The Behavior of Multi-Tiered Mechanically Stabilized Earth (MSE) Retaining Wall

Ananya Srivastava[1[0000-0001-9166-0933]], Sagar Jaiswal[2[0000-0001-9702-5973]], and Vinay Bhushan Chauhan[3[0000-0002-9004-7165]]

[1]Department of Civil Engineering, Madan Mohan Malaviya University of Technology, Gorakhpur, 273010, India
ananyashri.work@gmail.com
[2]Department of Civil Engineering, Madan Mohan Malaviya University of Technology, Gorakhpur, 273010, India
sagarjaiswal.work@gmail.com
[3]Department of Civil Engineering, Madan Mohan Malaviya University of Technology, Gorakhpur, 273010, India
chauhan.vinaybhushan@gmail.com (✉)

Abstract. With the advent of ever-growing urbanization and industrialization, there exists a requirement for heavy infrastructures that can retain heavy earth masses and are sustainable in its functioning. The conventional earth mass retention methods using rigid retaining walls are not preferred for most of the projects, as they are expensive and are time-consuming for the construction when compared to the recently developed methods of earth mass retention by Mechanically Stabilized Earth (MSE) structures. MSE walls having large height when constructed in a single tier, often require a huge volume of excavation and an effective land area which is impossible to attain every time. Therefore, the most suitable alternative is to construct it in a tiered fashion. The tiered MSE walls can tolerate large differential settlements without distress, give a sound performance, are aesthetically appealing, are cost-effective, convenient, and provide simplicity in construction. However, the configuration of such walls may present several engineering challenges that have not been covered by the conventional design methods and calculations. This study aims to assess the performance and response of a multi-tiered 12m high (*H*) MSE wall and compare it with a single-tiered MSE wall through numerical solutions based on finite element modeling. From the outcomes of this study, it is found that the normalized maximum lateral displacement of the facing of the wall (Δ/H) is 5.4% and 1.71% in the single-tiered and three-tiered wall system respectively. Also, the factor of safety in three-tiered and single-tiered wall systems observe a growth of 9.4% and 8.4% respectively when the reinforcement length is increased, which establishes the improved performance of the tiered MSE walls and justifies its usage in place of single-tiered MSE walls.

Keywords: Retaining wall, Finite Element Modeling, Failure plane, Tiered MSE wall

1 Introduction

A mechanically stabilized earth (MSE) retaining wall is a complex structure comprising alternate layers of soil reinforcement elements and the compacted backfill, attached to a wall facing. The steadiness of such a wall system is a derivative achieved from the interaction between the backfill and soil reinforcements which further provides internal and external stability to the wall system. MSE retaining wall consists of reinforcements embedded into the soil mass to work as soil wall and able to sustain the lateral earth pressure and any other lateral load-induced due to natural or man-made activity in the vicinity of the wall structure.

Often, the favorable geographical and topographical conditions required for the construction of a tall MSE wall are hard to achieve as the empty land space might not available [1]. Thus in this situation, the MSE walls can be built in a tiered fashion, with an offset distance, *D* which is the distance between the modular block facings of the successive tiers of the tiered MSE wall, which in turn also reduces the maximum tensile stresses in the reinforcement layers lying in the lower section of the wall [2]. This develops the fundamental performance and finances of construction as well as permits the erection of walls with complex geometries. Furthermore, a single-tiered MSE wall possesses very high tensile stresses in the reinforcing layers positioned at the deeper depths due to a high overburden pressure exerted by the backfill column situated over it. Consequently, the preferred factor of safety (FOS) is accomplished by either ensuing a reinforcement that has a high load-bearing capacity or by the positioning of two reinforcing layers very closely i.e. decreasing the vertical spacing between the layers of reinforcement.

As suggested by FHWA [3], for tall MSE walls, the preference must be given to tiered walls from the perspective of constructability as a monolithic wall creates several difficulties related to the foundation soil and requires some additional safety measure to avoid the failure of the MSE wall. The configuration of a tiered wall system allows a new start with a new leveling pad. It also lessens the vertical stresses on the facing elements and authorizes better control of the vertical alignment of the wall face.

From the available literature on MSE retaining walls, [4-6] it is evident that multi-tiered walls render a better outcome in comparison to single-tiered tall walls, especially when it is necessary to erect an MSE retaining wall which is competent in terms of stability, fiscal concerns, and visual appeal.

The design of the MSE retaining wall as per AASHTO [7] recommendations and NCMA [8] design manual define the guidelines for up to two-tiered walls only. The criteria for the design of a two-tiered wall can be extended to walls with more than two tiers as recommended by FHWA [3]. For such structures, the compound and global stability evaluation become even more specific and critical. “Regarding the internal stability analysis, the conditions for additional vertical stress can be used for walls with more than two-tiers, provided that only the proximately superimposing tier is considered to subsidize the increase in vertical stress on the lower tier” [2]. There also subsists an elastic solution based on a hypothesis of “rigid” walls for appraising additional vertical stresses in a specified tier of a multi-tier wall due to the influence of all superimposing tiers. "Regardless of the approach used for estimating the increase in vertical stresses for evaluation of internal stability, the analysis of tiered walls should proceed from the top wall to the bottom wall so that the stresses are properly accumulated and accounted for in the design of the bottom-most wall" [9].

Therefore given the above, this study aims to evaluate the behavior and performance of tiered wall system and compare its outcomes with the single-tiered wall of similar height, while evaluating their stability in terms of FOS and presents an understanding of the possible failure modes of these complex infrastructures. For the aforementioned goal of this research work, a plane strain model is used for the numerical replication of the MSE walls, also evaluation of the same is performed by implying the strength reduction technique and incorporating the finite element method (FEM) for the assessment of the FOS of MSE retaining walls under several assumed variations of design parameters.

2 Numerical Modeling

Given the objectives set for the present study, a detailed and extensive numerical analysis has been performed with the help of a numerical computational tool OPTUM G2 [9], a finite element program dedicated to geotechnical deformation and stability analysis under plane strain conditions.

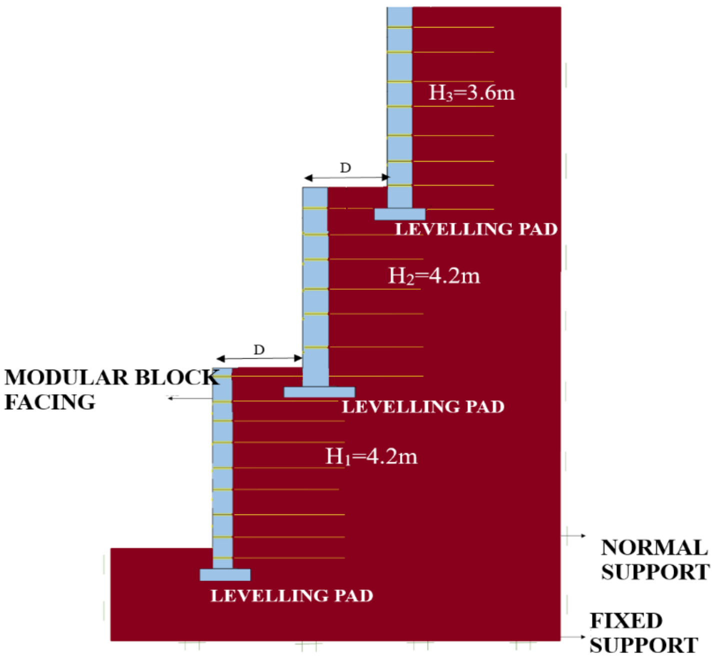

Fig. 1. A three-tiered MSE wall model (12m) considered in the present study

The MSE wall considered in the current study is a three-tiered wall system reinforced using a geogrid element and having a total height of the wall H, 12m where the individual height of the wall at each tier is given as $H_1 = H_2 = 4.2$m, $H_3 = 3.6$m, where, H_1 is the height of lowermost tier, H_2 is the height of middle-tier and H_3 is the height of uppermost tier having a rigid facing (concrete blocks). The configuration of the MSE wall numerical model is considered according to the FHWA (2009) [3] design recommendations. Another single-tiered MSE wall of similar height (12m) is also constructed under the same guidelines to provide comparative results in this study. Figs. 1 and 2 show the three-tiered MSE wall and single-tiered MSE wall considered in this study respectively.

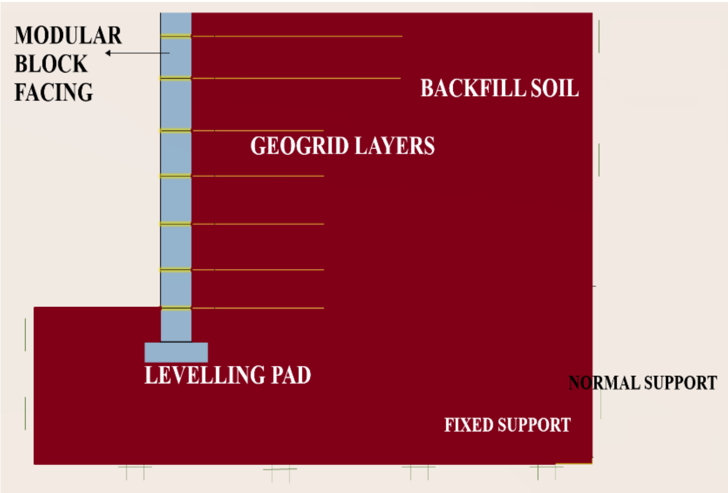

Fig. 2. A single-tiered MSE wall model (12m) considered in the present study

For the system, a stiff leveling pad fabricated with concrete of the proportions 2 × 0.2 m^2 (in elevation) is rested on the soil (as shown in Fig. 2). On top of this, a concrete facing having dimensions "1.5m × 0.6m" (in the vertical direction) is positioned, above which a backfill layer having a boost of 0.6m is placed. To simulate the field-building procedure to model the MSE wall, before placing the next facing in the form of a concrete block, a reinforcing layer of the preferred length, *L* is positioned on backfill, such that a section of the reinforcement length is sealed amid the consecutive rigid facings. Afterward, these backfill material is again positioned over the geogrid layer and this process is continued until the required height of the wall is attained [11].

To simulated the numerical model, the lateral boundaries were secured by normal support to prevent the movement of the soil in the horizontal directions. Fixed supports were applied to the bottom of the soil foundations to avoid the soil movement in both the horizontal and vertical directions.

Furthermore, due to the absence of any similar study in the available literature using experimental evaluation (either small scale or full-scale model) or numerical/analytical modeling, the present numerical model could not be validated. Howeer, every possible precaution has been taken while modeling the retaining wall to predict the behavior of the multi-tiered walls precisely.

The reinforcement length (*L*) is varied from 0.6 *H* to 0.8 *H* for the parametric study. The selection of reinforcement length of 0.6 *H*, which assists with the guidelines as recommended by NCMA [7], 0.7 *H*, is following the guidelines suggested by FHWA [2] and 0.8 *H* is considered for the evaluation of the fact that will any further change in the reinforcement length might affect the factor of safety or not and it also verifies the recommended length of the reinforcement by FHWA [3] and NCMA [8]. These variations in the length aim to represent the modification in the performance and behavior of the tiered wall in static loading circumstances.

The offset distance, *D* amid the successive consecutive tiers is kept constant in this study for the tiered MSE wall system. The offset distance, *D* can be determined using Eq. 1 as mentioned follows [2].

$$D \leq H_u \tan\left(45 - \frac{\phi_r}{2}\right) \tag{1}$$

Where H_u is the height of the upper tiers in the tiered MSE wall and ϕ_r is the friction angle of the soil mass. The upper-tier exerts a surcharge over the lower tiers and the behavior of both the tiers is dependent on each other [3]. The concrete facing blocks, footing, leveling pad, are modeled as linearly elastic materials with a unit weight of 25 kN/m^3. Backfill soil is modeled as an elastoplastic material with a Mohr-Coulomb failure criterion. "The force transfer mechanism among two different materials is simulated as an elastoplastic interface and interface coefficient values like 0.7 and 0.8 for geogrid-soil and geogrid-block interfaces respectively, are assigned at all the interfaces in this MSE wall and footing system" [11].

Furthermore, MSE walls are constructed to resist the lateral earth pressures primarily from the retained backfill. Also, the calculation of the distribution and the magnitude of lateral forces on retaining wall systems under all the loading circumstances has always been a significant area of investigation for geotechnical engineers, as the total push on the wall is the crucial aspect to decide the sectional proportions of the retaining structures. By decreasing the lateral earth pressure on the wall, sectional dimensions of the wall can be significantly reduced, which would lead to the overall economy in the construction of retaining wall [12].

For the present numerical analysis, the six-node triangular elements with a three-point Gaussian integration rule is adopted for higher accuracy of the findings from the model. To estimate the efficiency of the numerical model to investigate the behavior of the MSE walls, a sensitivity analysis is carried out by ranging the number of elements in mesh from 2000 to 6000 and found that 4000 number of elements are sufficient for the considered mesh for simulation [9] and noted that the selected number of elements produces a very fine mesh and refined geometry is significant for achieving reasonable performance.

3 Results and Discussion

Based on the outcomes of the present analysis of the single-tiered and three-tiered MSE wall of the same height are analyzed, compared, and discussed in the present section. The effect of the reinforcement length on the maximum displacement of the wall facing, (Δ) the effect of the reinforcement length on the stability of the wall, effect of the variation of the stiffness of the geogrid on the FOS, the economic benefit of the tiered wall system, effect of tiers on the stability of the wall system and the potential failure planes are discussed below.

The reinforcement length has been varied from 0.6 *H* to 0.8 *H* in the present study for both the single-tiered and three-tiered wall systems. Fig. 3 illustrates the variation of the maximum displacement of the wall facing and the variation of FOS of the single-tiered and three-tiered wall systems w.r.t normalized reinforcement length. As evident from the observed variation of the lateral displacement of the wall facing (Δ/H) in the three-tiered wall system is maximum with a value of 1.71% with the least reinforcement length of 0.6 *H* and is minimum at *L* = 0.8 *H* having $\Delta/H = 1.32\%$. Also, it can be observed that the tiered wall system faces lesser Δ/H w.r.t single-tiered wall system.

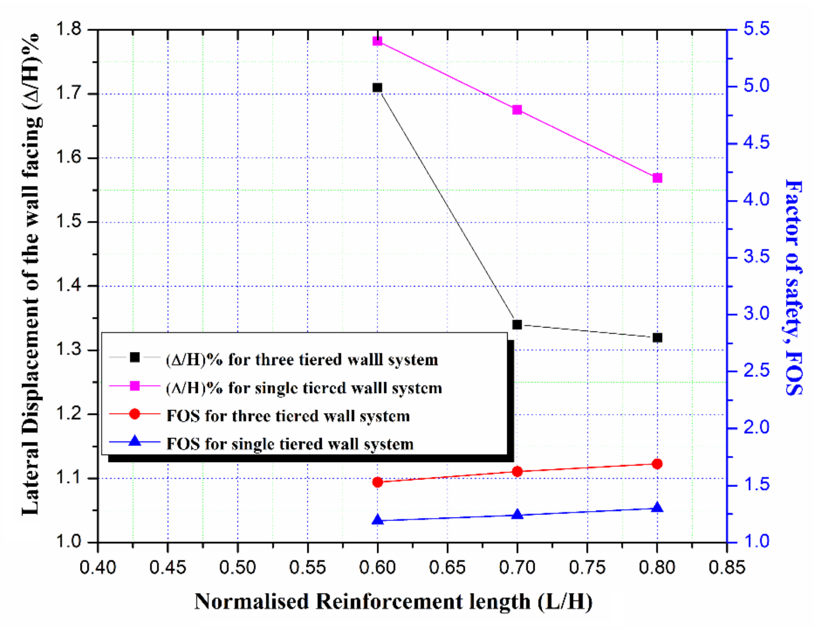

Fig. 3. Variation of normalized maximum displacement of the wall facing Δ/H and FOS of the single-tiered and three-tiered wall systems w.r.t normalized reinforcement length, *L/H*

The single-tiered wall system shows up to a 75% increment in the Δ/H values than the three-tiered wall system, thus highlighting the superiority of the tiered system of walls, in terms of lesser wall movement. This high value of lateral displacement is undesirable for the safe design of the MSE wall system and any structure existing in the vicinity of the retaining structure may prove fatal for MSE walls of greater heights.

The reinforcement length majorly contributes to the overall constancy of the MSE wall. Also, in both the single and three-tiered wall arrangement, the corresponding factor of safety w.r.t the varied reinforcing lengths (in ascending order) increases considerably, which is shown in Fig. 3. Despite the increment in reinforcement lengths from 0.6 *H* to 0.8 *H*, the single-tiered wall system cannot even achieve the minimum criterion of a safer design (i.e. FOS = 1.5) [2]. Contrary to the behavior of the single-tiered wall system, the three-tiered wall system performs undeniably better in terms of FOS values. Even at the minimum length of the reinforcing layer, which is 0.6 *H*, the FOS achieved by the three-tiered wall system is 1.53, satisfying the required criterion of the safe design. Moreover, as the reinforcement length varies to a higher value, there is a significant rise in the FOS, which is 29% greater than the conventional single-tiered MSE wall. The variation of reinforcement length causes the FOS to rise by 9.4% in the three-tiered wall system while varying the *L/H* from 0.6 to 0.8 at a given spacing of 0.6m.

To investigate the reinforcement configuration for the single-tier wall to reach the minimum FOS, the vertical spacing between the successive layer was reduced to 0.4m and it was noticed that the FOS improved and achieves the required minimum FOS of 1.5 for the safer design of the retaining structure [3].

For single-tier MSE walls, the use of reinforcing length *L/H* = 0.6, the FOS was noted as 1.44 and found to be 1.54 and 1.6 corresponding to *L/H* = 0.7 and 0.8, respectively. Although the FOS of the single-tiered wall system increases with *L/H* ratio, still it is lesser than the maximum FOS achieved by the three-tiered wall system. Moreover, the reduction in vertical spacing caused an additional introduction of 10 more layers of geogrid, which shall increase the cost of construction of the wall. Thus from an economic point of view, the construction of the three-tiered MSE wall was found to be more suitable.

In the case of single-tiered walls the minimum design FOS is not achieved, therefore to attain the required FOS either the vertical spacing in between the reinforcing layers is reduced, the stiffness of the geogrid is increased or the length of the reinforcing layer is increased. Therefore given the above, some more numerical simulations have been conducted by increasing the length of the reinforcing layer, increasing the stiffness of the geogrid, and decreasing the vertical spacing between the geogrids. The results so obtained are discussed below.

The stiffness of the geogrid (*EA*) was increased from 500 kN/m to 2000 kN/m while keeping the vertical spacing between the successive reinforcement layers as 0.6m for both the wall systems. With the increase in stiffness of the geogrid, the FOS of the wall systems increased substantially. The three-tiered wall and single-tiered wall systems experienced an increment of FOS by 16% and 26%, respectively. Fig.4 represents the graph depicting the variation in FOS values w.r.t the change in axial stiffness of the geogrid. As evident with the increased stiffness, the single-tiered wall system exhibited a higher growth in the FOS values. But the cost of geogrid increases with the increment in its stiffness, thus suggesting that the viable option is to construct the wall in a three-tiered system, to attain the same stability.

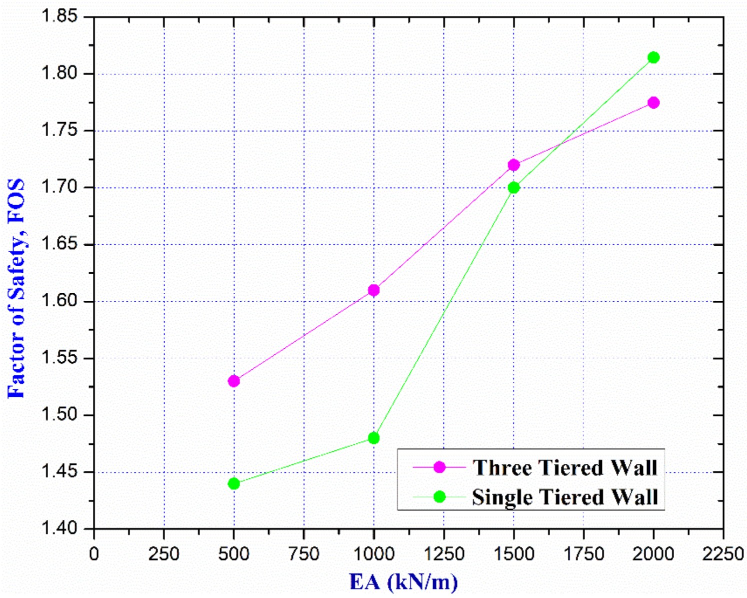

Fig. 4. Variation of the factor of safety w.r.t stiffness of the geogrid in single-tiered and three-tiered wall systems

For the single-tiered wall system, the reinforcement length was increased to achieve the minimum required FOS for the safe design. It was noted that at *L/H* equals 1.0, the FOS was found to be 1.56. During the simulations on the three-tiered wall systems, similar stability conditions were obtained at *L/H* = 0.6 whereas it took an increment of 40% in the *L/H* ratio for the single-tiered wall to achieve the same benchmark of stability. This percentage shall further increase and play a vital role in the tiered MSE walls of greater heights. Thus, it can be safely suggested that in terms of FOS, the construction of the three-tiered wall is a better substitute.

The analysis of the 12m high, three-tiered wall system, and single-tiered wall system have shown that the number of tiers has a substantial impact on the stability of the wall system. The tiered wall system exhibits the highest FOS value of 1.7, which is quite appreciable w.r.t the serviceability of the structure. Also, the three-tiered wall satisfies the minimum desirable criterion of the factor of safety at all the varied reinforcement lengths in this study. Whereas in the single-tiered, the stability of the structure suffers a setback, and the maximum FOS achieved is 1.30 in this case at *L/H* = 0.8. The above evaluation suggests that the construction of the tiered wall structure is markedly more beneficial and feasible than the single-tiered conventional wall systems.

The precise assessment of the potential failure plane behind the retaining wall provides a desired outcome to understand the behavior of the wall and design the retaining structures efficiently [13-14]. The analysis of the critical failure plane, for the single-tiered and three-tiered wall systems, has been carried out to understand its possible modes of failure of such walls and is discussed below by the shear dissipation diagram. The dissipation is often a good indicator of the intensity of plastic deformation.

From the noted failure planes, it is observed that for the single-tiered and three-tiered wall system (as shown in Figs. 5 and 6), the soil mass underneath the offset vastness could not overlap with the potential failure plane. In the single-tiered wall system, there occurs disruption in the soil mass beneath the leveling pad instead of the reinforced zone sandwiched between the geogrid, due to which before any failure in the reinforced zone, the leveling pad descends downwards (as shown in Fig. 5). The single-tiered wall fails in overturning as one single entity with the concrete block facings being laterally dislocated. The failure plane occurs in a wedge outline, commencing from the leveling pad and spreading towards the end of the topmost reinforcement layer. This observed specific actions might be accredited to the statistic that the inclusive width of reinforced soil mass acts as the sole unit which causes the movement of supported mass laterally away from the backfill in this single-tiered wall system. In the three-tiered wall, under static loading, a combined potential failure plane passes below the walls and meets at the ends of the lowermost reinforcement layer in each wall, and further extending towards the backfill surface.

The potential failure plane doesn't interact with the uppermost tier at all, as the upper-tier wall acts as a stationary load to the lower walls due to its proximity, and subsequently upsurges the stresses in the bottom portions of the lower tiers of the MSE wall. The critical failure plane originates from the toe and transmits from the end of reinforcements provided at the second-tier and further extends towards the backfill, as depicted in Fig. 6. In the case of a multi-tiered wall, each tier is disordered contrarily in its manner, not acting as a single entity as in the case of a conventional single-tiered wall system.

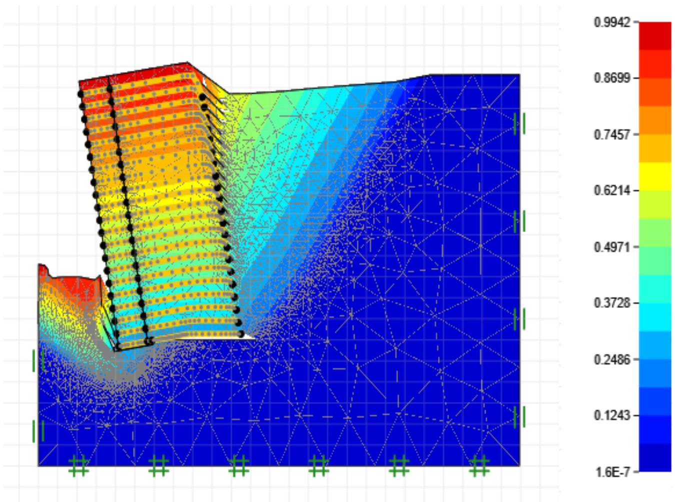

Fig. 5. Deformations and distribution of shear dissipation of the single-tiered MSE wall model (12m) considered in the present study

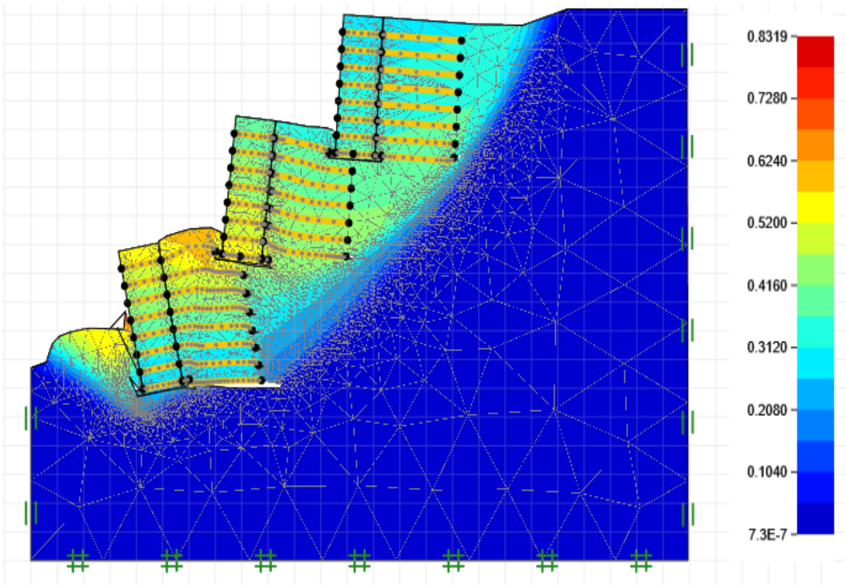

Fig. 6. Deformations and distribution of shear dissipation three-tiered MSE wall model (12m) considered in the present study

4 Conclusions

The present study assesses the stability of the MSE walls reinforced with geogrid, the effect of the reinforcement length, the effect of the number of tiers, and the modes of failure of a 12m high (*H*) three-tiered and single-tiered wall system. The offset distance, *D*, is taken as 3m so that the wall system acts one whole unit, and the upper tier of the three-tiered wall system, exerts a surcharge over the lower tiers. The reinforcement length *L* is varied from 0.6 *H*-0.8 *H* satisfying the design requirements laid by NCMA [8] and FHWA [3]. From the results obtained from the present study, it is apparent that the above-mentioned parameters play a significant role in improving the overall stability of MSE walls. The factor of safety (FOS) value for the three-tiered wall system is found to higher than the FOS for single-tiered tall MSE retaining wall systems for a given configuration of the reinforcement. Therefore, this study highlights the fact that whenever the need arises to construct a high MSE wall, it is safe and convenient to construct multi-tiered MSE retaining walls as a substitute.
Moreover, some distinctive conclusions drawn from the study are mentioned as follows:

1. The reinforcement length plays a major role in providing stability to the MSE structure. The stability of the three-tiered wall system in this study is up to 75% higher than the stability achieved in the single-tiered wall system. The individual growth of 9.4% and 8.4% in FOS values is observed in three-tiered and single-tiered wall systems, respectively, when the reinforcement length is

varied from 0.6 *H* to 0.8 *H*. This growth in the FOS values shall increase substantially when MSE walls of greater heights are erected. This proves that the effect of the tier is prominent and the tiered wall exhibits better performance than the conventional single-tiered wall of similar height.

2. With the increase in stiffness of the geogrid, the FOS of the wall systems increased substantially. The three-tiered wall and single-tiered wall systems experienced an increment of FOS by 16% and 26%, respectively. As evident with the increased stiffness, the single-tiered wall system exhibited a higher growth in the FOS values. But the cost of geogrid increases with the increment in its stiffness, thus suggesting that the viable option is to construct the wall in a three-tiered system, to attain the same stability.
3. The maximum lateral displacement of the wall facing, Δ/H is 5.4% and 1.71% in the single-tiered and three-tiered wall system, respectively. Again, the tiered wall systems emerge as a viable alternative for situations in place of a single-tiered wall. The maximum lateral displacement of the wall facing is found to be inversely proportional to the length of reinforcement. As the reinforcement length increases from 0.6 *H* to 0.8 *H*, maximum lateral displacement decreases from 1.71% to 1.32% and from 5.4% to 4.2% in three-tiered and single-tiered walls, respectively.
4. A three-sided chunk shear failure configuration is observed in a three-tiered MSE wall system where the critical failure plane of the upper tiers combines with the failure plane of the lower tiers into a single failure plane propagating towards the horizontal backfill surface having a significant inclination with the vertical. It is also witnessed that the soil mass underneath the offset distance does not intersect the failure path. The single-tiered wall fails in overturning as one single entity with the concrete block facings being laterally dislocated. The failure plane occurs in a wedge outline, commencing from the leveling pad and spreading towards the end of the topmost reinforcement layer. This behavior may be due to the fact that the reinforced zone acts as a sole unit which causes the whole massive reinforced zone to move laterally away from the backfill in this single-tiered wall system.

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