing major damages to buildings, roadways, embankments, retaining walls, etc. have become a common scenario in the world. The distortion of earth retaining structures due to excess ground movement is a serious area to be taken care of. Mechanically Stabilised Earth (MSE) retaining walls have achieved significant acceptance from the 1970s based on their benefits of cost-effective construction, pleasing aesthetics, and simple construction techniques. MSE walls are predominantly used in seismic prone areas where it shows satisfactory performance during the earthquake and its aftershocks. The extensive employment of reinforced earth structures in the field demands proper investigations to predict the responses under probable loading conditions to make sure satisfactory performance during their lifetime. MSE wall system consists of soil reinforcement, backfill material, facing element and foundation soil. The relative movement between the reinforcement and the backfill soil reduces the lateral earth pressure from the retained soil. The shear strength of the soil and the tensile strength of the reinforcement contribute to the stability of the structure. High resistance to seismic loading on account of their flexible nature is one of the desirable features of reinforced soil retaining walls. Many researchers [1,2,3,4] have conducted numerical study on MSE wall subjected to static loading and suitability of the wall for practical applications are well evident from their work. An earthquake resistant structure shall consider the effect of earthquake motions on its each component. The overall performance of the MSE wall system is very much influenced by the soil reinforcement and backfill interaction. The reinforcement length (L/H ratio), stiffness of reinforcement, friction angle of reinforced soil, and friction angle of retained soil are important parameters governing the stability of the wall. The Federal Highway Administration (FHWA) and AASHTO [5, 6] recommends a reinforcement length of 0.7H or not less than 2.4m, while National Concrete Masonry Association recommends a



length of $0.6H$. The inadequate reinforcement length affects the stability of the wall and ends in excessive horizontal displacement.

Kibria et al. [7] conducted a parametric study to understand the influence of reinforcement stiffness and length in the overall performance of retaining wall based on a case study of MSE wall located at State Highway 342 in Lancaster, Texas. The horizontal movement of the MSE wall was between 300 and 450 mm within 5 years of construction with an average movement of 4.5 mm/month. The study reveals that the inadequate length of the reinforcement layer is a reason for the excessive wall movement. The effect of reinforcement stiffness was not significant at a wall height of 4 m. According to the results, reinforcement stiffness and length were identified as influential parameters affecting the horizontal movement at a specific MSE wall height. Segrestin and Bastick [8] also conducted finite element analyses to understand the seismic response of soil-reinforced structures. In their studies, the elastoplastic behaviour of the soil was simulated by varying the modulus of elasticity as a function of observed deformations. The results of the study indicated that the distribution of dynamic tensile forces along the strips is fairly uniform and does not give significant change in the position of points of maximum tension. Unlike the FHWA recommendation, Segrestin and Bastick [8] suggested that the active failure zone is not affected much by the earthquake loading, and therefore the width of this area should be limited to $0.3 H$.

In most of the prevailing design methods, the dynamic response of retaining wall is not considered in the design, but the wall is designed to resist any movement for the predicted design load. This method has the disadvantage of the high cost of construction as the wall is assumed to have zero movements throughout its design life. However, a displacement-based design allows the wall to displace for an amount less than the permanent displacement of the wall, thereby reducing the construction cost to a great extent. Hence knowing the permanent displacement of the wall is the prior step for the performance-based design of MSE wall.

2. Description of the Problem

A mechanically stabilised earth wall holding loose cohesionless soil is chosen for the present study. The numerical model of the MSE wall is modelled in the finite-difference software, FLAC 7.0. The wall model is subjected to velocity time histories of real earthquake records. The important parameters of ground motion such as peak ground acceleration (PGA) and predominant frequency of motion (f_n) are changed in each analysis to study its influence on the response of the wall. The retaining wall model is further studied to evaluate the influence of strong-motion parameters on the permanent displacement of the wall. The acceleration time histories, settlement behind the panel, amplification characteristics, axial force in the reinforcement and the permanent horizontal displacement of the wall are analysed at various points of interest in the model.

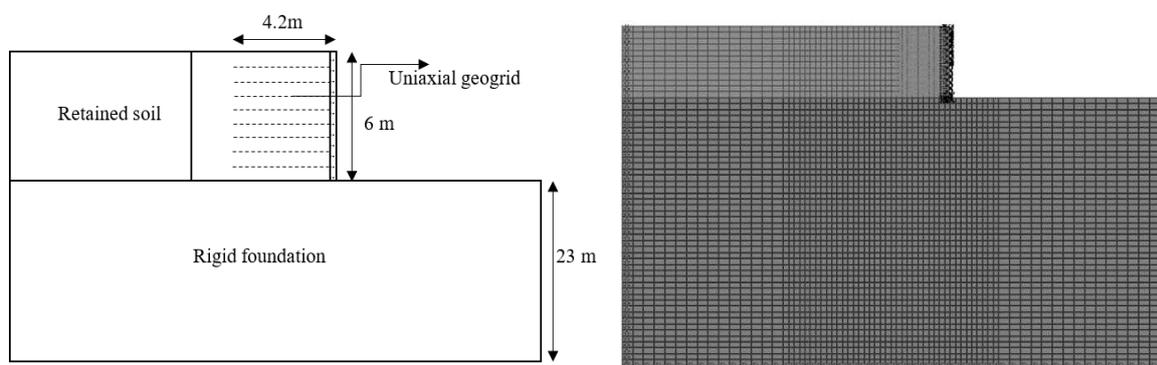


Figure 1. (a) Geometry of the MSE wall model used for the present study (b) Generated mesh of MSE wall.

3. Wall geometry and soil properties

A MSE wall with a geometry of 6m height and 5m width is modelled for the numerical study as shown in Figure 1 (a). The wall and the retained soil are assumed to rest on a rigid foundation. A uniaxial

geogrid of tensile strength 55kN/m and mass density 0.51kg/m³ is adopted from Liu [9]. The reinforcements of configuration 0.7H length and 0.5m spacing was selected to develop the numerical model where H is the height of the wall. Closer spacing of reinforcement is adopted in the present study to focus on the influence of strong-motion parameters on the response of the wall. The rigid foundation of concrete for a depth of 23 m is used to avoid the rotation of model during the analysis. A distance of 25m from the wall to the left vertical boundary and 15 m to the right vertical boundary are selected to satisfy the boundary conditions. The backfill, retained soil and foundation properties used in the present study are mention in Table 1. The backfill soil is assigned as medium dense silty sand [9]. An elastoplastic Mohr-Coulomb model is assigned for both reinforced and retained soil. The choice of a simple constitutive model to predict the behaviour of reinforced soil walls is justified by the previous studies. A simple constitutive model like Mohr-Coulomb was found adequate to predict the behaviour of an MSE wall [10]. Further Bathurst and Hatami [11] analysed the behaviour of continuous panelled retaining walls using finite difference analysis in which the constitutive model used for backfill soil was Mohr-Coulomb model and the numerical model was found to give fairly accurate predictions on the seismic response of the wall. Input parameters needed for the Mohr-Coulomb model are bulk modulus, shear modulus, density, cohesion, friction angle and dilation angle. The reduction in shear modulus of the soil and its corresponding damping property is also considered for the study according to Darendeli [12]. The shear modulus and bulk modulus of the soil is calculated based on the formulation proposed by Ishihara [13] as shown below,

$$G = 7000 * (2.17 - e)^2 / (1 + e) * \sigma_m^{0.5} \quad (1)$$

$$K = G_0 \frac{2(1+\nu)}{3(1-2\nu)} \quad (2)$$

Table 1. Soil and wall properties

Soil Type	Backfill	Retained soil	Base
Void Ratio	0.45	0.65	-
Mass Density (kg/m ³)	1815	1700	2300
Friction Angle (°)	39.4	33	-
Dilation Angle (°)	5	5	-
Shear Modulus (MPa)	$7000 \frac{(2.17 - e)^2}{(1 + e)} (\sigma_o)^{0.5}$		
Cohesion (kPa)	0	0.5	-
Poisson's Ratio	0.3	0.3	0.17
Model	Non-linear hysteretic + Mohr-Coulomb failure criterion + viscous damping		Linear elastic

4. Selection of earthquake data

The real records of the acceleration time history of five earthquakes are collected. Five real records of earthquakes, which are Bhuj (2001), Tabas (1978), Izmit (1999), Loma Prieta (1989), and Kobe (1995), are used for the present study. Figure 2 represents the seismic excitations used for the present study. The uncorrected acceleration time histories are filtered and baseline corrected before using for the analysis. The selected strong-motion time histories possess a range of PGA's from 0.1g to 0.5g and predominant frequency from 2.17 to 6.25 Hz. The velocity-time histories of the input seismic excitation are used as an applied motion to the model. The absorbing boundary at the base fails to replicate the same motion when the motion is applied as acceleration time histories during the analysis.

5. Description of the numerical model

The two dimensional numerical model of the MSE wall is developed using the finite difference method. The generated mesh for the retaining wall model is shown in Figure 1 (b). The meshing of the model is

provided using finer square grid zones near the wall and coarser meshing with an aspect ratio 2 towards the boundaries, sizes of which ensured an accurate wave transmission of maximum frequency [14] expressed as

$$f_{max} = V_s/[0.8\Delta_l] \quad (3)$$

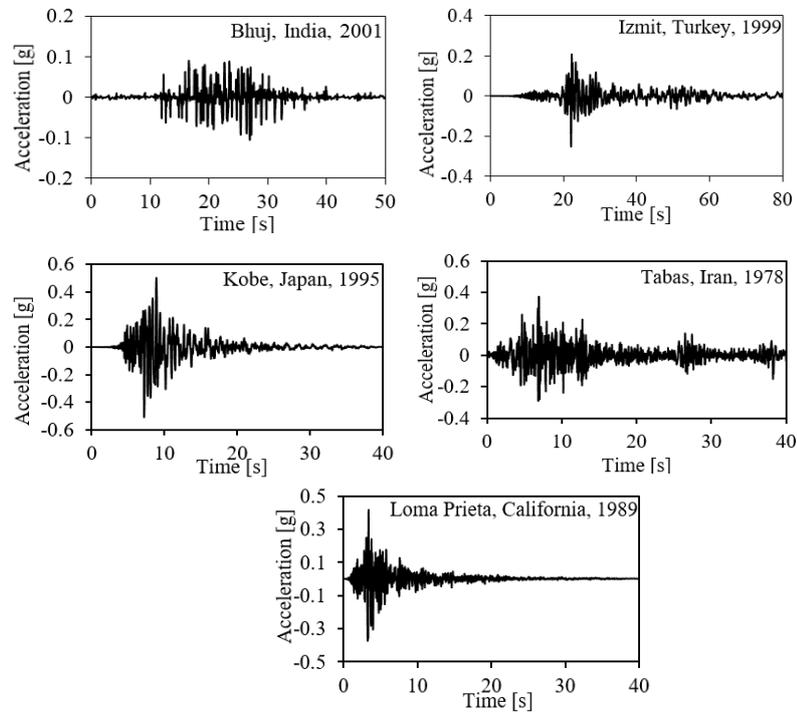


Figure 2. Seismic excitations

The increased mesh size towards the model boundaries helped in reducing the computational time significantly. The rotation of the model is expected in the analysis due to the significant difference in model depth along the side boundaries is prevented by providing a higher foundation depth of 23m. The specified properties in Table 1 are assigned to soil and wall zones. Interface elements are used in the model to define the boundaries between soil and wall and between the panels.

The interface properties such as shear (k_s) and normal stiffness (k_n) are assigned to the interface elements along with interface friction angle. The interface stiffness is set to ten times the equivalent stiffness of the stiffest neighbouring zone to prevent any slip or separation [15]. The apparent stiffness (expressed in stress-per-distance units) of a zone in the normal direction is according to [14] expressed as,

$$k_n = 10 * \max \{ [K + 4/3G]/\Delta z_{min} \} \quad (4)$$

Where K , G and Δz_{min} are the bulk modulus, shear modulus and the width of the smallest adjoining zone in the normal direction. The absorbing boundary is applied at the model base and free field boundary applied at both the vertical boundaries of the model. Lysmer and Kuhlemeyer's [16] absorbing boundary of independent viscous dashpots placed vertically and horizontally at the boundaries are adopted in the present analysis. The free-field boundary absorbs the outward wave propagation and preserve the non-reflecting property. The numerical analysis in the MSE wall model is carried out in two stages. In the first stage, the static equilibrium of the model is achieved and the unbalanced force is brought to a minimum. The wall is constructed stage by stage and the equilibrium of the model is maintained at each stage of construction. In the second stage, the dynamic analysis is executed. Since an absorbing boundary is assigned at the base of the model, the input seismic excitation is applied as velocity-time history, because the applied acceleration time history need not necessarily match the input motion. The numerical model is analysed for a total of 5 sets of seismic conditions of varying PGA's

and frequencies. The influence of PGA and frequency can be analysed in each case. Rayleigh viscous damping of 0.1% is provided to capture soil damping at very low strains.

The reinforcement material is modelled as linear elastic-plastic cable elements with zero compressive strength. Cable elements are one-dimensional axial elements that can take tension or compression but not bending moment. The end of the cable was rigidly attached to the grid point at the back of the facing panel in each case. Hatami and Bathurst, Yu et al. [17, 18] carried out a static analysis of reinforced earth walls implementing cable elements with strain-dependent stiffness values to model the reinforcement and grout of the cable element to model the interface between reinforcement and the soil. Bathurst and Hatami, El-Emam et al. [11, 19] used cable elements of constant stiffness value to model reinforcements during dynamic simulation of reinforced soil walls. A large bond strength along the reinforcement-backfill interface was selected to prevent slip of the reinforcement and to simplify the model [20]. The friction angle between wall-soil interfaces by Ling et al. [21] is adopted in the present analysis. The segmental concrete panel is also modelled as linear elastic elements. The base panel is hinged at the bottom. The interface is modelled as a linear spring slider system with interface shear strength defined by Mohr-Coulomb Failure criterion. A similar approach has adopted by researchers [11, 17] to model interface between panel and backfill.

6. Results

The developed numerical model of MSE wall is conducted a parametric study where the influence of PGA and predominant frequency of motion is evaluated. The relative horizontal displacement of the wall, settlement of the soil behind the wall, the axial force on the reinforcement, and the amplification of strong motion along the backfill are evaluated and results are represented as graphs below.

The relative horizontal displacement of the MSE wall at different wall heights under the given input motions is shown in Figure 3. The influence of PGA and predominant frequency on the displacement of the wall during the seismic excitation is visible from the results. The range of wall displacement when the wall is subjected to the strong motion of PGA between 0.1g and 0.51g and frequency 2.17 to 6.25 Hz is observed to be very narrow. The wall displaced more as the PGA of motion increased, but the combined effect of PGA and frequency did not show much difference in the horizontal displacement of the wall. As the predominant frequency of the strong motion is increased, the backfill and the retained soil surfaces have severely disturbed.

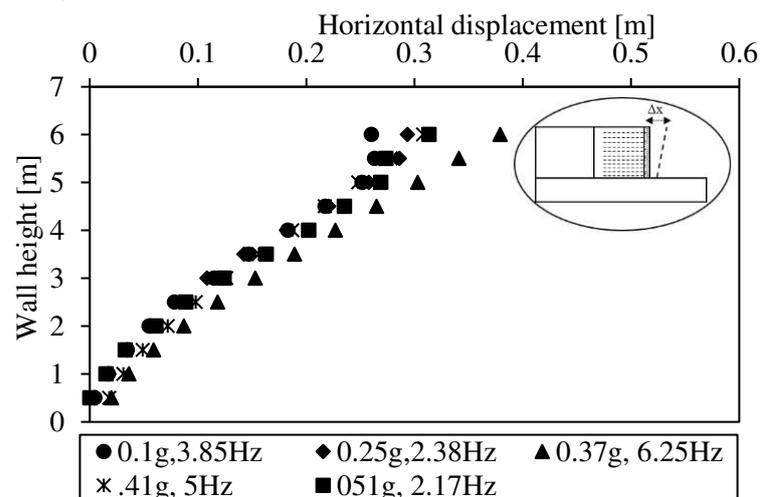


Figure 3. The relative horizontal displacement of the wall under different PGAs and frequencies.

The settlement of the soil behind the wall is also an important parameter to be addressed while designing. The settlement should be minimum for the safe functioning of neighbouring structures. In the present study, the settlement up to 8m distance behind the wall for all the five cases of seismic excitation is calculated and shown in Figure 4. At higher frequencies (5Hz and 6.25Hz in the analysis),

the ground surface has disturbed severely and large heaving is observed on the surface. However, at lower frequencies, the settlement is observed close to the panel and heaving is observed beyond the wall.

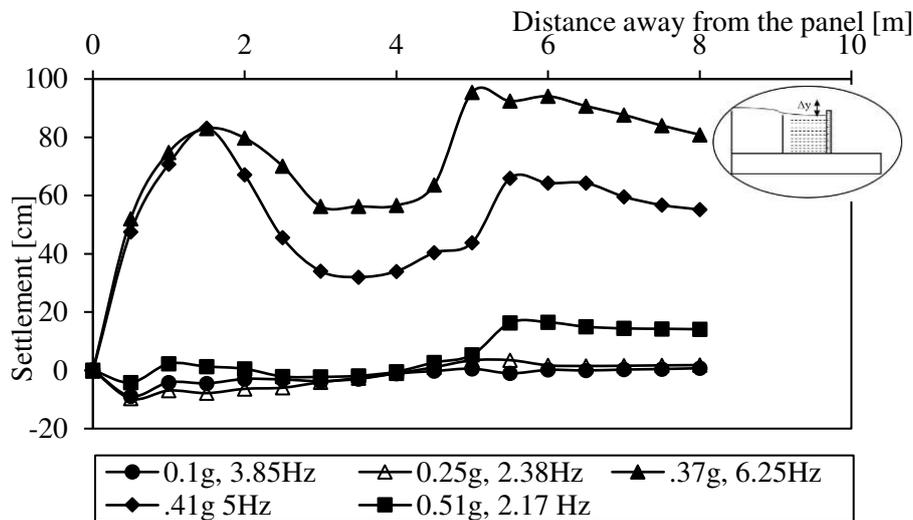


Figure 4. Comparison of the settlement of soil behind the wall

The amplification of seismic motion is an important factor to incorporate in the seismic design of retaining structures. Amplification is defined as the factor by which the input motion is being amplified while the wave propagates through the soil media. For the present study, the amplification factor is defined as the ratio of the peak ground acceleration experienced at the backfill to the peak ground acceleration of the input motion. Amplification phenomena are influenced by many factors such as the non-linear behaviour of ground, ground motion characteristics, and wall properties. Amplification of strong motion always demands an improved design methodology, which is necessary for the current design practice. In the present study, amplification of motion along the backfill is studied with the five earthquake conditions. The amplification factor is calculated from the numerical results and is shown in Figure 5.

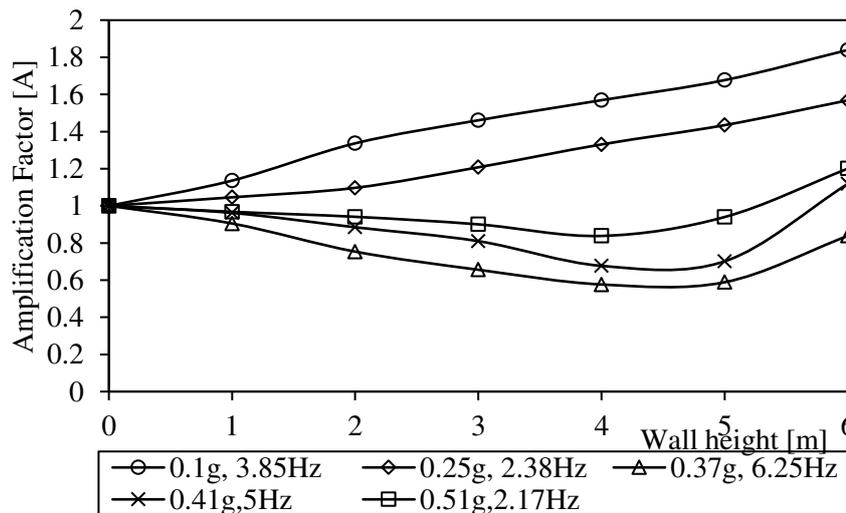


Figure 5. Variation of amplification factor with PGA and frequency of motion.

The figure shows that at lower peak ground acceleration, the strong motion propagating through the backfill is amplified. However, at higher PGAs the motion gets attenuated and de-amplification happens. The input motion of PGA 0.1g and 0.25g in the present analysis got amplified to a factor of 1.9 and 1.6.

Notwithstanding, the influence of the frequency of motion is also clearly visible from the results. When the model is subjected to input motions of higher PGAs, lower frequency motion is de-amplified more than high-frequency motion.

The combined interaction of soil reinforcement and backfill soil reduces the lateral pressure on the wall. Hence the axial force on the reinforcement should be monitored to make sure the wall is stable throughout its service period. In Figure 6, the maximum axial force in the reinforcement at the end of each analysis is shown. Higher axial load is observed towards the wall top, hence a reduced reinforcement length towards the base of the wall is an economical option for the design of reinforced walls. At high-frequency motion, this trend of axial force distribution is disturbed due to more heaving at the surface. Figure 6 shows that when the model was excited under Tabas earthquake condition, with a frequency 6.25Hz and PGA of 0.37g, large heaving was observed and the combined tension and compression has changed the distribution pattern of the reinforcement.

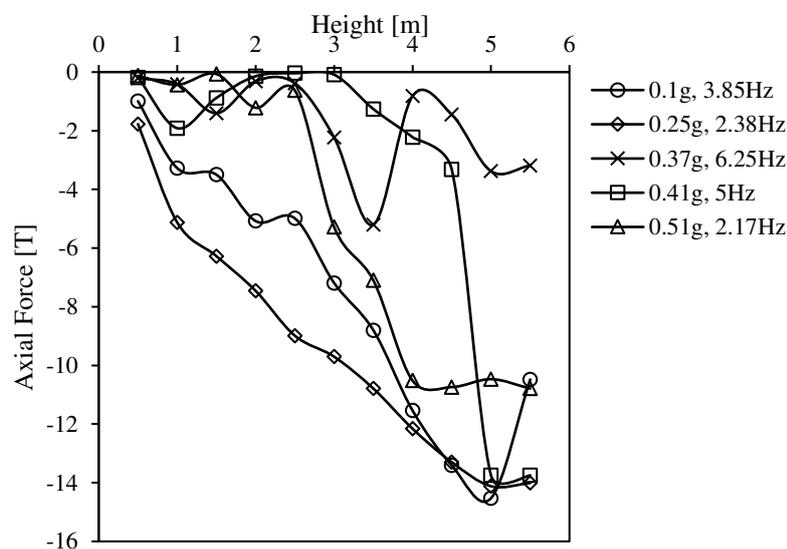


Figure 6. Maximum axial force in the reinforcement at the end of each analysis

7. Conclusions

A two-dimensional MSE wall model is analysed in a 2D explicit finite difference software. The results of the study in terms of horizontal displacement of the wall, settlement of the soil behind the panel, amplification of input motion, and axial force in the reinforcement are determined.

1. The influence of strong-motion parameters such as peak ground acceleration and predominant frequency on the horizontal displacement of the MSE wall is studied. The combined effect of PGA and frequency of motion created a narrow range of horizontal displacement of the wall. The wall displaced more as the PGA of motion is increased.
2. The settlement of soil behind the wall for all the five cases of seismic excitation reveals that at higher frequencies, the backfill and the retained soil surfaces have severely disturbed and large heaving is observed. However, at lower frequencies, the settlement is observed close to the panel and heaving is observed beyond the wall.
3. Amplification of strong motion as the wave propagates through the backfill is studied for all the five seismic excitations. The study divulges that at lower peak ground acceleration, the strong motion propagating through the backfill gets amplified, however, the motion gets attenuated at higher PGAs. The input motion of PGA 0.1g and 0.25g in the present analysis got amplified to a factor of 1.9 and 1.6.

4. Axial force in the reinforcement is large towards the top of the wall and reduces significantly towards the bottom of the wall. However, a disturbing pattern of axial force is observed when the frequency of motion is higher than 5 Hz.

References

- [1] Ling H I, Tatsuoka F and Tateyama M 1995 Simulating performance of GRS-RW by finite element procedure *J. Geotech. Eng.* **121** 4 pp 330–40
- [2] Ling H I, Cardany C P, Sun L X and Hashimoto H 2000 Finite element study of a geosynthetic-reinforced soil retaining wall with concrete-block facing *Geosynthetics International* **7** 3 pp 63–88
- [3] Rowe R K and Ho S K 1997 Continuous panel reinforced soil walls on rigid foundations *Liq. Cryst. Ordered Fluids* **123** 10 pp 912–20
- [4] Karpurapu R and Bathurst R J 1995 Behavior of geosynthetic reinforced soil retaining walls using the finite element methods *Comput. Geotech* **17** pp 279–99
- [5] Elias V, Christopher B R and Berg R R 2001 *Mechanically stabilized earth walls and reinforced soil slopes, design and construction guidelines* Federal Highway Administration (Washington, DC)
- [6] AASHTO 1996 *Standard Specifications for Highway Bridges* 16th Edition (Washington, DC, USA) pp 849-58.
- [7] Kibria G, Sahadat H M D and Khan M S 2014 Influence of soil reinforcement on horizontal displacement of MSE wall *Int. J. Geomechanics* **14** 1 pp 130–41
- [8] Segrestin P and Bastick M J 1991 *Int. J. Rock Mechanics and Mining Sciences & Geomechanics Abstracts* **28** 1
- [9] Liu H 2009 Analyzing the reinforcement loads of geosynthetic-reinforced soil walls subject to seismic loading during the service life *J. Performance of Constructed Facilities* **23** 5 pp 292–302
- [10] Huang B, Bathurst R J and Hatami K 2009 Numerical study of reinforced soil segmental walls using three different constitutive soil models *J. Geotech. Geoenviron. Eng.* **135** 10 pp 1486–98
- [11] Bathurst R J and Hatami K 1998 Seismic response analysis of a geosynthetic reinforced soil retaining wall *Geosynthetics International* **5** pp 127-166
- [12] Darendeli B M 2001 Development of a new family of normalize modulus reduction and material damping curves *Ph. D. Dissertation* Univ. of Texas at Austin p 362
- [13] Ishihara K 1996 *Soil Behaviour in Earthquake Geotechnics* Oxford Science Publications
- [14] Kuhlemeyer R L and Lysmer J 1973 Finite Element Method Accuracy for Wave Propagation Problems *Journal of Soil Mechanics & Foundations* **99** SM5 pp 421-427
- [15] Itasca 2011 *FLAC 2D. Fast Lagrangian Analysis of Continua in 2-Dimensions* Version 7.0 Manual (Minneapolis, MN)
- [16] Lysmer J and Kuhlemeyer R L 1969 Finite Dynamic Model for Infinite Media *J. Engineering Mechanics* **95** EM4 pp 859-877
- [17] Hatami K and Bathurst R 2005 Verification of a numerical model for reinforced soil segmental retaining walls *Geo-Frontiers Congress 20* (Austin, Texas, United States)
- [18] Yu Y, Bathurst R J, Allen T M and Nelson R 2016 Physical and numerical modelling of a geogrid reinforced incremental concrete panel retaining wall *Canadian Geotechnical Journal* **53** 12 pp 1883-90.
- [19] El-Emam M M and Bathurst R J 2007 Influence of reinforcement parameters on the seismic response of reduced scale reinforced soil retaining walls *Geotextiles and Geomembranes* **25** 1 pp 33–49.
- [20] Yu Y, Bathurst R J and Allen T M 2016 Numerical modeling of the SR-18 geogrid reinforced modular block retaining walls *J. Geotech. Geoenviron. Eng.* **142** 5
- [21] Ling H I, Leshchinsky D and Chou N N S 2001 Post-earthquake investigation on several geosynthetic reinforced soil retaining walls and slopes during JiJi earthquake of Taiwan *Soil Dynamics and Earthquake Engineering* **21** 4 pp 297–313