DCT 158

Reinforced Multitiered Walls

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June 2003

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Report submitted to

Delaware Department of Transportation

and

National Concrete Masonry Association

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This work was sponsored by the Delaware Center for Transportation and was prepared in cooperation with the Delaware Department of Transportation. The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views of the Delaware Center for Transportation or the Delaware Department of Transportation at the time of publication. This report does not constitute a standard, specification, or regulation.

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Abstract

Current design of mechanically stabilized earth (MSE) walls shows that the tensile stress in the reinforcement increases rapidly with height. To take advantage of both the aesthetics and the economics of MSE walls while considering high heights, multitiered walls are used. In such walls, an offset between each pair of adjacent tiers is introduced, thus reducing the tensile stress in the reinforcement in lower tiers. However, design guidelines for multitiered MSE walls is lacking. AASHTO 98 design guidelines are limited to two-tiered walls with zero batter. In fact, this design is purely empirical using "calibrated" lateral earth pressures adopted from limited guidelines developed for metallic strip walls. Empirical data available for multitiered walls is limited, and it seems to be non-existent for geosynthetic walls. In fact, generation of an extensive database for tiered walls is a major challenge, since there are practically limitless configurations for such systems. As an alternative, this study presents the results of parametric studies conducted in parallel using two independent types of analyses: one is based on limiting equilibrium (LE) and one on continuum mechanics. The premise of this work is that if the two uncoupled analyses produce similar results, an acceptable level of confidence in the results can be achieved. This confidence stems from the fact that LE is currently being used for design of reinforced and unreinforced slopes; the agreement with continuum mechanics facilitates its extrapolation to use in MSE walls (which are only semantically different from reinforced steep slopes).

Parametric studies were carried out to assess the required tensile strength as a function of reinforcement length and stiffness, offset distance, fill and foundation strength, water, surcharge, and number of tiers. It is concluded that, properly used, the LE approach can be extended to the analysis of multitiered walls.

Introduction

The first commercial proprietary mechanically stabilized earth (MSE) wall system was introduced in the 1960s. It utilizes metallic strips to tie back precast concrete panels that retain soil. Its use worldwide has increased dramatically since the 1970s, mainly due to its economics and aesthetics. Competitive wall systems using welded wire grids were introduced in the mid 1970s. Geosynthetic-reinforced walls were first used in the 1980s, however, they lacked attractive facings. In the 1990s, the aesthetics problem was resolved by the introduction of segmental retaining walls (SRW) using geosynthetic reinforcement combined with modular dry cast blocks. This technology quickly gained acceptance, especially in the private market.

SRWs cost less than the alternative walls, especially when the wall heights are in the 6- to 8-m range. Based on current design methods, the geosynthetic spacing must get closer as the wall gets taller to alleviate stresses at both the reinforcement and its connection to the facing. Consequently, beyond a certain height, the cost of SRW walls increases. However, if the walls are constructed in a tiered fashion, the reinforcement stresses diminish, and the economics of SRW walls likely prevails even when tall walls are used. In addition to structural benefits, tiered walls allow for creative aesthetics.

The objective of this study is to characterize the stability of multitiered walls by quantifying the effects of offset distance, fill quality, foundation soil, reinforcement length and stiffness, water, surcharge, and number of tiers. To attain this objective, a continuum mechanics-based approach was used. To enable the use of the findings in design, a limit equilibrium approach modified for reinforcement was verified against the continuum mechanics analysis.

Overview of Current Design

Basic design of MSE wall systems determines the reinforcement layout to ensure internal stability so that (1) the long-term tensile stress of the reinforcement is not exceeded, and (2) the reinforcement can indeed develop the design load without being pulled out at its anchored rear-end. It also ensures that the front-end connection between the reinforcement and the facing does not exceed the available connection capacity. External stability calculations verify that the wall system does not undergo direct sliding as a coherent mass, that the eccentricity along its base is acceptable (or, alternatively, that its stability against overturning about its toe is satisfactory), and that the system is stable against compound and global (slope) failure. Internal deformation of MSE walls occurs mainly during construction and, typically, its post-construction magnitude is not a design issue if reasonable quality of fill is used with reinforcement possessing sufficient long-term tensile strength.

Internal and external stability decreases exponentially as the height of the wall increases. To alleviate tensile stresses in the reinforcement and at the connections to the facing, the reinforcement can be placed at increasingly closer spacing. This leads to increased cost of reinforcement and construction. Alternatively, "benching," setback, or offset is used in which the facing continuity is disrupted by an offset of the face. The end result is a wall having the desired overall height with reduced reinforcement stresses. In fact, if the offset is large, each tier may perform internally independent of the other tiers. However, overall global (slope) stability might be affected. The obvious tradeoff is losing areas to benches that otherwise could potentially be used for, as an example, right-of-way.

Design of MSE wall systems is addressed in AASHTO 98 guidelines, which include up to two-tiered walls. The design for two-tiered walls is a straight adaptation of the methods developed by a certain company for its specific metallic product which is substantially different from SRW systems. Two questions arise as a result of this adaptation. First, this design approach is empirical and, objectively, it had very little field verification relevant to failure conditions. Second, this design approach is limited to metallic ("inextensible") structures. Straightforward extrapolation to geosynthetic ("extensible") walls is questionable. This extrapolation becomes critical when SRW walls are high, since it implies very large connection load values typical of metallic walls, while these loads are smaller in flexible systems such as SRW. The problem of extrapolation of an approach developed for high-quality backfill (typically used with metallic reinforcement) may become even more critical, as lower quality backfill is often used in SRW systems. Furthermore, the AASHTO 98 empirical approach is limited to a maximum of two-tiered walls. In reality, walls with five tiers and more are successfully and economically constructed. Hence, there is a clear need to rationally use a sound geotechnical approach to deal with the design of realistic multitiered wall systems. The cost-effectiveness of multitiered reinforced walls, as well as its aesthetics, makes it prudent to generate design knowledge for multitiered walls. Considering the practically non-existent design of multitiered reinforced walls, the objective of this work is to produce knowledge that may lead to sound design.

Limit Equilibrium Method

Limit equilibrium methods have been used for decades to safely design major geotechnical structures. It is also the method of choice for the design of geosynthetic reinforced slopes (e.g., Elias and Christopher, 1997). Inclusion of reinforcement in limit equilibrium is rather straightforward (e.g., Leshchinsky, 1999). The Bishop Method, utilizing a circular arc slip surface, is probably the most popular limit equilibrium method; it is simple to apply and, although not rigorous in the sense that it does not satisfy horizontal force limit equilibrium, in many practical problems it does yield results close to rigorous limit equilibrium methods. In this work, the Bishop Method was modified to include reinforcement as a horizontal force intersecting the slip circle. Unlike the approach by Elias and Christopher (1997) which uses the reinforcement contribution as pure moment, the modified approach considers the reinforcement to produce tensile force to restrain the active wedge (circle). In the modified formulation of the Bishop Method, this tensile force generates moment as well as affects the normal force on the slip surface, thus affecting Coulomb's shear resistance. This modified formulation is consistent with the original formulation by Bishop (1955). The mobilized reinforcement strength at its intersection with the slip circle depends on its long-term strength, its rear-end pullout capacity (or connection strength), and Bishop's factor of safety. The analysis assumes that when the soil and reinforcement strengths are reduced by the factor of safety, a limit equilibrium state is achieved (i.e., the system is at the verge of failure), meaning that in this state, the soil and reinforcement mobilize their respective strengths simultaneously. Obviously, limit equilibrium is physically meaningful only at the verge of failure, regardless of whether reinforcement is invoked. However, if one can define or predict this state, then in design one can assure that a certain minimum margin of safety (i.e., factor of safety) against that state exists. That is, one can ensure that the existing soils and reinforcement are stronger by a certain margin than the value rendering the verge of failure. The Bishop option in the ReSSA (2.0) software, developed by ADAMA Engineering (2002) and an outgrowth of version 1.0 licensed to FHWA, was utilized to generate the results in this work. A detailed discussion of this software can also be found in the literature by Leshchinsky (2002).

It should be stated that AASHTO 98, as well as the British Standard BS8006 (1995), differentiate between reinforced steep slopes and walls by setting a boundary of the face inclination as 70°. This angle establishes an arbitrary limit on the applicability of empirical ("experimentally calibrated") lateral earth pressures commonly used in designs of walls. However, limit equilibrium is not using lateral earth pressures and, therefore, it should not be subjected to arbitrary limits. In fact, while Elias and Christopher (1997) stated that the 70° slope (or 20° batter) limit for walls, they recommended that walls should be assessed also for global stability using a limit equilibrium approach. This recommendation is particularly strong for two-tiered walls. The notion of lateral earth pressures leads to required long-term tensile strength of reinforcement that is about twice as large as that required for slope stability using limit equilibrium analysis. That is, the lateral earth pressure approach leads to linear increase with depth in required strength, while the slope stability approach mobilizes uniformly the available strength of reinforcement; clearly, the two approaches are not compatible. Consequently, the approach used in this work not only provides information about multitiered walls, but also removes the well-recognized conservatism imposed by using lateral earth pressures. It does not distinguish between reinforced walls and slopes but rather provides a unified approach that is consistent with slope stability design in geotechnical practice.

Continuum Mechanics-Based Numerical Method

In recent years, numerical methods have been increasingly used for analyzing slope stability including the computation of its factor of safety. San et al. (1994) indicated that finite element and limit equilibrium methods could consistently determine the locations of critical slip surfaces and required tensile strength of reinforcement in geosynthetic-reinforced slopes. Ugai and Leshchinsky (1995) showed that slip surfaces and the corresponding factor of safety for three-dimensional slope stability problems predicted by finite element and limit equilibrium were very close. Dawson et al. (1999) concluded that the factors of safety of unreinforced slopes obtained using a finite difference method (FLAC - Fast Lagrangian Analysis of Continua) were in good agreement with those using the limit equilibrium method and a log-spiral slip surface. Han et al. (2002) used the same finite difference software (FLAC) to obtain factors of safety of unreinforced and geosynthetic-reinforced slopes similar to those rendered by the Bishop method (limit equilibrium method). The technique for computing the factor of safety of slope stability in the numerical method (FLAC) used herein is discussed later on.

As compared with limit equilibrium methods, continuum mechanics-based numerical methods have the following advantages in assessing the factor of safety of slope stability (Cundall, 2002) – see also Table 1:

(1) No pre-defined slip surface is needed;

(2) The slip surface can be of any shape;

(3) Multiple failure surfaces are possible;

(4) No statical assumptions are needed;

(5) Structures (such as footings, tunnels, etc.) and/or structural elements (such as beams, cables, etc.) and interfaces can be included without concern about compatibility; and

(6) Kinematics is satisfied.

It should be noted, however, that generalized limit equilibrium procedures do not require an *a priori* assumed slip surface (i.e., the critical general-shaped surface can be determined numerically), thus making statements 1 through 3 generally inaccurate. A complicated and large problem may require significant computation time for numerical methods. The inclusion of structural elements and interfaces may create numerical instability leading to questionable solutions. Some specific searches are difficult to perform (for example, surficial slope instability needs to be prevented in order to study the deep-seated slope stability). Localized and inconsequential failures, which may not be of interest to the study (e.g., locally overstressed soil), may mislead the investigation. In short, while continuum mechanics-based methods rigorously satisfy equilibrium and boundary conditions, it generally requires an experienced analyst to properly use it. However, being of a higher hierarchy in mechanics, if properly used, it can serve effectively to substantiate the validity of a simpler limit equilibrium approach that uses an *a priori* assumed failure mechanisms and fails to rigorously satisfy equilibrium (e.g., Bishop Method). That is, it can justify the use of a simpler and more tangible approach.

Considering the rigor of the continuum mechanics-based numerical method, the program FLAC was adopted in this study to evaluate multitiered MSE walls. The computed factors of safety and their respective slip surfaces were compared with those obtained using the Bishop Method as produced by the program ReSSA (2.0). The ability of FLAC to assess slope stability in a similar manner to limit equilibrium (i.e., the same definition of factor of safety) makes such a comparison meaningful.

Modeling

The geometry and material properties of the baseline model used in this study are shown in Figure 1. Since the factor of safety is determined based on a state of yield, or verge of failure, it does not depend much on the elastic parameters: Young's modulus (E) and Poisson's ratio (ν) when using FLAC. If the system contains soils with largely different elastic parameters, it will require more time to solve for the factor of safety; however, its effects on this factor would be small, since it depends mainly on Mohr-Coulomb strength parameters. Hence, constant values of E = 40MPa and ν = 0.25 were used in FLAC. A small value of cohesion equal to 2.5kPa was used for blocks to prevent possible local failure of the block facing, thus enabling one to focus on global failure modes. The Mohr-Coulomb failure criterion was used for strength between stacked blocks, for the reinforced and retained fill, and for the foundation soil. The bond strength between reinforcement and reinforced fill was assumed equal to 80% of the fill strength, the same as in the limit equilibrium analysis when considering pullout resistance.

Table 1. Numerical Solutions and Limit Equilibrium Methods

	Numerical solution	**Limit equilibrium**
Equilibrium	Satisfied everywhere	Satisfied only for sliding mass
Stresses	Computed everywhere using field equations	Normal and shear stresses are computed on the critical surface
Deformation	Part of the solution	Not considered
Failure	Yield condition satisfied everywhere; failure surfaces develop "automatically" as condition dictate	In simplified methods, failure allowed only on certain pre-defined surfaces; no check on yield condition elsewhere
Kinematics	The "mechanisms" that develop satisfy kinematic constraints	Kinematics are not considered – mechanisms may not be feasible

modified based on Cundall, 2002

To investigate the influence of the various parameters, one parameter deviated from the baseline case while all others were kept unchanged. The same models were used in numerical and limit equilibrium analyses.

It has been shown by Dawson et al. (1999) that the constitutive model used to describe the soil pre-failure behavior in FLAC had little effect on the failure surface or its respective factor of safety. The same was also observed in this work. Although the pre-failure displacements are different for various constitutive models, the actual state of failure is affected very little. The lack of sensitivity of the system at failure to the pre-failure constitutive models can be attributed to the same lack of sensitivity of the computed stress field (in a global sense) combined with the dependence of failure only on the Mohr-Coulomb criterion, which depends on normal stresses only. This phenomenon simplifies the application of a continuum mechanics numerical model when considering a failure state. It also makes a comparative study between FLAC and limit equilibrium less speculative and thus more conclusive.

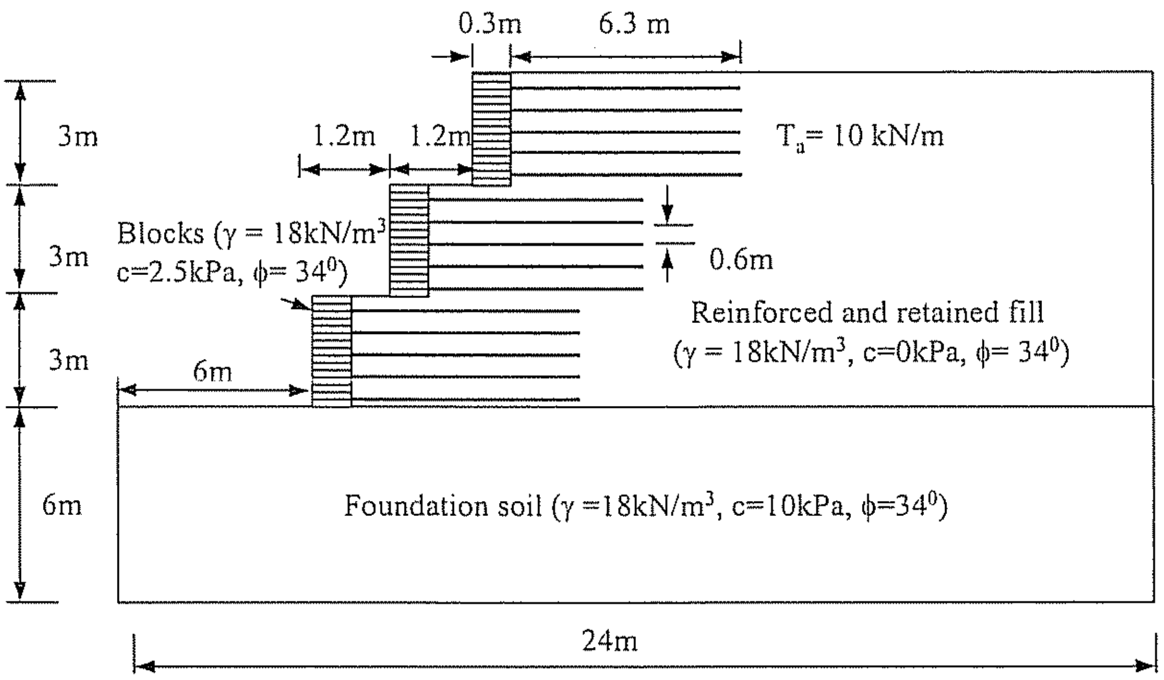


Figure 1. Baseline model for limit equilibrium and numerical analyses

Method of Approach

The ReSSA (2.0) software developed by ADAMA Engineering (2002) was utilized for the limit equilibrium analysis. FLAC 2D, Version 4.0, developed by the Itasca Consulting Group (2002), using a finite difference approach, was adopted in this study for the continuum mechanics-based analysis.

A shear strength reduction technique is used in FLAC to solve for a factor of safety consistent with limit equilibrium and slope stability. Originally this approach was presented by Zienkiewicz et al. (1975) in conjunction with finite element analysis. Dawson et al. (1999) demonstrated the use of the shear strength reduction technique in FLAC, producing results similar to limit equilibrium predictions for simple unreinforced slopes using log spiral mechanism. For simple slopes, the Bishop Method yields nearly identical results to log spiral analysis, which, unlike Bishop's, is rigorous from the limit equilibrium analysis viewpoint. Hence, the conclusions by Dawson et al. (1999) are equally applicable to the Bishop Method, the limit equilibrium method utilized in this work.

In the strength reduction technique, a series of trial factors of safety are used to adjust the cohesion, c, and the internal angle of friction, ϕ, of the soils as follows:

$$c_{trial} = \frac{c}{Fs_{trial}} \qquad (1)$$

$$\phi_{trial} = \arctan\left(\frac{\tan\phi}{Fs_{trial}}\right) \qquad (2)$$

Adjusted strength parameters of soil layers are re-inputted iteratively until satisfaction of boundary conditions and equilibrium anywhere in the continuum is achieved. The strength reduction continues by increments until the adjusted cohesion and friction angle render the slope unstable, being on the verge of failure. The amount of strength reduction needed to reach this state is, by definition, the same factor of safety as in limit equilibrium analysis; i.e., it signifies the margin of safety against collapse of an existing slope.

In this work, the required long-term tensile strength of reinforcement was first determined using ReSSA (2.0). The strength value was varied iteratively while all other variables were held constant until the computed factor of safety of the wall system was equal to 1.0. When the factor of safety is 1.0, the system is at the verge of failure; thus, it corresponds to a physically meaningful state of limit equilibrium. This tensile strength of reinforcement was then inputted to FLAC analysis to compute the factor of safety for the same system. If for the same problem FLAC produces a factor of safety of approximately 1.0 (and a shear zone that is similar to the trace of the limit equilibrium trace of the critical surface), the "benchmark" of limit equilibrium state produced by ReSSA (2.0) is considered equivalent to FLAC. Consequently, this benchmark is confirmed in a theoretical context by higher hierarchy, more rigorous, mechanics. It should be noted that in limit equilibrium analysis, it is convenient to apply the factor of safety also to the reinforcement strength (unlike the version of FLAC used which applies it only to the soil strength); however, selecting a factor of safety of Fs=1.0 in limit equilibrium makes this difference in definition inconsequential in the framework of this study provided the resulting Fs are similar.

Results

Summary

The parametric study in this project included the following parameters: offset distance, reinforcement length and stiffness, fill quality, foundation soil, water, surcharge, and number of tiers. Table 2 shows the resulting Fs as a function of the required reinforcement strength for all parameters excluding the offset distance. Details and the influence of offset distance are discussed in the following sections. In this study, the reinforcement length is defined based on AASHTO 98 guidelines, i.e., the reinforcement length measuring from the back of the wall facing. The effect of each parameter was investigated by changing its value from the baseline case while all other parameters were left unchanged. The required reinforcement strength was obtained by using ReSSA (2.0), the limit equilibrium approach, to render a tiered wall system with Fs=1.00. This calculated strength was used by FLAC to compute the factor of safety of the system based on continuum mechanics. As shown in Table 2, the computed factors of safety using FLAC are nearly identical to those obtained using ReSSA (2.0), except for the effect of foundation soil.

It should be pointed out that the trace of the critical slip surface predicted by ReSSA (2.0) was within the range of the failure zone predicted by FLAC, except for the case of weak foundation soil. In the context of limit equilibrium, the combination of the factor of safety and critical slip surface constitutes the solution. Consequently, the complete limit equilibrium solution for the cases studied, excluding the case of weak foundation, was in good agreement with that rendered by the continuum mechanics approach.

Table 2. Summary of Parametric Study

Case Studied	**Parameter Value**	**Tensile Strength (kN/m)**	**Fs (Continuum mechanics)**	**Fs (Limit equilibrium using Bishop)**
Baseline	$N_t = 3$, $H = 9m$, $d_{os}=1.2m$, $N_r = 1$, $L = 6.3m$, $J = 1000kN/m$, $\gamma=18\ kN/m^3$ $c_r=0kPa$, $\phi_r= 34^{\circ}$, $c_f=10kPa$, $\phi_f=34^{\circ}$, $q = 0kPa$, $h_w =$ N/A	10.0	0.99	
Fill quality	$c_r=0kPa$, $\phi_r = 25^{\circ}$	22.0	0.99	

Case Studied	Parameter Value	Tensile Strength (kN/m)	Fs (Continuum mechanics)	Fs (Limit equilibrium using Bishop)
Reinforcement length	L = 4.2m	11.4	0.98	1.00
Reinforcement stiffness	J=100,000 kN/m	10.0	1.03	
Reinforcement type	N_r = 2	7.5 (upper 8 layers) 11.0 (lower 7 layers)	1.01	
Foundation soil	c_f=0kPa, ϕ_f = 18°	10.0	0.86 (bearing failure)	
Water	h_w= 3m	9.25	1.01	
Surcharge	q = 20 kPa	11.6	1.02	
No. of tiers	N_t= 5, d_{os} = 0.6m	10.1	1.00	

Note: c_f = cohesion of foundation soil; c_r = cohesion of reinforced and retained fill; d_{os} = distance of offset; H = total height of tiered walls; h_w = height of water table above the foundation soil; J = stiffness of reinforcement; N_r = number of reinforcement type; N_t = number of tiers; q = surcharge on the uppermost tier; ϕ_f = friction angle of foundation; ϕ_r = friction angle of reinforced and retained fill; γ = unit weight of all the soils.

Effect of Offset Distance

The effect of offset distance on the required reinforcement strength is presented in Figure 2. Each tier in this figure is 3 m high; offsets between adjacent tiers are equal. It can be seen that an increase of offset distance reduces the required reinforcement strength. As expected, the required strength in three-tiered walls is greater than that in two-tiered walls, while the required tensile strength in two-tiered walls is greater than that in one-tiered walls. When the offset becomes significantly large (2.4 m or 80% of the height of an individual wall for the baseline case), however, each tier functions independently and the required strengths in two- and three-tiered walls are equal to that in one-tiered walls.

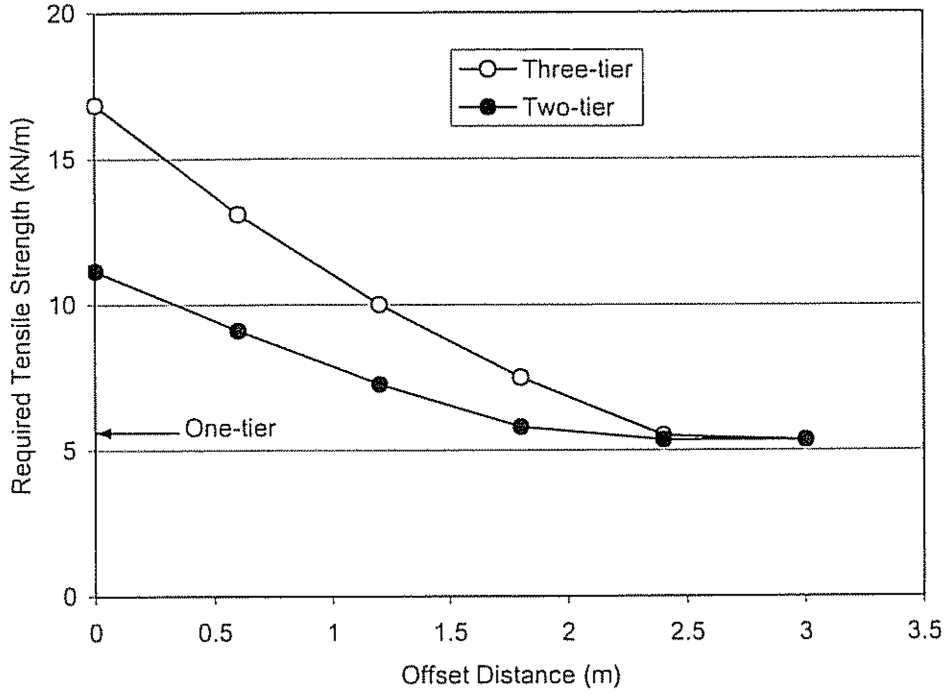


Figure 2. Effect of offset distance on required reinforcement strength (each tier is 3 m high)

Effect of Fill Quality

The effects of reinforced and retained fill quality were investigated using a lower friction angle of the fill compared with the baseline case. The results of the required tensile strength of reinforcement using two different fills are presented in Figure 3. The friction angle of 25° represents a low-quality fill (silt), which is often used in geosynthetic reinforced walls in the private sector. The baseline case uses a friction angle of 34°; it corresponds to selected fill and is the default value following the public sector design (AASHTO 98). Figure 3 shows the effects of offset distance on the required reinforcement strength; the trends are similar to the baseline case. However, the maximum offset distance for the tiered walls to function independently is larger when low-quality fill is used. In addition, the low-quality fill requires higher reinforcement strength. The behavior exhibited by low-quality fill is obvious, since it provides less shear resistance, thus requiring stronger and longer reinforcement. An increase in the number of tiers results in a significant increase of required strength of reinforcement.

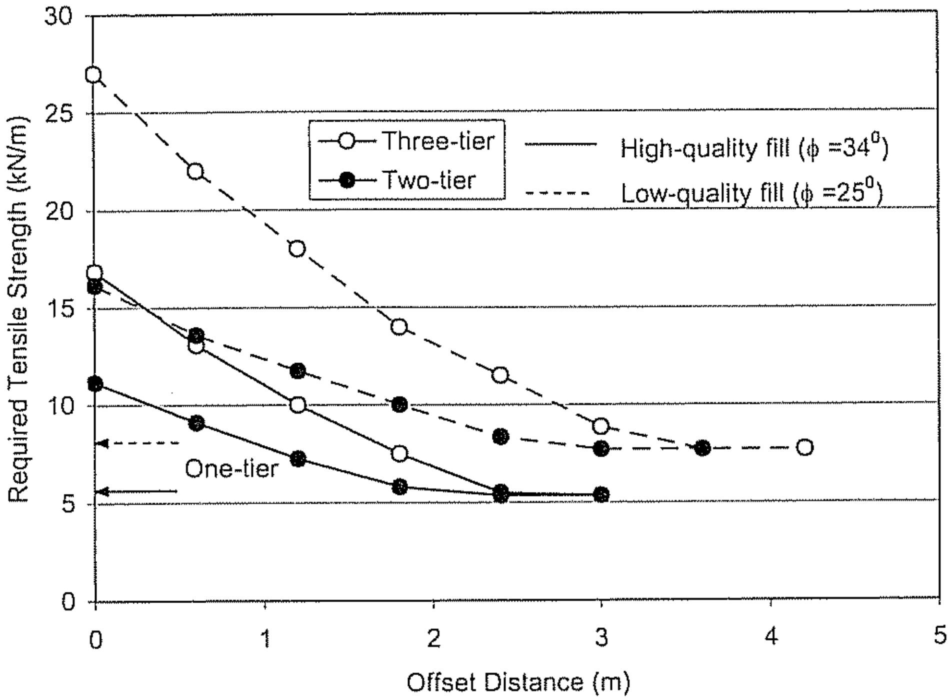


Figure 3. Effect of Fill Quality on Required Reinforcement Strength

Effect of Reinforcement Length

AASHTO 98 guidelines (AASHTO, 1998) and NCMA design (NCMA, 1997) define the reinforcement length differently. AASHTO, which is commonly used by the public sector, measures the reinforcement length from the back of the wall facing while NCMA, which is often used by the private sector, defines length from the front of the wall block facing. In this study, the reinforcement length is defined based on AASHTO 98 guidelines. In addition, AASHTO requires a minimum length of L=0.7H while NCMA requires L=0.6H; however, in either approach, guidelines for tiered walls are lacking.

Two different reinforcement lengths were used to investigate the length effects. The longer reinforcement length of 6.3 m (baseline case) was selected based on 70% height of three-tier walls, while the shorter reinforcement length of 4.2 m was selected based on 70% height of two-tier walls. The results of required strength of reinforcement with these two reinforcement lengths are presented in Figure 4. It can be seen that no difference in strength exists for two-tiered walls for the lengths used; simply, even the shorter reinforcement was long enough to resist pullout and develop its strength. However, the difference in required tensile strength of reinforcement is obvious for the three-tiered walls when the offset distance is less than 1.8m (equivalent to 60% height of individual walls).

The longer reinforcement required less strength than the shorter reinforcement since some layers had limited contributions due to possible pullout. In fact, as shown in Figure 5 some layers are inside the active soil mass thus not contributing at all to global stability. Reduced contribution by some layers must be compensated by others so as to maintain equilibrium. As a result, the tradeoff for using shorter reinforcement can be an increase in the required strength of reinforcement.

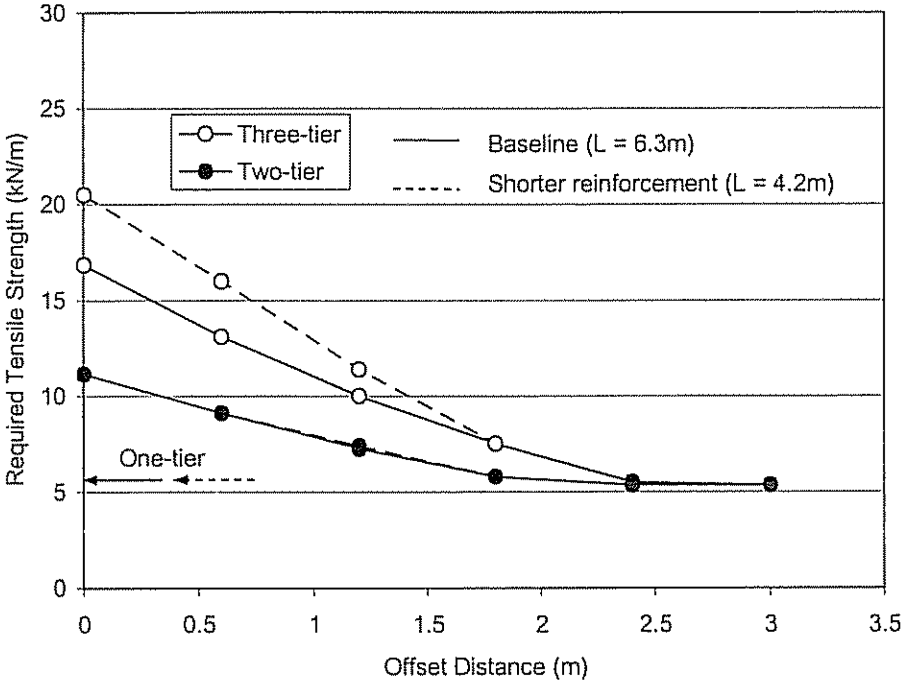
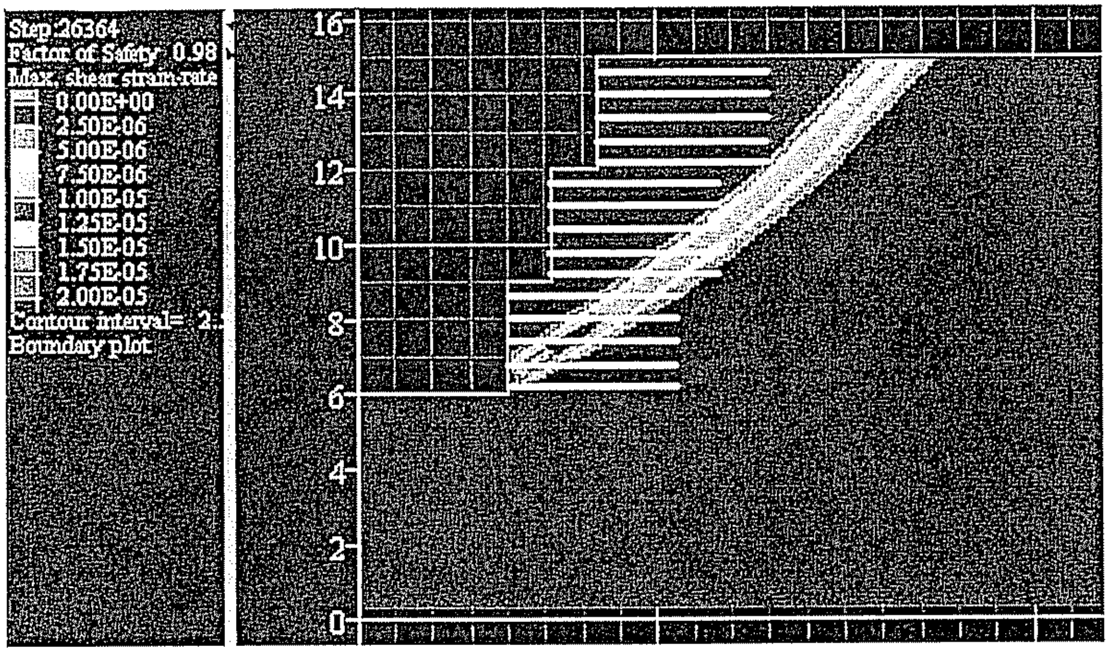
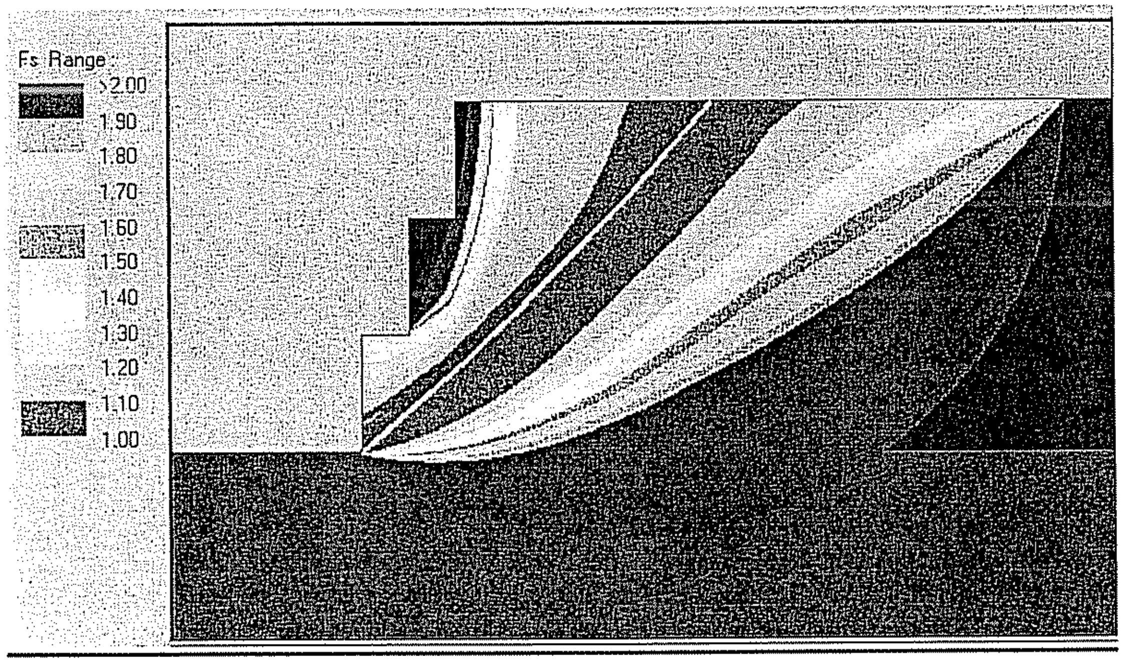


Figure 4. Effect of reinforcement length on required reinforcement strength

Note that Figure 5b represents the spatial distribution of the safety factors providing a diagnosis of the stability of the analyzed slope (i.e., "safety map," Baker and Leshchinsky, 2001) as produced by ReSSA (2.0) for the specified search domain using Bishop analysis. The superimposed slip circle in this figure agrees well with the shear zone predicted by FLAC (Figure 5a). The zone within which Fs varies between 1.00 and 1.10 is rather thick showing that, practically, there are many surfaces yielding similarly low safety factors. The range of the same safety factors can be viewed as an equivalent presentation to the shear zone in FLAC, since the reciprocal of the safety factors reflects the level of soil strength mobilization.



a. FLAC: Predicted shear zone superimposed over reinforcement layout



b. ReSSA (2.0): Spatial distribution of safety factors superimposed by the critical slip surface

Figure 5. Critical surfaces for short reinforcement: FLAC and ReSSA (2.0)

Effect of Reinforcement Stiffness

The effect of reinforcement stiffness on the required strength was investigated using FLAC by assigning two significantly different stiffness values: 1,000 kN/m for the baseline case and 100,000 kN/m for the other case. As shown in Table 2, for the range of stiffness values used, there is negligible difference in the computed factors of safety. It can be concluded that the reinforcement stiffness does not play a significant role in the required strength of reinforcement when global stability is concerned. It is important to note that limit equilibrium analysis cannot consider the effects of reinforcement stiffness. Consequently, the insight gained from a continuum mechanics-based analysis is important in ascertaining that stiffness is not a significant factor when assessing the global stability of the reinforced system. The result implies that, for example, a wall system reinforced with metal or geosynthetic can be analyzed using limit equilibrium analysis.

Effect of Reinforcement Type

Two different clusters of reinforcement layers, each possessing a different strength, were investigated. The upper 8 layers of reinforcement had a strength of 7.5 kN/m, the lower 7 layers 11.0 kN/m. The limit equilibrium and numerical methods yield nearly identical factors of safety of the multitiered system as shown in Table 2.

Effect of Foundation Soil

The effect of foundation soil was investigated by introducing a weak foundation under the multitiered MSE wall. The weak foundation had cohesion of 0 kPa and friction angle of 18° instead of cohesion of 10 kPa and friction angle of 34° for the baseline case. As shown in Table 2, the calculated factor of safety using FLAC, 0.86, is lower than the factor of safety using Bishop's circular arc method (1.00). Figure 6, which was produced by FLAC, shows that bearing failure under the facing instigates the global failure.

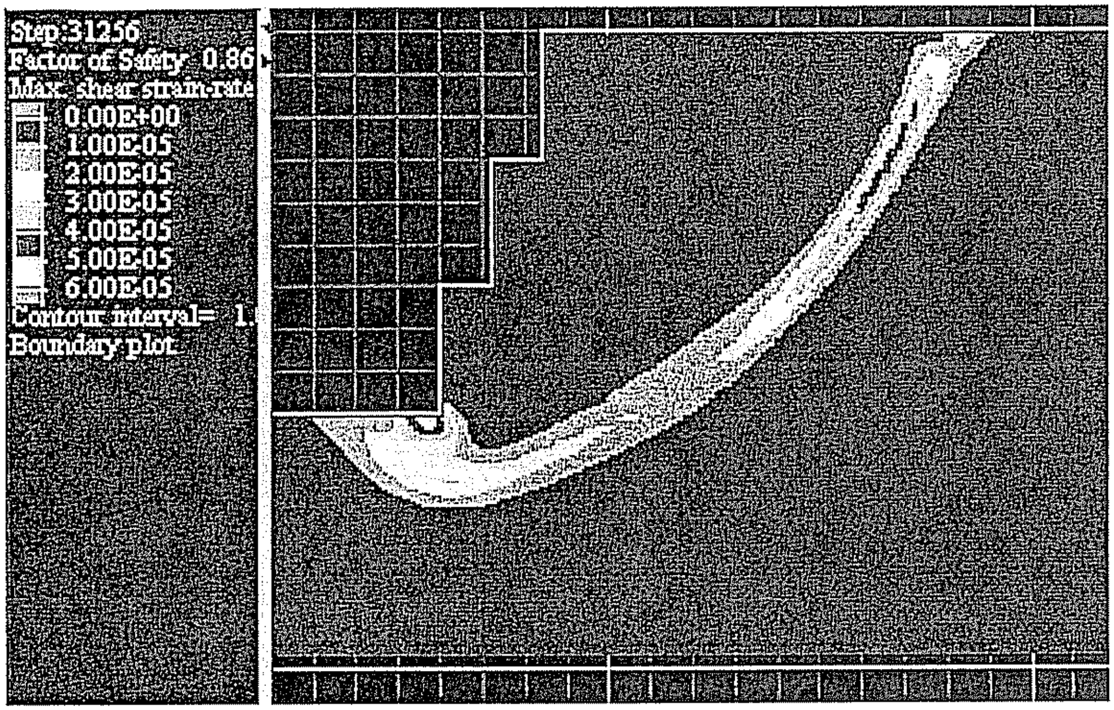
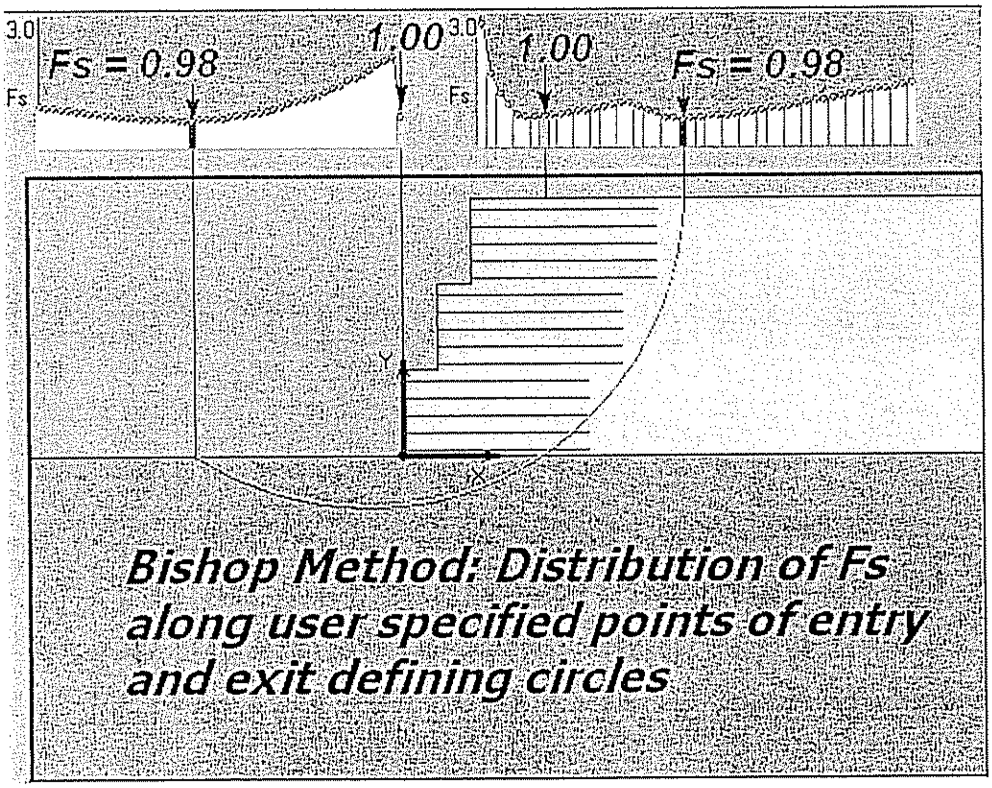


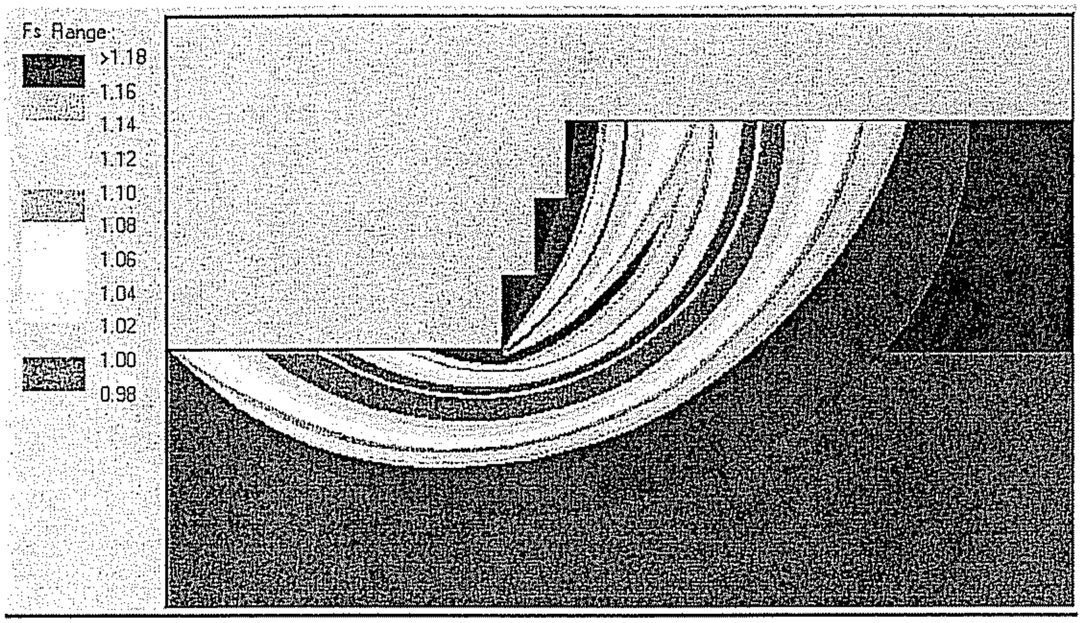
Figure 6. Bearing Failure of Multitiered MSE Wall in FLAC

The good agreement between FLAC and the limit equilibrium for all other cases contrasted with the poor agreement for this case makes it interesting to further investigate this foundation problem. Figure 7a shows that the problem has two minima when using Bishop circular arc analysis. ReSSA (2.0) uses specified points of entry and exit for slip circles, basically examining all combinations of points to define circles. Figure 7a at its top portion shows that Fs=1.00 for an "internal" slip circle resulting in the required reinforcement strength (see Table 2). However, if the reinforcement is not long enough (or the foundation soil is weak), deep-seated failure may develop and the strength of the reinforcement in such a case plays little role; i.e., two layers are intersected at their rear end. In fact, one can see that for the deep-seated failure, the minimum is flat (typical to many slope stability problems) implying that slip circles not intersecting the reinforcement at all are practically equally critical. Problems with flat minimum or multiple minima are ideally suited for review using the safety map as a diagnostic tool (Baker and Leshchinsky, 2001). The safety map produced by ReSSA (2.0) is presented in Figure 7b. The spatial distribution of safety factors presented in Figure 7b clearly shows that there are two zones with practically the same Fs: one is a narrow zone within the reinforced soil; the second is a wide zone around the reinforcement and through the foundation. It is interesting to note that the safety map shows that the safety factors within the reinforced soil are not uniform. Mobilization of soil and reinforcement strengths is reciprocal to the safety factor value by virtue of the definition of safety factor in limit equilibrium. Hence, while the limit equilibrium implies that maximum mobilization occurs at the intersection of the *critical* slip surface and reinforcement layer, the layer could also be mobilized at other locations along its horizontal length, inverse to the safety factor. That is, limit equilibrium through the perspective of the safety map could also be used to assess the reinforcement mobilized strength along its length. Nevertheless, while this examination of results shows the possibility of deep-seated failure, it fails to explain the difference in the computed Fs with FLAC.

Examination of the shear zone in Figure 6 shows that it does not really resemble a circle. Consequently, the possibility of a different failure mechanism in limit equilibrium needs to be investigated. The option of using a 3-part wedge exists in ReSSA (2.0); the stability analysis employed is the Spencer Method (Spencer, 1967). Figure 8 shows the critical result for Spencer's. Once again, the failure is dominated by the foundation soil. Note that Fs dropped to 0.92. The main reason for the lower value of Fs can probably be attributed to the shape of the slip surface. Although different methods of stability were used, the authors' experience is that, typically, Spencer will render slightly larger Fs. However, when a circular arc is an unlikely critical mechanism, the 3-part wedge adapts better to the weak geology, producing lower Fs. It should be pointed out that there were other 3-part wedges yielding smaller Fs than 0.92 (e.g., 0.90). However, these surfaces were excluded because their lines of thrust (i.e., line connecting the resultants of interslice forces) were outside the sliding mass.



a. Distribution of Safety Factors vs. Specified Points Defining Test Circles



b. Spatial View of Safety Factors

Figure 7. Diagnostic perspective using ReSSA(2.0): Bishop method

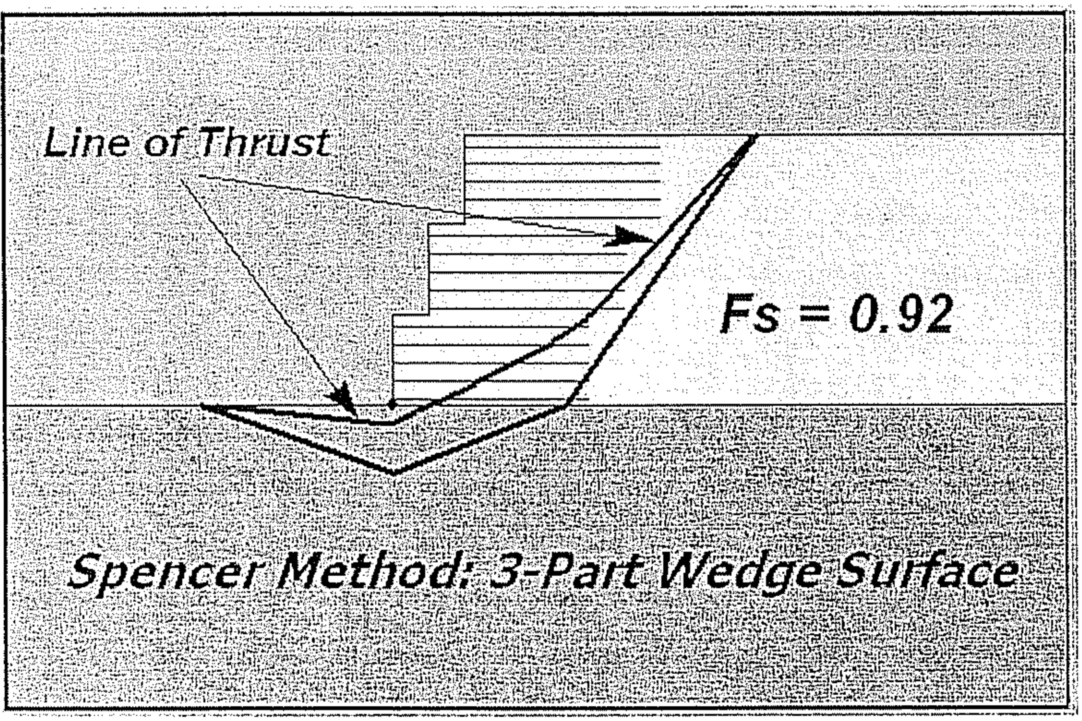


Figure 8. Noncircular failure mechanism

The practical difference between Fs of 0.92 (by Spencer Method) and 0.86 (using FLAC) is small. However, the predicted critical surfaces deviate. Hence, it is likely that using the Spencer method applied to a polygonal slip surface with more than 3 parts will yield closer agreement in this particular case.

Effect of Water

Multitiered MSE walls could be used as waterfront earth structures. In this parametric study, the water table is 3m high above the toe in either side of the wall. The effective stress analysis results are presented in Table 2. The Bishop method and the continuum mechanics analysis yielded nearly identical factors of safety of 1.0. The required strength of 9.25 kN/m is smaller than that for the baseline case. Simply, the water in front of the multitiered wall helps "stabilize" it. However, the required reinforcement strength may significantly increase if there is a rapid drop-down of water in front of the wall. Hence, the implications of this comparison should be viewed in the context of a parametric study.

Effect of Surcharge

MSE walls are commonly used to support traffic load as well as superstructures. The effects of surcharge on the stability of multitiered MSE walls and the required reinforcement strength were investigated in this study. The computed factors of safety of the multitiered MSE walls under a uniform surcharge of 20 kPa on the top of the upper tier using the Bishop method and FLAC are presented in Table 2. It is shown that the factors of safety are nearly identical using these two different methods. As compared with the baseline case, the addition of surcharge on the top of the wall increased the required strength of reinforcement from 10 kN/m to 11.6 kN/m.

Effect of Number of Tiers

The effect of number of tiers was discussed before. In the discussed cases, individual tiers have the same height (3m). An increase in the number of tiers increases the total height of the tiered wall system. MSE walls can be constructed for any number of tiers, each having a different height. Different from the baseline case, a 5-tier wall was investigated. Each tier was 1.8 m high with an offset distance of 0.6 m. The total height of the multitiered wall was 9.0 m, which is equal to that for the baseline case. The total offset distance from the lowest tier to the uppermost tier was 2.4 m, which is also the same as the total offset for the baseline case. As shown in Table 2, the required strength for this 5-tier wall is equal to that for the baseline case. It indicates that multitiered MSE walls having the same total height and total offset distance require the same reinforcement strength. That is, the same average face slope and total height renders the same required strength. However, this observation should not be generalized unless an extensive parametric study supports it.

Design Implications

Design of MSE walls determines the required layout and long-term tensile strength of the reinforcement needed to satisfy specified margins of safety. To simplify the process, current design of reinforced walls divides the analyses into various aspects of stability: internal, external, and global. The end result is a synergy of all simplified analyses. In an actual structure, however, there is only one state that is most critical. Rigorous analysis such as that used in FLAC can detect the critical state for each layout and reinforcement tensile strength without assuming *a priori* the prevailing mode of failure.

The parametric study presented here implies that compared with continuum mechanics-based analysis used as a benchmark for a system on the verge of failure, properly conducted limit equilibrium analysis can produce the required tensile strength and layout of the reinforcement reliably. This allows for a rational design of reinforced earth structures having complex boundary conditions using a simple type of analysis (e.g., multitiered wall geometry, surcharge loads, water, soft foundation, and more). The categorization into internal, external, and global stability commonly used in the design of reinforced walls (employing lateral earth pressure theories) is not needed if proper slope stability analysis is conducted. Using a diagnostic tool such as a safety map enables the designer to realize the state of stability beyond the most critical one.

Walls are often designed to have sufficient capacity of the connection between the reinforcement and facing units. Currently, the required connection capacity is calculated based on lateral earth pressures. The connection load can also be determined using limit equilibrium analysis by conducting surficial stability analysis. Such analysis can consider the connection capacity (i.e., strength), the distance of a test slip surface from the connection (i.e., added connection strength capacity due to interaction between the block and the reinforcement layer – front-end pullout resistance), and the soil mass defined by the test slip surface. The connection aspect in design, however, is beyond the scope of this work.

Conclusions

Limit equilibrium and continuum mechanics-based analyses were used in this study to investigate the stability of multitiered MSE walls. The analyses were conducted within the framework of a comparative parametric study. The comparative analyses indicate the following:

1. Properly used slope stability limit equilibrium analysis of multitiered MSE walls yielded nearly the same factors of safety against collapse as the continuum mechanics-based analysis. The observed agreement indicates that the limit equilibrium approach can be used to determine the required tensile strength and layout of reinforcement for multitiered MSE walls. It should be noted that a similar approach is already being used in practice for the design of complex reinforced slopes (i.e., slopes with inclination smaller

than 70°). The authors think that further research is needed to verify whether limit equilibrium analysis can replace the lateral earth pressure approach in wall design thus making the existing arbitrary boundary of 70° unnecessary. When reinforced walls will be considered as reinforced slopes with small batter, the design would be unified, consistent, and applicable to complex boundary conditions.

2. An increase of offset distance reduces the required tensile strength of reinforcement. Hence, with properly designed tiered system, great heights can be achieved.

3. An increase of the height of multitiered walls having small offsets increases the required tensile strength of reinforcement.

4. Low-quality fill requires higher tensile strength and longer reinforcement than high-quality fill.

5. The effect of reinforcement length depends on the height and offsets of the multitiered MSE walls and quality of fill.

6. Bearing or deep-seated failure could control the required length and strength of the reinforcement if a weak foundation soil exists.

7. For the problem studied, Bishop's circular arc analysis yielded results similar to the continuum mechanics-based analysis. However, when a weak foundation exists, the controlling failure mechanism could assume a different geometry. The problem of assuming *a priori* the prevailing failure mechanism is a general limitation of *most* (but not all) limit equilibrium analyses.

8. Water could have an impact on the required tensile strength of reinforcement. While a horizontal phreatic surface on each side of the wall may increase stability, a sudden draw down may greatly decrease stability, thus requiring stronger and longer reinforcement.

Acknowledgement

This research work was sponsored by the Delaware Transportation Institute and the National Concrete Masonry Association. This support is greatly appreciated.

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