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Parametric Study of Mechanically Stabilised Earth Wall using PLAXIS

Arshika Tomar[1], Jagdish Lohar[2] and Neha Shrivastava[3]

[1] Department of Civil Engineering, Malaviya Institute of Technology, Jaipur, Rajasthan, India, 302017
[2] Department of Civil Engineering, Malaviya Institute of Technology, Jaipur, Rajasthan, India, 302017 ORCID: 0000-0002-0177-6471
[3] Department of Civil Engineering, Malaviya Institute of Technology, Jaipur, Rajasthan, India, 302017 ORCID: 0000-0002-9742-4250

neha.ce@mnit.ac.in

Abstract. Mechanically stabilised earth (MSE) walls made of steel and geosynthetic reinforcing elements are now well-established technologies. MSE walls have been increasingly used in many civil engineering projects over the last 25 years as it offers economical and technical advantages over conventional retaining walls. However, the agencies using the MSE wall are now concerned about its failure. This study is intended to presents a parametric investigation on a validated finite element model of an MSE wall to evaluate the effect of geogrid length, strength, and soil friction angle on wall displacements. In PLAXIS 2D, a total of 120 permutations are modelled by varying geogrid length, strength, and soil friction angle, while wall geometry, boundary conditions, water table, and loading conditions kept constant for all cases. On the basis of the results of this parametric study, charts are constructed to demonstrate how the extreme displacement of the MSE wall is affected by various factors. The outcomes of this parametric analysis offer insights about the behaviour of an MSE wall and important reference information for comprehending the design procedure and specifications for any MSE wall.

Keywords: MSE wall; PLAXIS 2D; Parametric analysis

1. Introduction

A mechanically stabilised earth wall is defined as a composite retaining structure consist of alternate layers of fill in compacted form and reinforcing elements secured to a wall facia, as shown in Figure 1 [1]. The stability of the whole wall comes from how the backfill soil and reinforcements interact with each other. This involves friction and tension [2,3]. It results into an internally stabilised coherent gravity structure which is flexible which can support a variety of heavy loads and tolerate large differential settlements without causing structural damage [4–6]. Over the last 25 years, MSE retaining walls have become more common in many civil engineering projects. MSE walls are preferred over conventional types of retaining walls (e.g., Gravity, Semi-Gravity, Cantilever, and Counterfort) as it offers economic and technical advantages, including less site preparation and foundation requirements, diminution of acquisition of land for right-of-way, faster construction rate, sustainability in construction and stability for wall of heights more than 30 m [7–10].

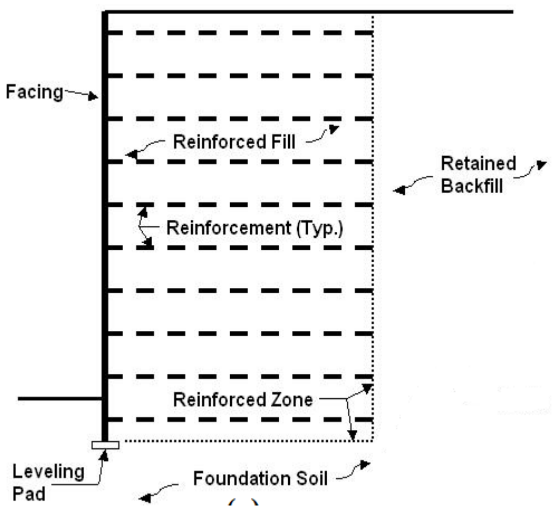

Figure 1. Components of MSE wall (modified after Berg et al., 2009)

The positive effects of soil reinforcement in an MSE wall come from the enhanced tensile strength of the soil and the enhanced shear resistance caused by friction at the interfaces between soil and geogrid. Two types of reinforcements are utilised in MSE walls: extensible and inextensible. In comparison to the soil's deformability, inextensible reinforcements exhibit substantially less deformation upon failure. Inextensible reinforcement includes materials like steel strips and bar mats. In contrast, extensible reinforcements exhibit deformation upon failure that is comparable to, or higher than, that of the soil. Materials such as geogrids, geotextiles, and woven steel wire mesh are all examples of extensible reinforcements.

Various computer programs by using numerical equations based on finite element (FE), finite difference or limit equilibrium were developed and employed for better understanding of the behaviour of MSE walls [11–13]. FLAC, MSEW, ReSSA and PLAXIS are such popular computer programs which can be used for numerical simulation and analysis of MSE walls.

Many parametric studies using such programs were also carried to get insights into the design and behaviour of MSE walls with different geometries, materials and loading conditions [13–20].

In a study conducted by Kenneth et al. [19], PLAXIS, a finite element programme, and UTEXAS4, a limit equilibrium programme, were used to examine stresses and stability of MSE retaining walls. The FE model was created for the wall. Several parametric studies were conducted in which the wall's properties, backfill-wall interaction, and soil's constituent parameters were investigated. On the basis of these findings, a FE model was created to examine the impacts of aspect ratio of wall on the vertical and horizontal stresses on the MSE Wall. In order to assess the impact of wall aspect ratio on the stability of MSE walls, limit equilibrium analysis was carried out. The impacts of wall aspect ratio were investigated in terms of factor of safety (FOS) parameters, expressed in terms of both soil shear strength and reinforcing strength. Bilgin et al.[21] looked into the primary failure mechanism that was used to determine the required reinforcement length and explored the possibility of reducing the minimum reinforcement length requirements. The influence of design factors on minimum reinforcement length and governing failure mode for reinforced soil retaining walls was also investigated. A variety of factors, such as surcharge, wall height, reinforced soil qualities, reinforcement vertical spacing, backfill soil properties, and foundation soil properties, were taken into account. On the basis of finding, it was suggested that the minimum length of reinforcement needed to prevent wall failure can be determined by either the wall's external or internal failure mechanism. Further, reinforcing lengths may be reduced to approximately half the wall height, from the standard 0.7 times as needed by various agencies worldwide. Yadhunandan et al. [20] predicted the behaviour of MSE walls of different heights (5 metres, 10 metres, 15 metres, and 20 metres) by varying the parameters such as berm width; foundation and backfill soil strength; spacing, strength, and stiffness of reinforcement; surcharge on reinforced backfill using PLAXIS 2D. For an MSE wall of any height to operate well, it was observed that suitable backfill soil should be put on the foundation soil. On weak foundation soil weak backfill soil is more suitable, on medium foundation soil medium backfill soil is more suitable and on good foundation soil good backfill soil is more suitable.

Using the finite element numerical programme PLAXIS 2D, Hulagabali et al. [15] analysed the impact of backfill and reinforcement on the behaviour of MSE walls. Soil parameters, including friction angle and retained and foundation soil unit weight, were studied to determine their effects on wall deformations. Deformations of walls are observed to be decreasing as friction angles of foundation soils are raised. Also, it was seen that, length of the reinforcements has significant effect on wall deformations. Deformations were reduced as the length of reinforcements increased. Hulagabali et al. [15] used the PLAXIS 2D to analyse the reinforced wall with different types of geogrids. Different types of soil were used for the backfill and the foundation, including sand, gravel, silt, and clay. Wall deformations, settlement behind the wall, and deformations of facing panel were observed for different types of reinforcements, backfill, and foundation soil. In the study, it was found that steel reinforcements behind the wall have less ground settlement along the horizontal profile. HDPE and steel reinforcements performed better than PET Geogrid because they deform and settle less than PET Geogrid. Gravel was found to have less of an effect on wall deformation because it drains well. Even the settlements behind the wall were found to be lesser for gravel material. As a result, it is used as a reliable backfill and foundation material. Evaluation of the impact of surcharge loads on MSE wall behaviour was also done. Deformations were seen to be lower for surcharge loads of smaller magnitude. Mahmood T. [17]performed research on a failing MSE retaining wall in Rockville, Maryland to identify the causes, patterns, and modes of collapse. By comparing the outputs with actual failed walls, the author calibrated the FE model.

Many parametric studies were conducted by using various finite element computer programs. Though, the parametric studies on experimentally validated models are limited. This paper presents a parametric study on a validated finite element model of a MSE wall to assess the influence of geogrid length, their strength and friction angle of soil on wall displacements. A total of 120 combinations are modelled in PLAXIS 2D by varying geogrid length, strength and friction angle of soil while wall geometry, boundary conditions, water table and loading conditions are kept constant for all cases.

2. Finite element modelling

The numerical modelling and analysis of the MSE wall are carried out using the 2-D FE programme PLAXIS. Using points, lines, and other XY-plane elements, a 2-D geometry model is produced. The properties of the materials and the boundary conditions are defined, and then a FE mesh is built to carry out a FE analysis using PLAXIS. Water pressures and effective stresses are generated as the final step in the input process, which establishes the initial state.

In this paper, FE model uses plain strain type analysis. For shapes having uniform cross sections, plain strain model is usually used. It is assumed that there are no strains or displacements in the z-direction. However, normal stresses acting in z-direction are considered in analysis. In PLAXIS, either 6 noded or 15 noded triangle element can be used during modelling. The 15-noded element is used in the present study for the better accuracy for the calculation of stress and deformations at each point. Once the calibration of model is done, parametric study is conducted. The units, model and element used are summarised in Table 1

Table 1. Model, unit and elements used

Type	Unit	Model	Plain strain
Time	day	Element	15-Noded
Force	lb		
Length	ft		

2.1. Properties of materials and geometry of wall

Inputting the soil parameters into PLAXIS can be done with a number of different models. The Mohr-Coulomb model is used in this study. A Mohr-coulomb model needs five key input parameters: Elastic modulus (E), cohesion (c), friction angle (φ), Poisson's ratio (ν) and dilatancy angle (ψ). To calibrate the model, two soil types, one for reinforced fill and another for foundation are defined in the present study and their properties are shown in Table 2 which are taken from the study by T. Mahmood (2009). PLAXIS can deal soils with zero cohesion value, whereas few options may not perform well. Therefore, to avoid error in computations, a small value of cohesion is generally used in previous studies (Gurung, M., 2020, Bahera et al.,2016 and Pour et al., 2019). In the current study, all cases in the analysis were conducted with a very low magnitude cohesion equal to 1 lb/ft^2**.**

Table 2. Input Parameter for Mohr-Coulomb Model in present study (After Mahmood, T. [17])

Mohr-Coulomb		Fill	Natural
Type of soil		Drained	Drained
γ_{unsat}	[lb/ft^3]	130	120
γ_{sat}	[lb/ft^3]	130	120
K_x	[ft/day]	3.28	0.003
K_y	[ft/day]	3.28	0.003
E_{ref}	[lb/ft^2]	48000	84000
ν	[-]	0.3	0.35
c_{ref}	[lb/ft^2]	1	1
φ	[o]	24	32
ψ	[o]	0	2
$R_{inter.}$	[-]	0.67	1

'Plate' element was used for modeling of MSE wall facing units. At each node, it has rotational degree of freedom (DOF) as well as x- and y-translation DOF. These plate elements are capable to sustain axial forces. The blocks have depth of 8 inch except the top block which has 4 inch depth. The characteristics of both the block are shown in table 3 which are defined and assigned to respective plates. At the base of facial wall, a levelling pad is also given using the 'plate' element. The width of the levelling pad is maintained at 2 feet and is modelled by a plate element; the material attributes of the pad allocated to the plate element are shown in Table 3.

Table 3. Parameters of plates used in the analysis (after Mahmood, T.[17])

No.	Identification	EA [lb/ft]	EI [lbft^2/ft]	W [lbft/ft]	ν
1	4 inches block	2.48 x10^8	2.29 x10^6	259.55	0
2	8 inches block	4.96 x10^8	1.84 x10^6	259.55	0
3	Footing	4.15 x10^8	8.63 x10^6	72.5	0

Geogrids are capable of bearing tensile forces. These were modelled using 'geogrid' elements owning only one (axial) DOF at each node which cannot withstand compression. The axial stiffness of geogrid is taken as 1900 lb/ft^2 and poisson ratio is considered zero.

In PLAXIS 2D, in the interface (R_{inter}), the interaction between geogrid and soil is modelled by taking an appropriate value of the strength reduction factor. In the current study, R^{inter} equal to 0.67 is used while inputting the parameters for fill soil [17]. The modelling configuration, boundary conditions and used for simulation and analysis of MSE wall is shown in Figure 2. This geometry and boundary condition as well as the loading conditions were maintained same throughout the whole study program. Once the model is calibrated, the same model is used during the parametric study.

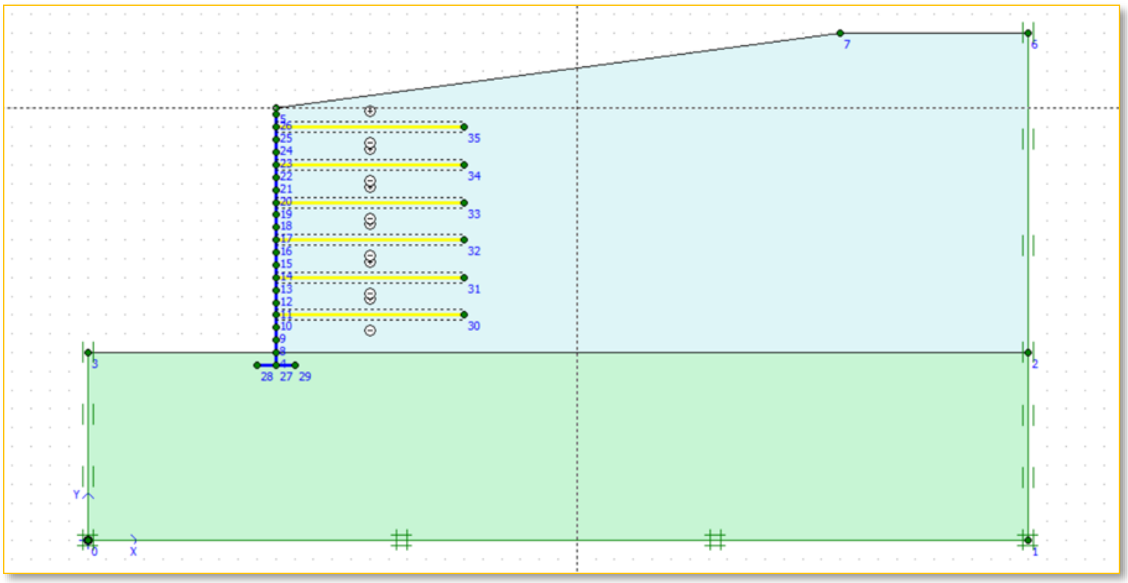

Figure 2. Geometry, boundary conditions, and loading conditions in the present study

All structural elements and clusters had their model geometry and material properties defined and assigned. After that, the model is broken up into finite elements so that FE calculations can be done. During the numerical modelling and calibration of model, water level was considered at mid depth. The water pressure is generated using phreatic levels for a groundwater flow scenario. Effective initial stress analysis in PLAXIS is performed using the K^0 technique. Figure 3 depicts the outcome after the creation of early effective stress.

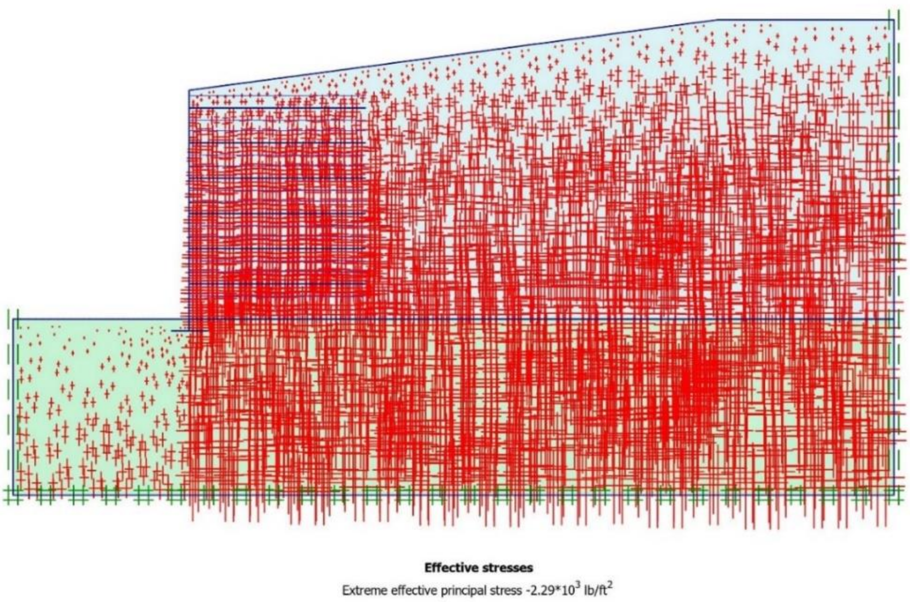

Figure 3. Effective stress distribution within MSE wall

After generating the effective stress and pore water pressure, the stability analysis of the wall is done automatically by PLAXIS. In analysis, the wall failed. The result is shown in the Figure 4.(a)

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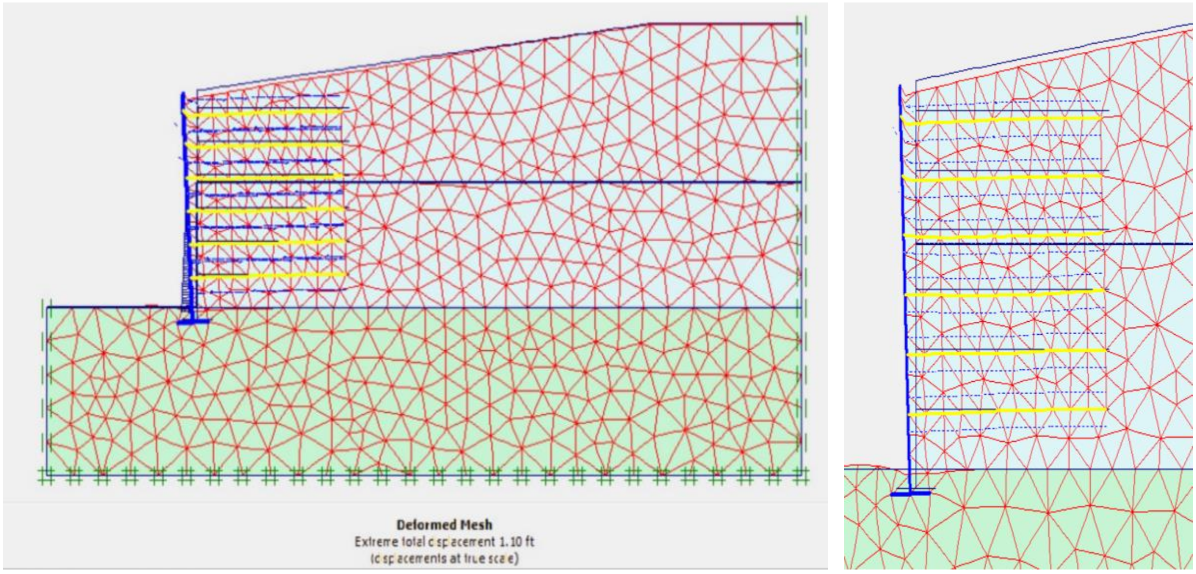
representing the deformed mesh. The extreme displacement in the MSE wall was 1.10ft. Figure 4.(b) shows a closer look at the deformed mesh.



(a) (b)

Figure 4. (a) Deformed mesh (b) Zoom in view of deformed mesh

2.2. Model Verification

The input data set for geometry and materials properties were taken from a study conducted on a failed MSE retaining wall located in Rockville, Maryland by Mahmood, T. [17]. Author investigated the possible cause, pattern and mode of failure by using a computer program PLAXIS after validation of the modelled wall by comparing it with the field wall. The results of the model simulation were similar to what was seen in the field wall.

In the present study, a MSE wall is modelled with the geometry and material properties as in the study by Mahmood, T.[17] using the same computer program PLAXIS. The results of the model in present study are consistent and comparable to the results presented by Mahmood, T. (2009) as shown in Table 4.

Table 4. Comparison of results of present study with the study by Mahmood, T.[17]

Parameters	Mahmood, T. (2009).	Present study
Active pore pressure (lb/ft^3)	1.08 x 10^3	1.11 x 10^3
Effective stresses (lb/ft^3)	2.26 x 10^3	2.29 x 10^3
Total displacement (ft)	1.27	1.10
Horizontal displacement (ft)	1.02	0.96
Vertical displacement (ft)	0.803	0.60

The reason behind the adoption of same model parameters as used in Mahmood, T. [17] is to validate the model to be used in present study for a parametric study to analyse the effects of variation in friction angle of fill, length and strength of geogrid on extreme displacements of a MSE wall.

2.3. Parametric study

After the model has been validated, parametric investigations are carried out using PLAXIS while maintaining the geometry, boundary, and water level constant. Main parameters which are responsible for the failure of MSE Wall i.e., properties of the geogrid and properties of the backfill are analysed in this study. A total 120 different combinations are studied by varying the geogrid length, their tensile strength and friction angle of backfill soil as presented in Table 5.

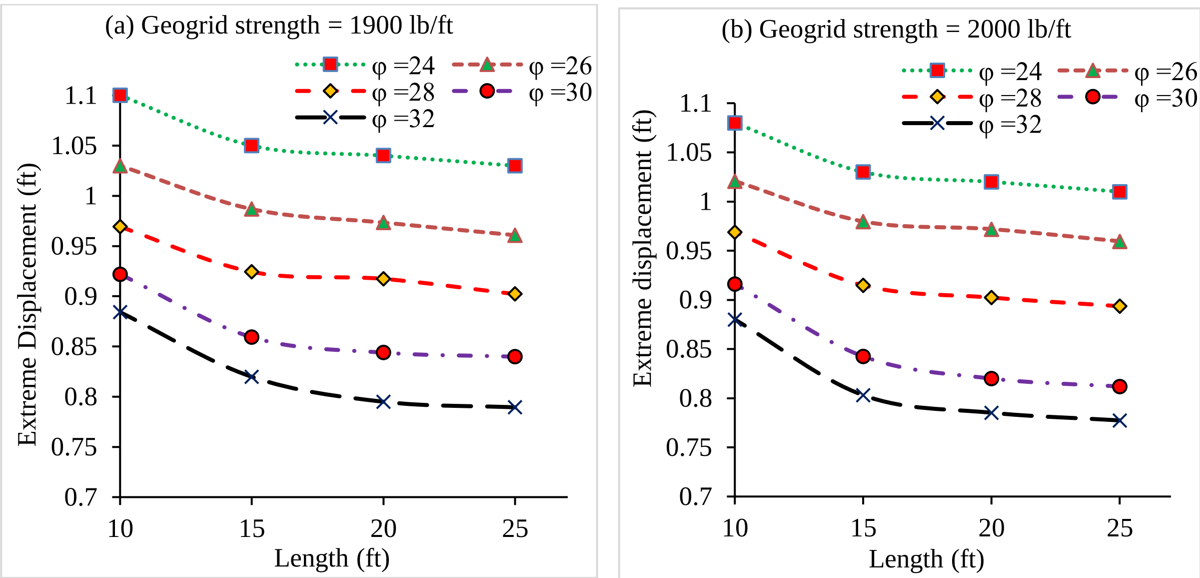
Table 5. Different Parameters and their value used in the analysis

Parameters	Value
Grid Length (ft)	10 15 20 25
Grid strength (lb/ft)	1900 2000 2400 2800 3200 3600
Friction Angle (Degree)	24 26 28 30 32

3. Result and discussion

3.1. *Effect of geogrid length*

Figure 5 shows the effect of geogrid length on extreme total displacement for the model wall with different geogrid strengths, where geometry, boundary conditions, water level, loading condition, facing and foundation properties were kept same. It is noticed that as the geogrid's length increases, the extreme displacement reduces, whereas the decrease in the displacement is significant only up to 15ft thereafter with increase in length, the reduction in extreme displacement is insignificant. This may be attributed to the wall height as the requirement of reinforcement is suggested up to 0.7 times the height of wall [1]. Similar relationship between extreme total displacement and geogrid length was observed when geogrid strength and friction angle of reinforced soil were varied.



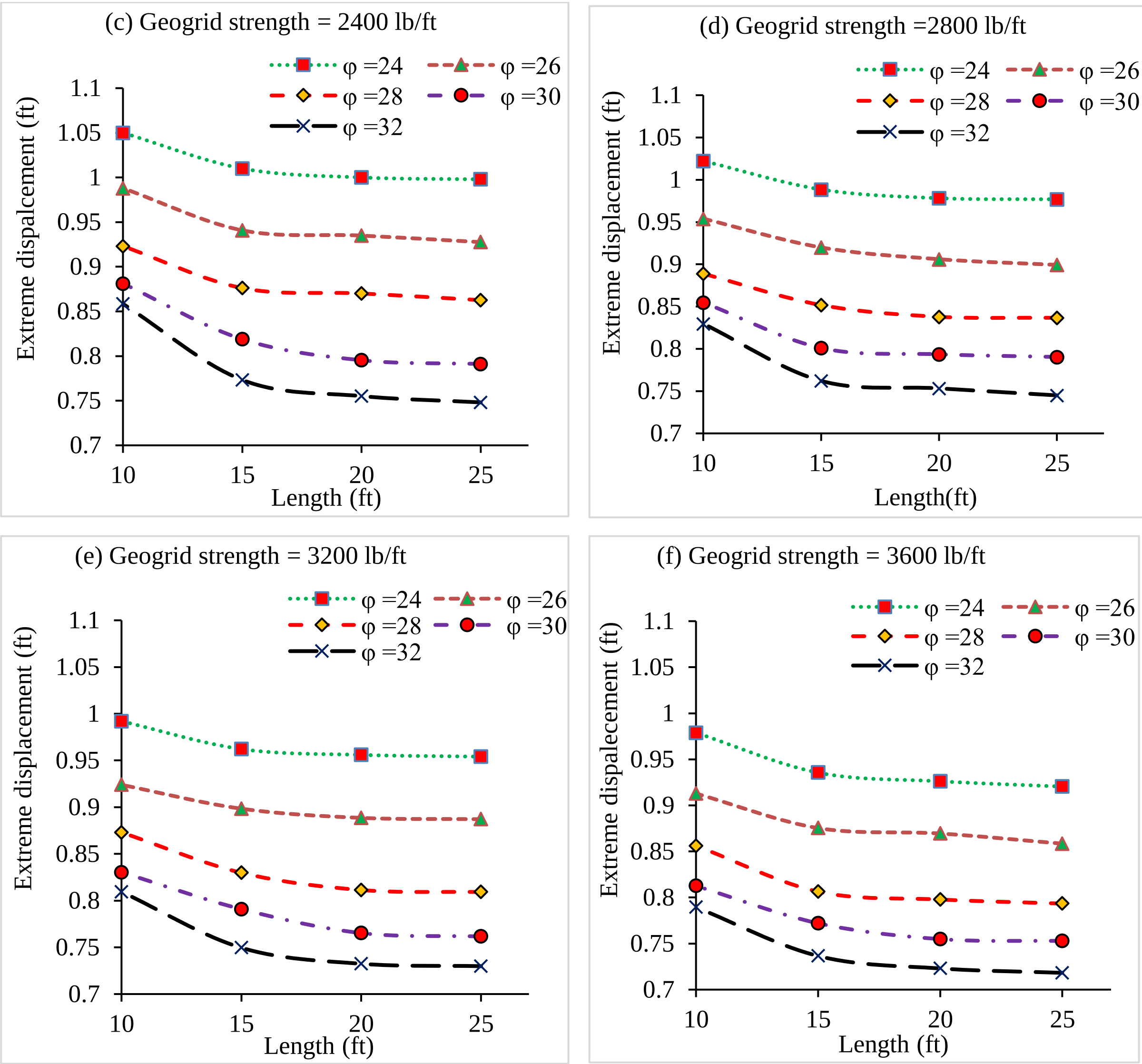


Figure 5. Effect of geogrid length on extreme displacement

3.2. *Effect of geogrid strength*

Figure 6 illustrates how the geogrid's strength affected the extreme displacement at various friction angle values, where geometry, boundary conditions, water level, loading condition, facing and foundation properties were kept same. It can be inferred from the graphs that for all the friction angles, with increase in the geogrid strength, extreme displacement reduces. It makes sense, since the pull-out stress of geogrid goes up as the strength of the grid goes up. So, it takes more force to move the geogrids from where they were originally placed. i.e., pull out resistance increases and hence the value of extreme displacement decreases.

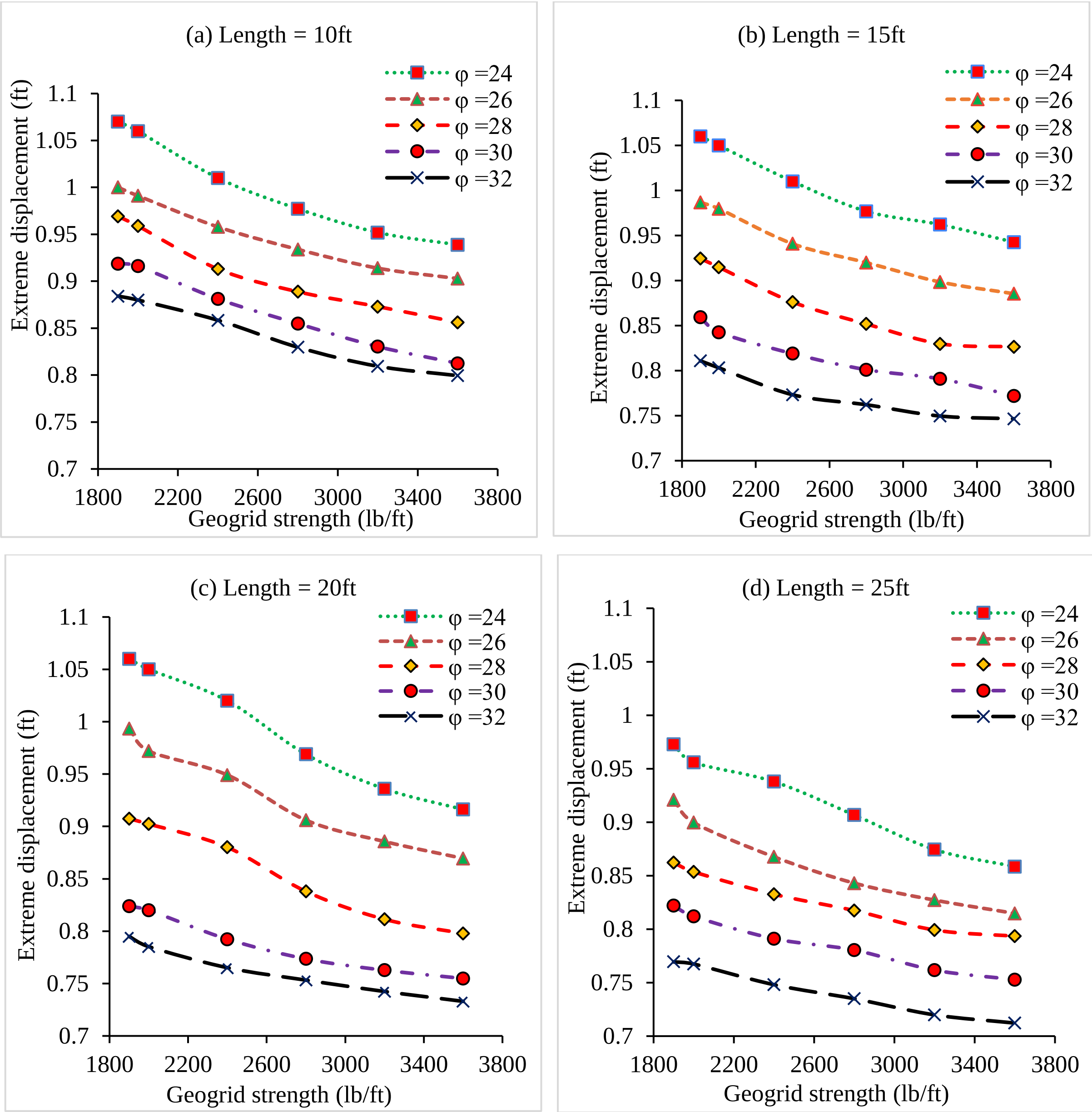


Figure 6. Effect of geogrid strength on extreme displacement

3.3. Effect of friction angle

Figure 7 depicts the impact of friction angle on the extreme displacement. When the friction angle is raised, the backfill soil becomes more stable, which in turn increases friction between the geogrid and soil interface, and the resulting decrease in wall movement.

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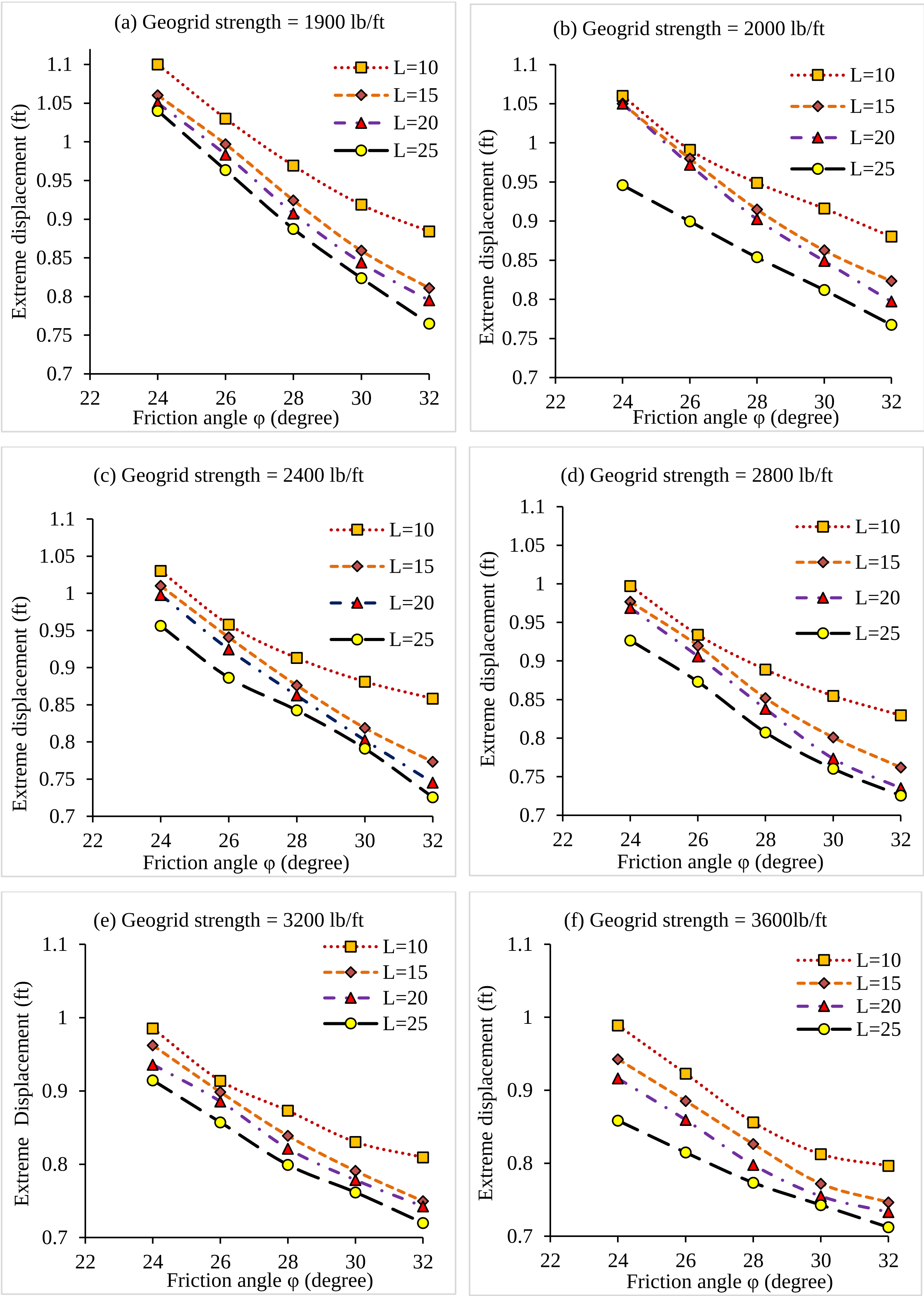

Figure 7. Effect of friction angle on extreme displacement

4. Summary and conclusions

In this study, a comprehensive parametric analysis is conducted to investigate the behavior of Mechanically Stabilized Earth (MSE) walls. This research aimed to provide valuable insights into the design and performance of MSE walls under varying soil and geogrid parameters. The key findings of our parametric study are summarized below, and their practical implications and significance for engineering practices are highlighted.

- With an increase in the length of the geogrid, the extreme displacement reduces, whereas the decrease in the displacement is significant only up to 15ft; after that, the reduction in extreme displacement is almost negligible with further increase in length.
- For all the friction angle, with increase in the geogrid strength extreme displacement reduces. It makes sense, given that the pull-out stress of geogrid increases as grid strength increases. Therefore, greater force is required to displace the geogrids from their initial position, i.e., the pullout resistance increases, and the value of extreme displacement drops.
- The displacement decreases as the friction angle increases because a higher friction angle indicates a stronger backfill and which provide more enhanced friction at the interface of soil and geogrid, hence reducing the movement of the wall.

In summary, the findings of this parametric study offer valuable insights into the behavior of MSE walls, with direct implications for engineering practices. These results not only enhance our understanding of MSE wall performance but also provide practical guidance for engineers and designers involved in MSE wall projects. Finding of this study contributes to the advancement of geotechnical engineering practices and promotes the efficient and safe construction of MSE walls in various applications.

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