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Effects of secondary short reinforcement layers on the behavior of block walls

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ABSTRACT: The effects of intermediate reinforcement on the behavior of MSE block walls were investigated with numerical models that simulate wall construction layer by layer up to failure under gravity loading. Parametric studies were carried out with the finite difference program FLAC. The effects of intermediate reinforcement were considered with respect to soil strength, foundation stiffness and reinforcement stiffness. It seems that the closely spaced primary and secondary layers act as an "extension" of the block facing, and thus change the wall behavior. Results of the parametric study imply that the introduction of intermediate reinforcement in a model with large reinforcement spacing has significant effects on the prevailing mode of failure, verge–of–failure height, and maximum forces and their location in the reinforcement layers.

1 INTRODUCTION

Current design of mechanically stabilized earth (MSE) block walls with geosynthetic reinforcement is based on limit equilibrium formulation with predetermined failure mechanisms. Reinforcement strength and layout result from stability analyses investigating all potential modes of failure. Present experience implies that this approach leads to conservative design for non–marginal conditions. However, limit equilibrium formulation cannot assess directly the effects of factors such as soil stiffness, reinforcement stiffness, connection type, reinforcement spacing and secondary reinforcement layers on the behavior and overall performance of MSE block walls. Realistic evaluation of these effects with respect to the prevailing mode of failure would allow for design leading to balanced and reasonably conservative design of MSE walls under normal and marginal conditions.

This paper reports some results of numerical analysis designed to investigate the effects of geosynthetic reinforcement spacing on the behavior of mechanically stabilized earth walls (Leshchinsky & Vulova 2001, Vulova 2000). It is focused on the effects of secondary reinforcement layers on the behavior of MSE block walls considering the soil shear strength, foundation stiffness, and reinforcement stiffness. Results of the parametric study imply that the introduction of intermediate reinforcement in a model with large reinforcement spacing has significant effects on the prevailing mode of failure, wall stability, and maximum forces in reinforcement.

2 NUMERICAL SIMULATIONS

Behavior of MSE block walls with geosynthetic reinforcement was investigated with numerical models that simulate wall construction layer by layer until failure under gravity loading occurs. Parametric study was carried out with the final–difference program FLAC 3.40 (Itasca 1998), which is able to identify failure mechanisms.

2.1 *Numerical model*

Numerical model was composed of reinforced soil, retained soil, foundation soil, facing blocks, and reinforcement layers. Material properties are based on literature data representing typical design values.

All soils were modeled by utilizing Mohr–Coulomb failure criterion and hyperbolic stress–strain relationship prior to failure. Baseline shear strength soil parameters were: angle of friction ϕ=34° and dilation angle ψ=7°, with a 'high' value of ϕ=45° and ψ=15°, and 'low' value of ϕ=25° and ψ=0°; unit weight was constant equal to 21.6 kN/m^3. Very stiff foundation soil was modeled with cohesion c=1000 kPa, and hyperbolic model parameter 1000 times larger that the baseline value.

Facing blocks with fixed size of 0.2 × 0.2 m were modeled as a linear elastic material representing concrete. All block–block, block–reinforcement and block–soil interfaces were modeled. Pure frictional connections were represented by interfaces with no cohesion. It is important to note that the model was able to capture the relative movements of the facing blocks at failure and pullout of the reinforcement from the blocks. For example, current investigation confirmed that pullout of top reinforcement layers at the facing did occur for models experiencing connection mode of failure.

Geosynthetic reinforcement layers were modeled with FLAC beam and cable structural elements with baseline stiffness of J=EA=2000 kN/m. Soft (ductile) reinforcement was modeled with reduced stiffness of EA=200 kN/m. In all simulations, the reinforcement length was equal to 1.5 m. Secondary reinforcement layers were 0.3 m long and had the same properties as the primary reinforcement. They were modeled with reinforcement layers with different properties along the length. The 'redundant' part (1.2 m long) was modeled with elastic properties 100 times smaller than the baseline values thus considered to have negligible effects. The current paper reports results for cases with primary reinforcement with spacing s=0.2 m and s=0.6 m, and cases with primary and secondary reinforcement with 0.6 m spacing of primary layers and 0.2 m spacing of secondary layers (s=0.6/02 m).

Total number of investigated cases is 19. Major results for 17 cases of the parametric study, subsequently discussed in the paper, are presented in Tables 1–6.

2.2 *Identified modes of failure*

The effects of secondary reinforcement layers were identified with reference to the predominant mode of failure. As simulated wall construction advanced by adding soil and reinforcement layers, scattered plastic zones developed within the soil mass. The initial state at which a shear zone was fully and consistently developed was termed 'verge–of–failure (VOF)' state. It represents a threshold state in which additional loads result in increasing deformations and progression toward failure. Physically, VOF state is equivalent to the limit equilibrium state. Wall height at VOF state represents the characteristic wall stability for a particular set of model parameters.

Four modes of failure were identified by observing the development of plastic zones within the soil during wall construction: connection, compound, external (direct sliding and toppling), and deepseated. For some models two modes of failure developed almost simultaneously, i.e. at the VOF state one mode prevailed followed closely by a second mode in the subsequent post failure states.

Connection mode of failure is characterized by a shear zone developed entirely within the reinforced zone near the facing (Fig. 1a). It is typical for models with reinforcement spacing larger than 0.4 m without secondary reinforcement.

Compound mode of failure is defined by a shear zone extending through the reinforced and retained zone (Fig. 1b). It is typical for models with very stiff foundation soil, soft (ductile) reinforcement, and models with secondary reinforcement layers (s=0.6/0.2 m).

External mode of failure corresponds to direct sliding/toppling mode with plastic zones evolving predominantly through the retained zone (Fig.1c). It is typical for models with closely spaced reinforcement, stronger reinforced soil and baseline stiff reinforcement.

Deepseated mode of failure represents failure around reinforced zone extending through the foundation soil (Fig. 1d). It is typical for models with close reinforcement spacing and relatively weak foundation soil.

3 EFFECTS OF SHORT REINFORCEMENT LAYERS ON FAILURE MECHANISMS

Effects of short reinforcement layers on failure mechanisms were identified by comparison between cases with primary combined with secondary reinforcement (s=0.6/0.2 m), and cases with primary reinforcement only with spacing equal to 0.2 and 0.6 m. The compound mode prevailed in all cases with primary and secondary reinforcement. The only exception was for the case with weak foundation soil, when at verge of failure the deepseated mode prevailed over the compound. Connection mode of failure was the typical mode of failure for cases without secondary reinforcement and spacing equal to s=0.6 m. For the cases without secondary reinforcement and spacing s=0.2 m, the mode of failure was predominantly external or deepseated, i.e. the shear zone developed outside the reinforced zone. The only exception was the case with weak soil (ϕ=25°) and very stiff foundation, when the compound mode prevailed but was closely followed by the external mode of failure. In general, the introduction of secondary reinforcement layers into models with large reinforcement spacing (s=0.6 m) changed the mode of failure from connection to compound. The extension of the secondary reinforcement layers from 0.3 m to 1.5 m (uniform reinforcement at 0.2 m) changed the prevailing mode of failure from compound to external or deepseated.

Soil strength affected the predominant mode of failure but not to the same extend as the reinforcement spacing and the introduction of secondary reinforcement layers. The very stiff foundation soil affected the predominant mode of failure by preventing the development of plastic zones in the foundation soil.

The effects of reinforcement stiffness on the predominant mode of failure were identified by comparison between cases with baseline reinforcement stiffness (J=2000 kN/m) and cases with reduced reinforcement stiffness (J=200 kN/m). Compound mode of failure was predominant for all cases with soft (ductile) reinforcement even for cases with high strength soil and closely spaced primary reinforcement (s=0.2 and 0.4 m).

4 EFFECTS OF SHORT REINFORCEMENT LAYERS ON WALL STABILITY

Effects on wall stability were identified with respect to wall height at verge of failure. Since the VOF state is equivalent to the limit equilibrium state and no factors of safety are presented, the VOF wall height can be used to evaluate wall 'stability'. It allows comparison between models with different properties with respect to wall stability. For example, the VOF height of the case with primary reinforcement at 0.2 m from Table 6 (ϕ=25°, very stiff foundation) is equal to 4.0 m, while the VOF height of the case with primary reinforcement at 0.6 m from Table 1 (ϕ=45°, baseline stiff foundation) is 3.8 m. The larger VOF height of 4.0 m signifies that the combination of model parameters for this case produces more stable structure then the combination of parameters for the case with VOF height of 3.8 m.

In general, the VOF wall height increases with the increase of soil shear strength, reinforcement stiffness and foundation stiffness, and with the decrease of reinforcement spacing. The introduction of secondary reinforcement layers significantly improved wall stability of models with 0.6 m spacing by stabilizing the reinforced soil at the facing. The closely spaced primary and secondary layers at the facing acted as an "extension" of the block facing, and thus changed the mode of failure from connection to compound, reduced wall deformations, and increased VOF wall height.

5 EFFECTS OF SHORT REINFORCEMENT LAYERS ON FORCES IN REINFORCEMENT

Effects of short reinforcement layers on reinforcement forces were assessed with respect to the maximum forces in primary and secondary layers. Maximum forces at the verge of failure were normalized with respect to the resultant of Rankine's lateral earth pressure, and the results are presented in Tables 1–6. For comparative purposes only, the maximum forces, calculated according to AASHTO design guidelines (AASHTO 1998), are also reported. The maximum forces in the primary reinforcement for the cases with primary and secondary reinforcement were calculated using Leshchinsky's (2000) approach, which is a direct extrapolation of AASHTO. Hence, it is denoted in this paper as 'AASHTO'.

For all investigated cases, the introduction of secondary reinforcement, the increase of soil shear strength, and the reduction in reinforcement spacing and reinforcement stiffness led to significant reduction of maximum reinforcement forces. The change of foundation soil stiffness from baseline to very stiff, also led to reduction in maximum forces in reinforcement.

The elevation and location of maximum force along the reinforcement length also changed. However, the variation was not directly related to changes in model parameters. The location of maximum force was more affected by the predominant mode of failure and the state at which they were captured. In many cases the maximum forces were located at or close to connections for states before or at verge of failure. During post failure states the distribution changed rapidly and depended on the prevailing mode of failure. The current paper is focused on models with pure frictional connection between the blocks. However, the effects of connection type were investigated with models with cohesion in the block–block and block–reinforcement interfaces representing structural type connection. The results show that the connection type affects significantly wall behavior by increasing wall stability and reducing wall deformations especially at the facing. It was observed that the introduction of secondary reinforcement layers always led to alleviation of the connection forces in primary reinforcement by carrying some load at the facing, and thus pushing the maximum force in the primary reinforcement away from connections (Figure 2).

Table 1. Summary of failure modes (ϕ=45°, baseline reinforcement of J=2000 kN/m, baseline stiffness of foundation soil).

Reinforcement spacing	Wall height at verge of failure	VOF maximum force in primary reinforcement*		VOF maximum force in secondary reinforcement*		Prevailing mode of failure
m	m	FLAC	'AASHTO'	FLAC	'AASHTO'	
0.6	3.8	0.269 at El. 0.8 m	0.250 at El. 0.8 m	–	–	1. connection 2. compound
0.6/0.2	4.6	0.199 at El. 1.4 m	0.216 at El. 0.8 m	0.065 at El. 0.6 m	0.093 at El. 0.4 m	compound
0.2	5.6	0.083 at El. 0.6 m	0.104 at El. 0.2 m	–	–	external

* Verge–of–failure (VOT) axial force is normalized with respect to the resultant of Rankine's lateral earth pressure.

Table 2. Summary of failure modes (ϕ=45°, baseline reinforcement of J=2000 kN/m, very stiff foundation soil).

Reinforcement spacing	Wall height at verge of failure	VOF maximum force in primary reinforcement*		VOF maximum force in secondary reinforcement*		Prevailing mode of failure
m	m	FLAC	'AASHTO'	FLAC	'AASHTO'	
0.6	4.6	0.207 at El. 0.8 m	0.216 at El. 0.8 m	–	–	1. compound 2. connection
0.6/0.2	5.4	0.170 at El. 1.4 m	0.182 at El. 0.8 m	0.055 at El. 1.6 m	0.069 at El. 0.4 m	compound
0.2	6.6	0.074 at El. 1.2 m	0.089 at El. 0.2 m	–	–	external

* Verge–of–failure (VOT) axial force is normalized with respect to the resultant of Rankine's lateral earth pressure.

Table 3. Summary of failure modes (ϕ=35°, baseline reinforcement of J=2000 kN/m, baseline stiffness of foundation soil).

Reinforcement spacing	Wall height at verge of failure	VOF maximum force in primary reinforcement*		VOF maximum force in secondary reinforcement*		Prevailing mode of failure
m	m	FLAC	'AASHTO'	FLAC	'AASHTO'	
0.6	1.2	0.475 at El. 0.2 m	0.660 at El. 0.2 m	–	–	connection
0.6/0.2	3.4	0.310 at El. 0.8 m	0.273 at El. 0.2 m	0.088 at El. 0.4	0.104 at El. 0.4 m	1. compound 2. deepseated
0.2	4.2	0.151 at El. 0.2 m	0.138 at El. 0.2 m	–	–	deepseated

* Verge–of–failure (VOT) axial force is normalized with respect to the resultant of Rankine's lateral earth pressure.

Table 4. Summary of failure modes (ϕ=35°, baseline reinforcement of J=2000 kN/m, very stiff foundation soil).

Reinforcement spacing	Wall height at verge of failure	VOF maximum force in primary reinforcement*		VOF maximum force in secondary reinforcement*		Prevailing mode of failure
m	m	FLAC	'AASHTO'	FLAC	'AASHTO'	
0.6	2.6	0.329 at El. 0.8 m	0.318 at El. 0.2 m	–	–	1. connection 2. compound
0.6/0.2	5.0	0.243 at El. 1.4 m	0.202 at El. 0.8 m	0.052 at 0.6 m	0.074 at El. 0.4 m	compound
0.2	5.4	0.095 at El. 0.8	0.108 at El. 0.2 m	–	–	1. external 2. compound

* Verge–of–failure (VOT) axial force is normalized with respect to the resultant of Rankine's lateral earth pressure.

Table 5. Summary of failure modes (ϕ=25°, baseline reinforcement of J=2000 kN/m, baseline stiffness of foundation soil).

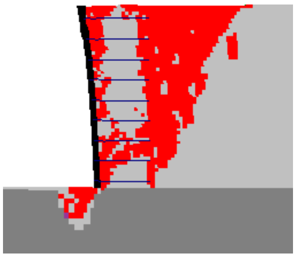
Reinforcement spacing	Wall height at verge of failure	VOF maximum force in primary reinforcement*		VOF maximum force in secondary reinforcement*		Prevailing mode of failure
m	m	FLAC	'AASHTO'	FLAC	'AASHTO'	
0.6	Less than 1.0 m	N/A	N/A	N/A	N/A	connection
0.6/0.2	1.8	0.549 at El. 0.2 m	0.478 at El. 0.2 m	0.161 at El. 0.4 m	0.173 at El. 0.4 m	1. deepseated 2. compound
0.2	2.0	0.274 at El. 0.2 m	0.278 at El. 0.2 m	–	–	deepseated

* Verge–of–failure (VOT) axial force is normalized with respect to the resultant of Rankine's lateral earth pressure.

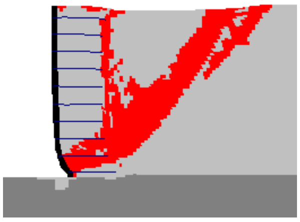
Table 6. Summary of failure modes (ϕ=25°, baseline reinforcement of J=2000 kN/m, very stiff foundation soil).

Reinforcement spacing	Wall height at verge of failure	VOF maximum force in primary reinforcement*		VOF maximum force in secondary reinforcement*		Prevailing mode of failure
m	m	FLAC	'AASHTO'	FLAC	'AASHTO'	
0.6	1.6	0.409 at El. 0.8 m	0.528 at El. 0.2 m	–	–	connection
0.6/0.2	3.0	0.261 at El. 0.80m	0.305 at El. 0.2	0.065 at El. 1.2 m	0.116 at 0.4 m	compound
0.2	4.0	0.133 at El. 0.4 m	0.144 at El. 0.2 m	–	–	1. compound 2. external

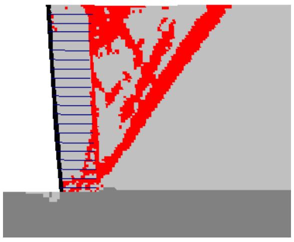
* Verge–of–failure (VOT) axial force is normalized with respect to the resultant of Rankine's lateral earth pressure.



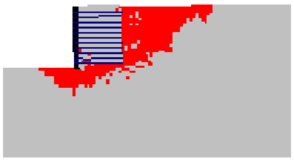
a) Connection mode of failure.



b) Compound mode of failure.

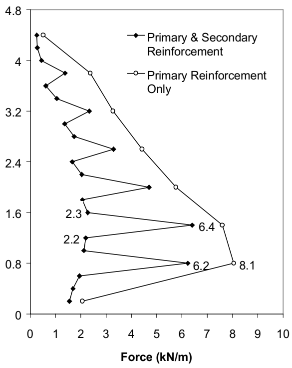


c) External mode of failure.

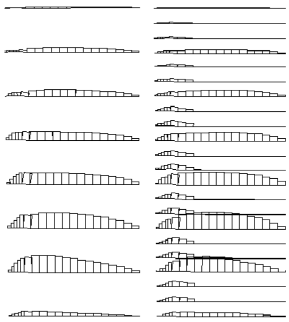


d) Deepseated mode of failure.

Figure 1. Typical modes of failure.



a)



b)

Figure 2. Axial forces in reinforcement (ϕ=45°, baseline reinforcement of J=2000 kN/m, very stiff foundation soil): a) Maximum axial forces in reinforcement; b) Typical distribution of axial force in reinforcement.

6 DESIGN IMPLICATIONS

Because of the complexity of the problem and the limitations of the numerical analysis, further research comprised of field monitoring, laboratory tests and numerical analysis, is desirable to evaluate the effects of reported findings on the design methodologies. For example, there are cases when 'AASHTO' maximum forces in reinforcement were less than the FLAC values at the VOF state, which implies that for these models the AASHTO approach could be relatively unconservative.

Leshchinsky (2000) proposed a computerized design procedure for alleviating the connection load for marginal conditions by considering short reinforcement layers. In summary, the contribution of the secondary layers in the calculations is accounted only at the connections and the result is reduced connection loads, and improved safety factors against pullout or break of the reinforcement at the connections. The validity of this proposal was confirmed for all cases by current numerical analysis. The level of conservatism with reference to AASHTO approach varied from conservative to overly conservative.

7 CONCLUSIONS

The numerical investigation of the effects of secondary short reinforcement layers on the behavior of MSE block walls with geosynthetic reinforcement and pure frictional connection was done with reference to the prevailing failure mechanism. The following major conclusions summarize the identified effects and outline the main aspects of further research:

– The introduction of secondary short reinforcement layers in a model with large reinforcement spacing changed the mode of failure from connection to compound, increased wall stability, and alleviated connection loads
– The extension of the secondary reinforcement layers from 0.3 m to 1.5 m (uniform reinforcement at 0.2 m) changed the prevailing mode of failure from compound to external or deepseated, increased wall stability, and reduced the maximum forces in the reinforcement
– Soil shear strength affected the predominant mode of failure but not to the same extend as the reinforcement spacing and the introduction of secondary reinforcement layers. The increase of soil shear strength led to an increase of wall stability and decrease of reinforcement forces
– The very stiff foundation soil affected the predominant mode of failure by preventing the development of plastic zones in the foundation soil. The cases with very stiff foundation were more stable and developed smaller reinforcement forces than cases with baseline stiff foundation soil
– The decrease of reinforcement stiffness from baseline stiff (J=2000kN/m) to soft (J=200kN/m) changed the prevailing mode of failure to compound mode even for cases with high strength soil and closely spaced primary reinforcement. It also led to a decrease of wall height at verge of failure and maximum forces in reinforcement
– The numerical model captured effects like pullout of reinforcement at the top of wall for models experiencing connection mode of failure, alteration of maximum force location of during wall construction, and development and progression of failure mechanisms.

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