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Parametric, Seismic & Static External Stability Analysis of Mechanically Stabilized Earth Retaining Wall

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Abstract. Mechanically Stabilized Earth (MSE) walls are an alternative engineering structure to traditional reinforced-concrete retaining walls with significant and adaptable height at a lower cost. The main objective of this study is to perform a detailed numerical analysis of the MSE wall considering the effect of parameters such as; reinforced soil, the vertical spacing between reinforcements, the tensile strength of reinforcement, surcharge magnitude, and wall height on the external stability of MSE wall under the static and seismic loading conditions. The analysis has been carried out using the Geo5 numerical tool to obtain the Factor of Safety (FS) against external stability checks. Variations of FS against overturning and sliding for wall-facing and reinforced blocks are compared for various parameters considered in this study. Also, Global Safety Factor (GSF) is analyzed using limit equilibrium methods. From the detailed parametric analysis for external stability of the MSE wall, it has been found that the GFS and the FS against overturning and sliding for wall facing are higher for minimum vertical spacing and greater reinforcement tensile strength. The increased surcharge magnitudes and wall heights reduce the FS. Reinforced soil with well-graded gravel has a significant effect on FS than clayey soil and poorly-graded sand.

Keywords: MSE wall; Factor of Safety; Reinforcement; Over-turning; Sliding; Global stability.

1 Introduction

1.1 Mechanically Stabilized Earth Retaining Wall (MSE Wall)

Reinforced earth-retaining (RE) wall or MSE wall, is a self-stabilized, cost-effective structure that withstands considerably larger differential settlements in comparison with conventional RC (reinforced concrete) retaining walls. The friction between geogrids (synthetic polymer reinforcement) and cohesionless soil keeps the structure in its position, exerting fewer lateral loads on precast panel members. Precast panel members align the structure, and support geogrids and soil mass to maintain the soil mass in position in an equilibrium. MSE walls can retain lateral forces by providing alternative reinforcement layers behind the facing wall, compacted with soil to form an integral part to prevent deformation. The shear stress developed on reinforcement produces tension in reinforcement, which results in the shear strength of the soil and a decrease in soil deformation (Koerner & Koerner, 2013). Some of the pluses of MSE walls with geogrid as reinforcements are their decorative feature, reduce maintenance, simplicity, durability, and rapidity of construction (Reddy & Navarrete, 2008). The types of MSE wall facings and reinforcements used depends on the specific application, soil conditions, and wall height (Kim & Bhowmik, 2012). The construction of an MSE wall is technically more feasible and requires less site preparation compared with a traditional concrete retaining wall (Allen et al., 2001). However, the requirement of site-specific materials, quality control of construction, and performance monitoring plan are considerable factors for the construction. MSE walls can fail due to low-quality fill soil, insufficient reinforcement length and strength, poor drainage quality of the backfill soil and a sudden drawdown of the water table, and weak foundation soil.

1.2 Literature Review

Different studies were carried out by researchers all over the world, to study the MSE wall behavior in varying loading conditions. Movement and stability of the existing MSE wall were studied (Konnur et al 2019) using a finite element (FE) and limit equilibrium (LE) slope stability analysis program GEO5. The effects of soil reinforcement on the excessive movement of the MSE wall were determined (Kibria et al 2014), and the analytical models were analysed to conclude that they are simple and improved tools than the full-scale Gravity Retaining Structure (GRS) wall by lateral movement estimation with modular block facing (Wu et al 2010). The behavior of non-uniform spacing of reinforcement on the performance of footing surcharged MSE Walls using FE analysis was observed (Leshchinky et al 2016). Studies were conducted on the deformation of walls, facing panels, and ground settlement behind them for various types of reinforcements, foundation soil, and backfill, for which the ground settlements were observed to be smaller for steel reinforcements behind the wall, along the horizontal profile (Hulagabali et al 2018a). Observations were made for the effect of backfill and reinforcement on MSE Wall behavior using the FE numerical tool PLAXIS 2D (Hulagabali et al 2018). Different types of foundations like Rammed Aggregate Pier (RAP), pile foundations, and drilled shafts have been involved in analysing the behavior of RE structures. Results show that the wall deformations, ground settlement, and facing panel deflections were less in the drilled shaft than in the RAP and pile foundation (Hulagabali et al 2018b). FLAC 3D was used for the numerical simulation to know the interaction between the drilled shaft and MSE wall, under a cyclic loading event, resulting in the gradual accumulation of the displacement (Huang et al 2019). The distance between the walls in synthetic and metallic strips influences the interaction between back-to-back reinforced walls (Lajevardi et al 2021). Back-to-back MSE walls are commonly used for embankments in bridges (Han, Leshchinsky, 2010). The shaking table tests conducted on the single-tiered and multi-tiered MSE walls were observed to demonstrate all seismic response characteristics exhibiting a better dynamic behavior in multi-tier MSE walls compared to single-tier walls (Safaee et al 2021).

Even after numerous researches, there is a gap in the MSE wall parametric understanding. Thus, this study is carried out to model MSE walls using the Geo-5 and check for external stability by varying the parameters such as., the vertical spacing between reinforcements (S_v), reinforced soil, surcharge magnitude (q), and wall height(H) on the external stability of MSE wall under the static and seismic loading conditions.

2 Methodology

2.1 Analysis of MSE Wall using GEO-5

A 3-dimensional analysis of the MSE wall is carried out using Geo-5 software based on the FE method. Numerical analysis is initialized by creating a model of suitable dimension followed by assigning material properties as per the research design (Fig.1).

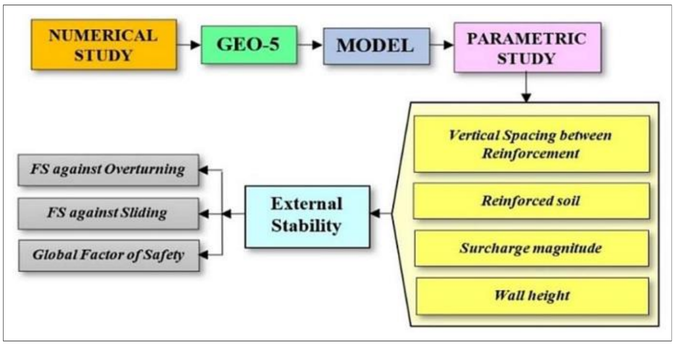


Fig.1. Research design considered for the numerical study

2.2 Input Parameter

The total wall height considered for this analysis is 12m with 60 blocks, block height 0.2m, block width 0.5m, block offset 0.5m, foundation height 0.5m, foundation width 1.5m, and foundation offset 0.5m. For this study, S_v is taken as 0.05H, the length of reinforcement is 0.7H (H=12m) with a tensile strength of T_{Ult} = 138.60 KN/m and a surcharge of 25 kPa is considered. Dimensions of modular blocks and foundations are kept the same. Backfill is taken to be well-graded sand (SW). A permanent load is considered along with a horizontal wall backfill. Fig. 2 and 3, represent the 2-D and 3-D views of the MSE wall. Table 1, shows the soil properties of backfill, foundation, and reinforced soil types considered for the analysis. Table 2, represents the S_v details for a 12m wall considered.

2.3 Seismic and Static Analysis

Analysis of MSE walls is carried out for both static and seismic conditions as the walls may be constructed in earthquake-prone areas, where earthquake magnitude may be very high. The pseudo-static analysis is considered with varying vertical and horizontal coefficients of earthquake (k_v and k_h) to consolidate the seismic loading. The seismic coefficients are dimensionless parameters, which represent the acceleration of earthquake as a fraction of acceleration due to gravity. Seismic force is the product of seismic coefficient and block weight (obtained by the area and unit weight of the block). As per AASTHO recommendations, the minimum FS against overturning failure for static loading is 1.5 and 1.125 for seismic loading conditions. Parameters considered to study external stability analysis of the structure under seismic and static conditions are S_v, reinforcement soil, q, and H.

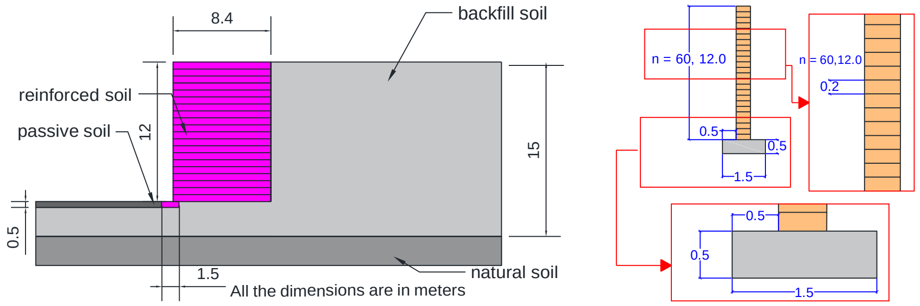


Fig. 2. Two-dimensional schematic view of the model (from left to right respectively), with dimensions in meters, considered for analysis

Fig.3. Three-dimensional schematic view of the model

Table 1. Properties of various soils considered for the analysis.

Soil properties	Units	GW	GM	SW	SM	SP	CL
Unit weight (γ)	kN/m^3	21	19	20	18	18.5	21
Internal friction angle (φ)	degree	38.5	32.5	36.5	29	33.5	19
Cohesion (c)	kN/m^2	0	0	0	5	0	12
Friction angle structural soil (δ)	degree	25.67	25.67	24.33	19.33	22.33	12.67

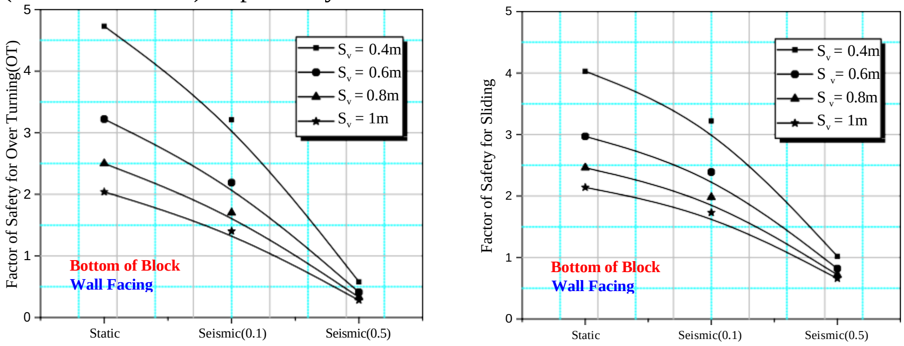
Table 2. Vertical spacing details for a 12m wall.

Vertical spacing (m)	0.4	0.6	0.8	1
No. of layers	30	20	15	12

3 Results and Discussions

3.1 The Factor of Safety (FS) against Overturning and Sliding

Effect of Vertical Spacing of Reinforcement. Four variations of S_v are used in this study i.e. 0.4m, 0.6m, 0.8m, and 1m with a wall height of 12m(Fig. 4&5). The FS against overturning and sliding [Fig. 4(a)&(b)] of the wall facing, decreases with an increase in S_v from 0.4m to 1m by about 58%, 56%, 66% and by about 45%, 47%, and 40% for static and seismic conditions (k_h=k_v= 0.1 & 0.5) respectively. The GSF of retaining wall for various S_v (Fig. 5) varies accordingly, with an increase in S_v from 0.4m to 1m by about 13%, 15%, and 90% GSF decreases from static to seismic conditions (k_h=k_v= 0.1 & 0.5) respectively.



(a) (b)

Fig. 4. FS against (a) overturning and (b) sliding (S_v variation).

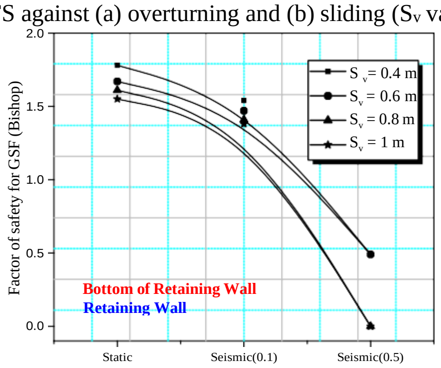
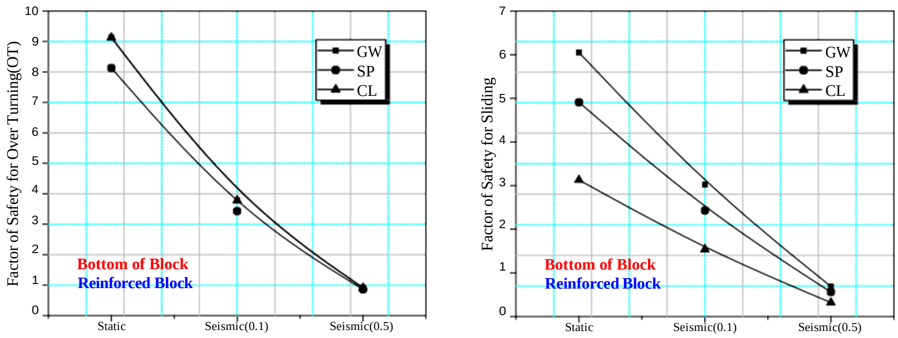


Fig. 5. Variation of GSF for different vertical spacings of reinforcement (S_v).

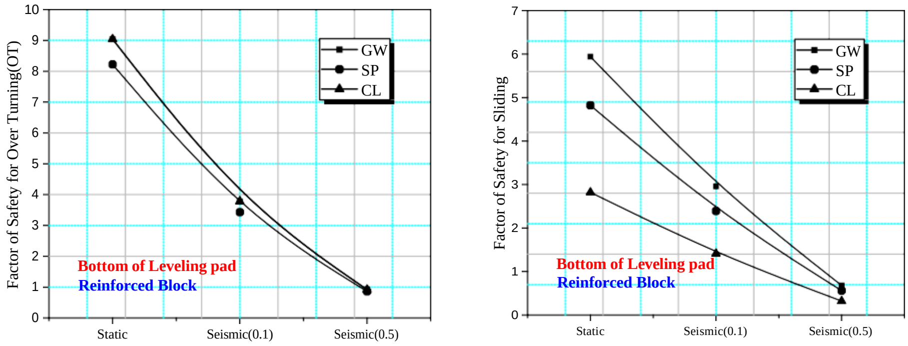
In general, overturning and sliding resistances, along with the global safety factors of the wall facing for minimum S_v, are higher and reduce along with seismic effect. Thus, the MSE wall is safer for static conditions, but for seismic zones, other methods of stabilizing the wall against earthquakes can be implemented and more reinforcements can be provided with lesser spacing between them as a remedial measure.

Effect of Reinforced Soil. For this analysis, reinforcements of length, L=0.7H (8.4m), and different reinforced soil such as well-graded gravel (GW), silty sand (SM), and clayey soil (CL) are considered (Fig. 6-9).



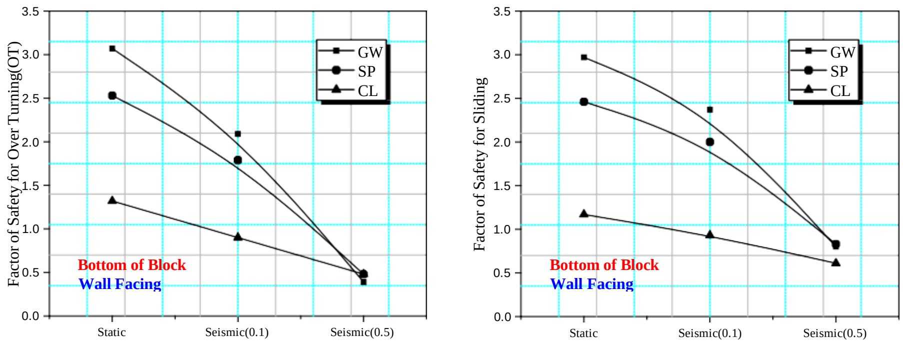
(a) (b)

Fig. 6. FS against (a) overturning and (b) sliding (Reinforced soil property variation) at the bottom of the block.



(a) (b)

Fig. 7. FS against (a) overturning and (b) sliding (Reinforced soil property variation) at the bottom of levelling pad.



(a) (b)

Fig. 8. FS against (a) overturning and (b) sliding of the wall facing (Reinforced-soil property variation).

The pattern of FS against overturning of the reinforced block at the bottom of the reinforced block and bottom of levelling pad respectively is shown for soils GW, SP, and CL (Fig.6(a) & 7(a)), where the FS against overturning decreases from static to seismic conditions (k_h=k_v= 0.1 & 0.5) and deviates by about 86%. It has no significant variations for GW and SP but decreases further for CL. The FS against sliding, however (Fig.6(b)&7(b)), decreases from static to seismic conditions (k_h=k_v= 0.1 & 0.5) with a deviation of about 16.6% and 50.2% between GW alongside SP, and GW with CL respectively. The FS against overturning and slilding[Fig. 8(a)&(b)] of the wall facing at the bottom of the reinforced block for soils considered (GW, SP&CL) decreases from static to seismic conditions (k_h=k_v= 0.1 & 0.5) by about 84% for overturning, however, the variation is of about 21% and 53% between GW alongside SP, and GW with CL respectively for sliding. Fig. 9., represents the variation of GSF of the retaining wall at the bottom of the reinforced block (for GW, SP, &CL), where the FS decreases with seismic activity by about 12%, and 68% for static and seismic conditions (k_h=k_v= 0.1 & 0.5) respectively.

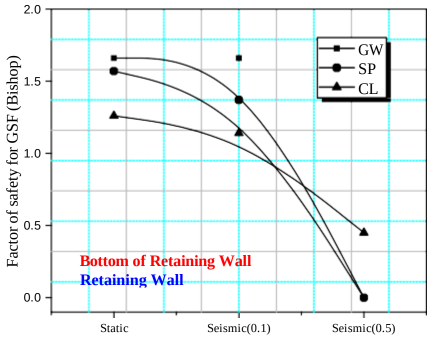
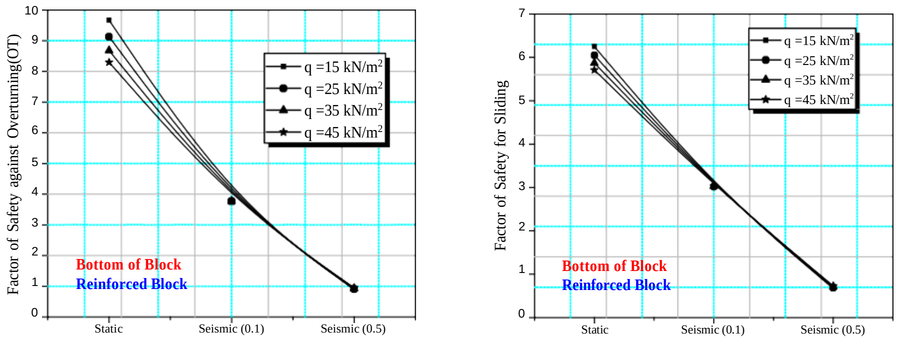


Fig. 9. Variation of GSF (Reinforced soil property variation).

In general, FS against overturning and sliding is maximum for GW and is considerably less for SP but is minimum for CL. Also, the global factor of safety of the wall follows the same trend. Even though the structure is within safe limits in static conditions, it turns out to be unsafe for seismic conditions, especially for zones with earthquake coefficient near 0.5, where other methods of stabilizing the wall against earthquakes should be used and more reinforcements of greater tensile strength and GW soil can be used for the reinforced block but if it is not available well-graded soil can be used. As a remedial measure, CL is avoided as reinforced soil if inevitable it can be improved or completely replaced.

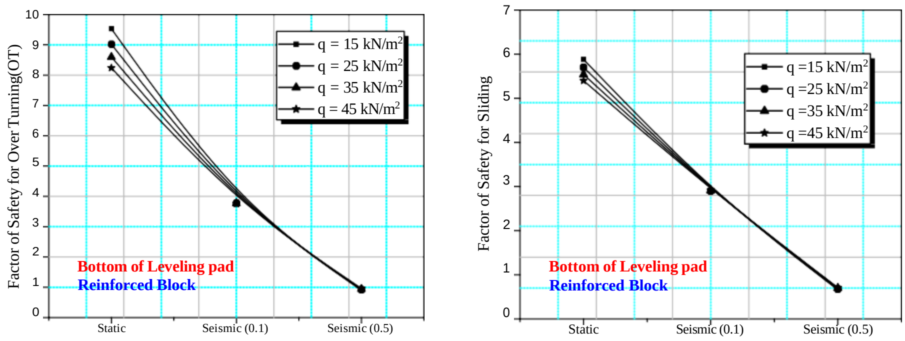
Effect of Surcharge. Surcharge loads considered (q in kN/m^2) are applied on the upper surface of the reinforced block with magnitudes of 15 kN/m^2, 25 kN/m^2, 35 kN/m^2, and 45 kN/m^2 (Fig. 10-13). The FS against overturning and sliding [Fig.10(a)&(b)] of the reinforced block at the bottom of the reinforced block for various surcharge values, where with an increase in q, from 15 to 45 kN/m^2 a decrement of FS of about 16% and 12.5% for static conditions is observed but no significant variations are noticed with the change in surcharge values for seismic conditions.

The FS against overturning and sliding [Fig.11(a)&(b)] of the reinforced block at the bottom of levelling pad, where with an increase in q, from 15 to 45 kN/m^2 FS declines by about 15.4% for overturning and by about 10.8% for sliding for static and there are no significant variations observed for seismic conditions (k_h=k_v= 0.1 & 0.5) with the change in surcharge values.



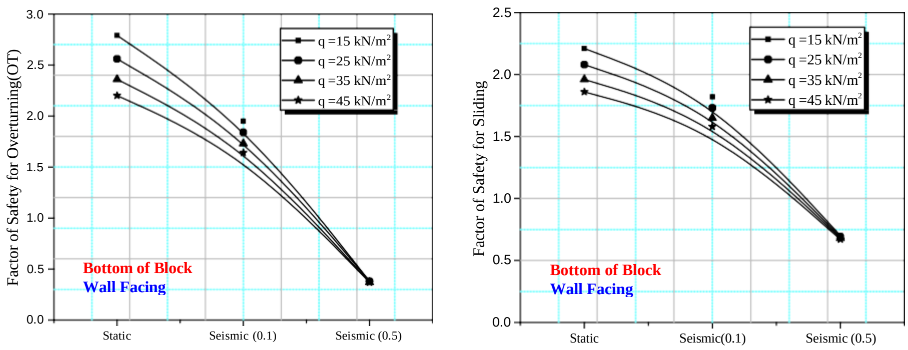
(a) (b)

Fig. 10. FS against (a) overturning and (b) sliding at the bottom of the block (variation of q).



(a) (b)

Fig. 11. FS against (a) overturning and (b) sliding at the bottom of levelling pad (variation of q).



(a) (b)

Fig. 12. FS against (a) overturning and (b) sliding of the wall facing (variation of q)

The FS against overturning and sliding [Fig.12(a)&(b)] of the wall facing at the bottom of the reinforced block, signifies that as q climbs from 15 to 45 kN/m^2, FS declines by about 21.4% for static and 20% for seismic conditions (k_h=k_v= 0.1) for overturning and by about 20% for static and 11% for seismic conditions (k_h=k_v= 0.1) for sliding respectively. Whereas, q becomes insignificant at k_h=k_v= 0.5 seismic condition.

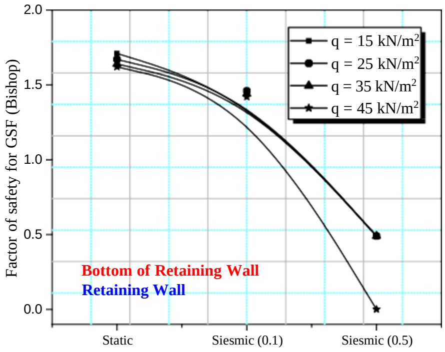


Fig. 13. Variation of GSF for a different surcharge, q

Fig. 13, shows the variation of FS against slope stability of the retaining wall at the bottom of the reinforced block, where the FS against overturning decreases with an increase in q, from 15 to 45 kN/m^2 by about 8%, 3.3%, and 98% for static and seismic conditions with earthquake coefficient of 0.1 and 0.5 respectively.

In general, with the increase in magnitudes of surcharge FS against overturning, sliding, and GSF of the wall facing and reinforced block decreases. Thus, the MSE wall is safer for static conditions, but for seismic zones, other methods of stabilizing the wall against earthquakes can be implemented like introducing more reinforcements with lesser spacing between them and using GW (even soils with higher friction angle) for the reinforced block as a remedial measure for a long run.

Effect of Wall Height. For this analysis, six wall heights of 2m, 4m, 6m, 8m, 10m, and 12m are considered (Fig. 14-17). The FS against overturning and sliding [Fig 14(a)&(b)] of the reinforced wall, at the bottom of the reinforced block for wall heights, H in m, signifies that an increase in H, from 2-12m brings a declination of FS by about 96%, 90%, 82% for overturning and about 77%, 62.5%, 50% for sliding for static and seismic conditions with earthquake coefficient of 0.1 and 0.5 respectively.

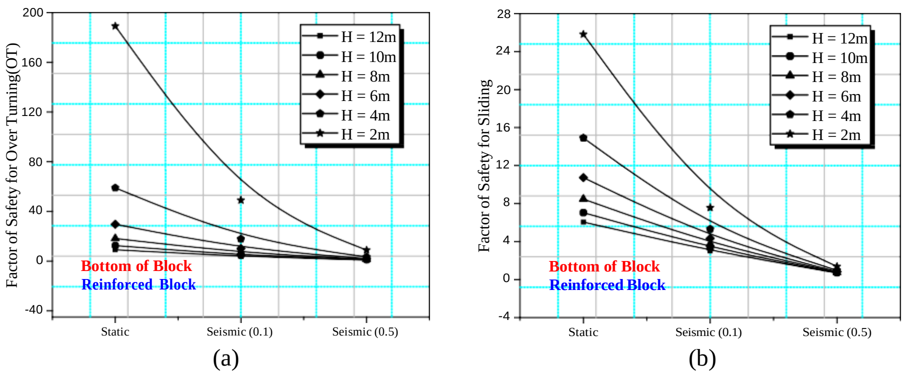
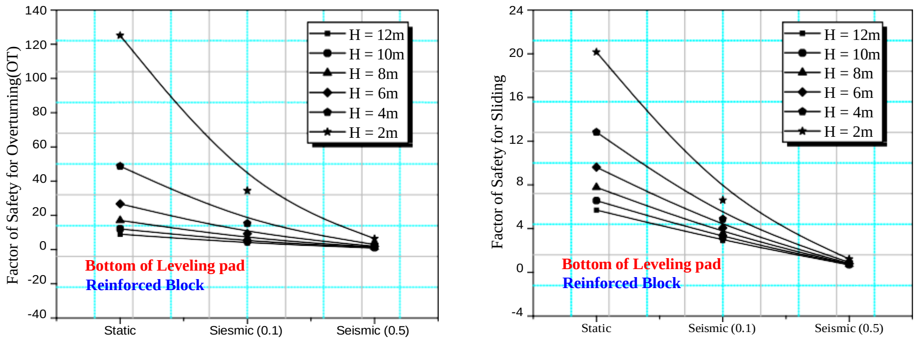
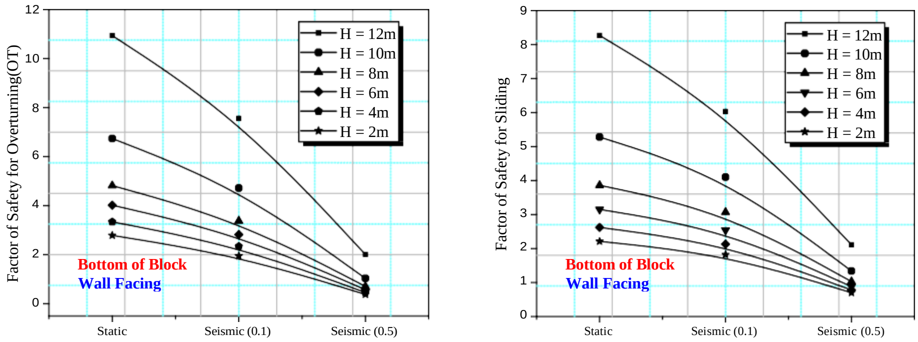


Fig. 14. FS against overturning (a) and sliding (b) at the bottom of the block (variation of H in m).



(a) (b)

Fig. 15. FS against overturning (a) & sliding (b) at bottom of levelling pad (variation of H in m)



(a) (b)

Fig. 16. FS against (a) overturning and (b) sliding of the wall facing (variation of H in m).

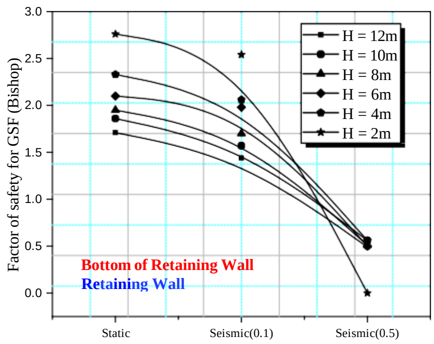


Fig. 17. Variation of GSF for different wall heights, H in m.

The FS against overturning and sliding [Fig 15(a)&(b)] of the reinforced wall at the bottom of levelling pad, for H, represents the FS decreasing as H climbs from 2 to 12m by about 92%, 83%, 80% for overturning and by about 72.5%, 57%, 51% for sliding for static and seismic conditions with earthquake coefficient of 0.1 and 0.5 respectively.

The FS against overturning and sliding [Fig 16(a)&(b)] of the wall facing at the bottom of the reinforced block, indicates the decline in FS with a raise in H, from 2-12m, by about 74.5%, 73.3%, 70% for overturning and by about 74.6%, 70%, 65% for sliding for static and seismic conditions with earthquake coefficient of 0.1 and 0.5 respectively.

Fig 17, shows the variation of FS for GSF of retaining wall for wall heights, H in m, at the bottom of the reinforced block, where the GSF decreases with an increase in H, from 2 to 12m by about 39.5% and 42% for static and seismic conditions with earthquake coefficient of 0.1 respectively, as for earthquake coefficient of 0.5 there is an increase of 84% with the increase in H, from 2 to 12m signifying the effect of lateral stresses of the earthquake.

In general, with the increase in magnitudes of wall height, H, the factor of safety against overturning, sliding, and GSF of the wall facing and reinforced block decreases. Thus, the MSE wall is safe for static conditions, but for seismic conditions, especially for zones with earthquake coefficient of around 0.5, other methods of stabilizing the wall against earthquakes should be used and optimum wall heights can be considered for construction as a remedial measure.

4 Conclusion

The conclusions of the study are as follows:

- FS overturning and sliding of the wall facing for a greater number of reinforcements (minimum S_v) are higher and reduce with seismic effect. Global safety factors are also higher for minimum S_v.
- FS against overturning, sliding, and global factor of safety is maximum for GW than SP but is exceptionally lower for CL.
- With the increase in magnitudes of surcharge factor of safety against overturning and sliding of the wall facing and reinforced block decreases.
- FS against overturning and sliding of reinforced block for greater wall heights are higher and reduces with seismic effect.

Thus, the parameters involved affects the stability of the MSE wall in various ways. Optimization of cost and design life period plays the key role in deciding the vertical spacing between reinforcements, their tensile strength, reinforced soil type, surcharge, and the optimum wall height. These are obtained by thorough investigation of the construction site and detailed design in the allotted budget. So, the parametric study is crucial for the initial investigation and further construction procedures.

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