Numerical modeling of a MSE wall under water infiltration using unsaturated soil properties

La modélisation numérique d'infiltration d'eau dans un mur de MSE en utilisant des propriétés de sols non saturés

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ABSTRACT
A 5.4-m high MSE wall constructed with marginal fills in the Research Triangle Park (RTP) of North Carolina experienced a localized failure in March, 2001, during a rainy period shortly after completion of wall construction. In this study, numerical simulations with unsaturated soil properties (elastic modulus, shear strength and permeability) were performed to provide better understanding of the behavior of this MSE wall at the end of construction and during rainfall.

RÉSUMÉ
Un mur de MSE d'une hauteur de 5.4 m construit avec du remblai marginal dans le Parc du Triangle de Recherches (RTP) de la Caroline du Nord a éprouvé une défaillance localisée lors d'une période pluvieuse peu après sa construction. Dans cette étude, des simulations numériques (modulus d'élasticité, force pure et perméabilité) furent effectuées pour fournir une meilleure compréhension du comportement de ce mur de MSE après sa construction et postérieurement lors de précipitations.

Keywords : MSE wall, unsaturated soil, infiltration, FLAC

1 INTRODUCTION

Prediction of MSE wall deformation due to rainfall infiltration is a complicated problem which includes seepage, shear strength, and volume change based on unsaturated soil mechanics principles. Several researchers have showed the failure mechanism of an earth structure due to rain infiltration using unsaturated shear strength based on limit equilibrium analysis. However, there are still several existing limitations for performing stress-deformation analyses based on unsaturated soil behavior. This is mainly due to the complexities of analysis utilizing the unsaturated soil constitutive law and the increased difficulties of performing experimental studies on unsaturated soils. Another major limitation is that most numerical simulation programs were developed assuming saturated soil mechanics and therefore adopted one stress state variable (either total stress or effective stress) to predict soil behavior. However, unsaturated soil behavior is explained using two stress state variables (net normal stress and matric suction) (Fredlund and Rahardjo, 1993). For the reasons mentioned above, prediction of soil behavior subjected to changes of both stress state variables is challenging.

A 5.4-m high MSE wall constructed with marginal fills in the Research Triangle Park (RTP) of North Carolina experienced a localized collapse in March, 2001 during a rainy period a few months after completion of wall construction. Since compacted soils are used as backfills, unsaturated soil mechanics plays a dominant role in the behavior of MSE walls. In this study, numerical simulations with unsaturated soil properties (elastic modulus and shear strength) were performed to provide better understanding of the behavior of the MSE wall both at the end of construction and during rainfall. The post-failure site investigation of the MSE wall showed that the backfill was possibly compacted very dry of optimum and that the backfill within a 1.2m- to 1.8m- wide zone behind the wall face was not properly compacted. Therefore, the effects of the low as-compacted water content and poorly compacted zone on the behavior of wall are highlighted.

2 PROJECT DESCRIPTION

The RTP MSE wall geometry and cross section are shown in Figure 1. The wall was built with 11 layers of 4.75m long polyester geogrid reinforcement (Fortrac 35/20-20 Geogrid, Huesker Inc.). Vertical spacings of reinforcements varied from 0.2m to 0.6m throughout the wall height, as shown in Figure 1. Commercially available Rockwood blocks (Classic 8, Rockwood retaining walls Inc.) were used as the facing system unit. The blocks were 300mm deep, 200mm high, and 450mm wide, and had a mass of 35 kg per unit. The facing batter of the wall was approximately 7 degrees from vertical, and the 2m-high back-slope portion (18 degrees) extended from the wall face. Crushed gravel (No. 57 stone) was used to infill the spaces between adjoining modular block units and to create a 300-mm thick drainage layer behind the wall facing. The connection between blocks relied on the friction between the contact block material and gravel material filled in the blocks. The locally available low plasticity silty soil (I_P =10) was used as backfill for the wall. According to the Unified Soil Classification System (USCS), the soil was classified as CL. The standard proctor test yielded a maximum dry density of 1.90g/cm^3 with an optimum water content of 11.7%.

3 NUMERICAL MODELING

In this study, efforts were made to investigate the behavior of the MSE wall using unsaturated soil properties as a function of soil suction. Special attention was given to modeling the relatively dry, low density zone behind the wall face. This poorly compacted zone could have occurred because this 1.2m- to 1.8m- wide zone of backfill was only lightly hand-compacted in order to avoid movements of the wall face. Therefore, this research focused on the behavior of the MSE wall assuming it was constructed with backfill compacted very dry side optimum (w = 4.8%, -7% of OMC). Also, the poorly compacted zone behind the wall face (1.6m wide) was taken into account in the simulation. The properties of soils compacted to dry densities of 1.79 g/cm^3 (R.C.= 94%) and 1.60 g/cm^3 (R.C.= 84%) were used

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to simulate well and poorly compacted backfills, respectively. These well and poorly compacted backfills were designated as soil H and soil L.

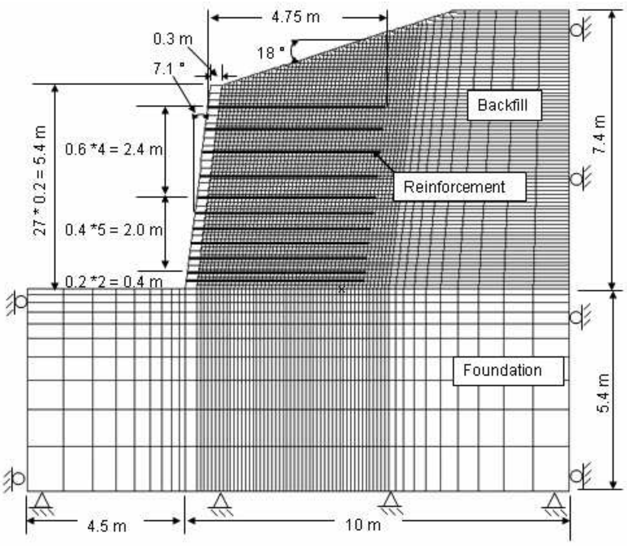

Figure 1. MSE wall geometry and numerical model used in FLAC

3.1 *FLAC model*

The finite difference code, FLAC (Itasca, 2000), was used to simulate the response of the reinforced wall during wall construction. The FLAC program has an excellent capability of modeling geotechnical engineering related stability problems and an extended programming ability providing a FISH programming code to allow users to define their own constitutive material model.

Figure 1 shows the numerical grids used for the MSE wall. The simulation modeled the sequential bottom-up construction of the wall facing, soil and reinforcement. The backfill and facing units of the wall model were elevated in lifts of 0.2 m, which was the same as the height of the modular block units, and the reinforcement layers were placed in the model as each reinforcement elevation was reached.

Lee (2000) developed a FLAC numerical model that was able to predict the behavior of a geosynthetic reinforced retaining wall at the end of construction. Figure 2 shows a cross section of a MSE wall model developed in FLAC. Elastic material elements were used to represent modular blocks, and Mohr-Coulomb material elements were used to represent the gravel column and the MSE wall backfill. The hyperbolic model with plain strain soil properties was used to simulate the gravel column response (Table 1). The behavior of the geosynthetic reinforcements was simulated using the cable element (Table 2) and interface elements were used to describe the interaction between backfill soil and modular block and interfaces between modular blocks (Table 3). Details for properties of cable and interface elements can be found in the FLAC manual (Itasca, 2000)

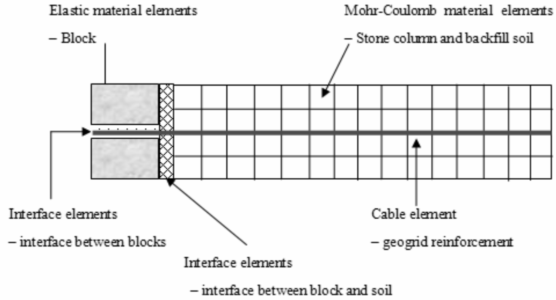

Figure 2. MSE wall modeled using FLAC (after Lee, 2000)

Table 1. Input properties for gravel column (extracted from Lee, 2000)

Properties	Values
Friction angle (ϕ)	55°
Dilation angle (ψ)	20°
Modulus number, *K*	4000
Failure ratio, R_f	0.73
Modulus exponent, *n*	0.5

Table 2. Summary of reinforcement input properties

Reinforcement Input properties	Within blocks	Within backfills
Young's modulus, *E*(kN/m^2)	84	84
Tensile yield strength, *Yield* (kN)	35	35
Compressive yield strength, *ycomp* (kN)	0.01	0.01
Shear stiffness, *kbond* (kN/m/m)	110.5× (σ_y)+3302	-
Cohesive strength, *sbond* (kN/m/m)	6.8 (if σ_y < 34.3 kPa) 28 (if σ_y >= 34.3 kPa)	-
Friction angle, *sfric* (degree)	20.5(if σ_y < 34.3 kPa) 48.7(if σ_y >=34.3 kPa)	-

Table 3. Summary of interface input properties

Interface input properties	Block-Block	Block-Soil
Normal stiffness, k_n (kN/m/m)	10.95×10^7	1×10^6
Shear stiffness, k_s (kN/m/m)	8500	8500
Friction angle, *fric* (degrees)	55°	55°

3.2 *Method of analysis*

A series of numerical simulations with unsaturated soil properties were performed in order to investigate the MSE wall behavior constructed during rainfall infiltration. Figure 3 shows the procedural flow chart that was used in this study. Details of each step of analysis are described as follows.

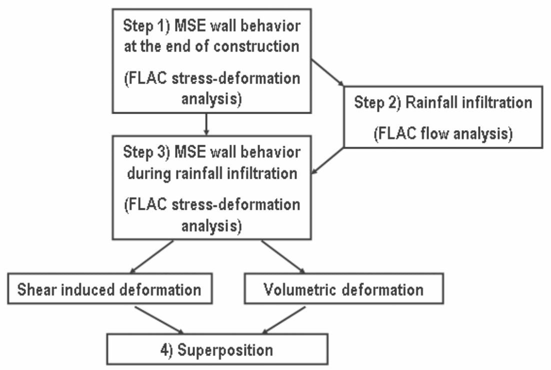

Figure 3. Analysis algorithm flow chart

3.2.1 *Step 1: Numerical simulation for the MSE wall behavior during construction*

The behavior of the MSE wall at the end of construction was predicted using the developed FLAC model that accounted for unsaturated soil properties (elastic modulus and shear strength) and the staged construction of the wall. The matric suction change due to loading (lifts of backfill) was computed in the model, and the properties of construction materials such as reinforcement, interfaces, and backfills were updated by the developed FISH subroutines based on changes in total normal stress and matric suction. The matric suction distribution within the backfill at the end of construction was stored in a data file and used as initial values in the subsequent flow analysis.

Based on the Soil-Water Characteristic Curve (SWCC) (Figure 4) and saturated strength parameters, shear strength under zero net normal stress (total cohesion, c) was predicted as shown in Figure 5. Vanapalli et al.'s procedure (1996) with

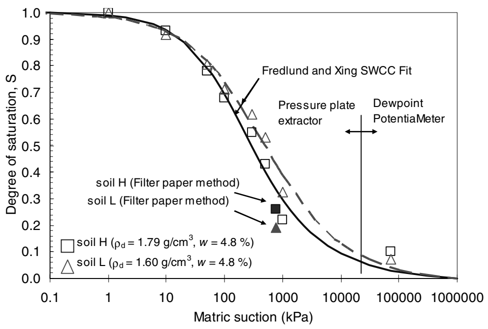

Figure 4. SWCC fits for the entire suction range

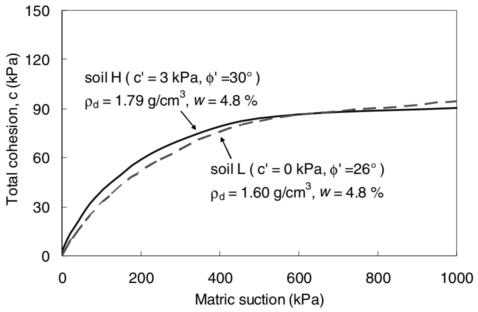

Figure 5. Total cohesion with respect to matric suction

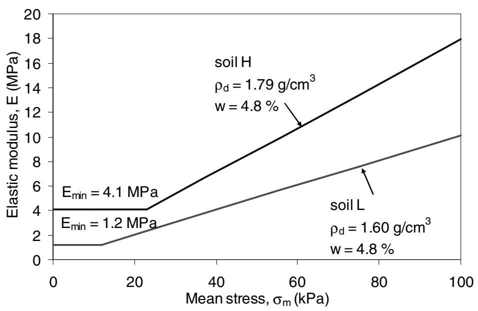

Figure 6. Undrained modulus functions with respect to mean stress

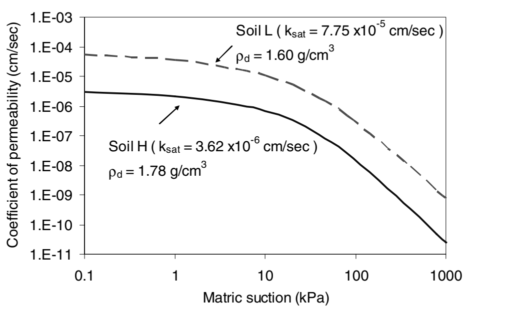

Figure 7. Coefficients of permeability with respect to matric suction

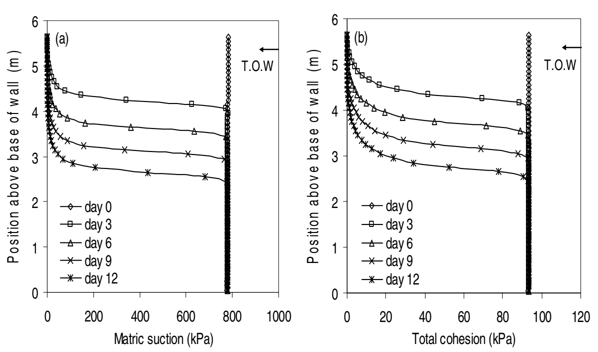

Figure 8. Profiles of (a) matric suction and (b) total cohesion at section-I

fixed residual suction value of 3000 kPa was adopted as a prediction method. Figure 6 shows undrained modulus functions with respect to mean stress for soils H and L. These functions were determined from the predicted pore pressure parameter, B' (=$\Delta u_w / \Delta \sigma_y$) and the drained constitutive relation that was measured from the conventional oedometer test. The prediction of pore pressure parameter was accomplished by modifying Hilf's equation (1948). The computed B' values for soils H and L were 0.06 and 0.1, respectively. The initial values of matric suction for soil H and L were 783 kPa (Rorie, 2006).

3.3.2 *Step 2: Transient seepage analysis for rainfall infiltration*

Transient seepage analysis using unsaturated permeability was conducted in order to estimate changes of matric suction within the backfill due to rainfall infiltration. van Genuchten equation (1980) was used in the model to predict coefficient of permeability functions with respect to matric suction (Figure 7). The matric suction distribution at the end of wall construction, which was computed in the previous step (step 1), was used as the initial condition for the seepage analysis. When the desired rainfall period (3, 6, 9, and 12days) was reached during the simulation, the matric suction distribution was stored in a data file. These stored values of matric suction were recalled and used in the following stress-deformation analysis

3.3.3 *Step 3: Numerical simulation for the MSE wall behavior during rainfall filtration*

Post-construction wetting of compacted backfill causes wall deformations. Two factors that induce the wall deformation due to wetting were considered in this study. These two factors are described as following:

a) *shear induced deformation*

Wetting generally results in significant loss of shear strength as well as increases in total unit weight. These adverse changes induce yielding of soil, and, in turn, plastic deformations.

Figure 8 shows the matric suction and total cohesion profiles during rainfall infiltration along section-I, located 1.4 m behind the wall face (in the middle of the poor quality backfill zone). Significant decreases (from 93kPa to 0kPa) in total cohesion are observed in the upper portion of the wall and the depth of this shear strength decreased zone increases as the rainfall period increases.

b) *volumetric deformation*

Matric suction change due to wetting causes volumetric deformation. Expansive behavior occurs in high density soils with high plasticity under relatively low stress conditions, and collapse behavior is observed in an open, partially unstable, partially unsaturated soil (i.e. soils compacted dry of optimum at low density) under relatively high stress conditions.

Noorany et al. (1999) developed a model for slope response analysis to compute wetting-induced slope deformation using FLAC. In his model, the wetting stresses were calculated from the wetting strain using the incremental form of Hooke's law. The wetting stresses were then added to the initial stresses within the soil elements and the FLAC model was cycled to equilibrium. In this research, several advanced features were added to the model developed by Noorany et al. First, the changes in degree of saturation due to water infiltration were smoothly defined from unsaturated flow analysis, as intermediate values between initial and saturated conditions were evaluated, rather than defined as one of two extreme conditions (either initial or saturated) by the prescribed wetting front. Also, the amount of volumetric strain in the process of wetting (between initial and saturated conditions) was estimated by the Percent Collapse Potential, *PCP*. The value of *PCP* was determined from the SWCC, assuming the wetting strain magnitude is proportional to the amount of moisture gain. Figure 9 shows the results of one dimensional oedometer tests for soils H and L. Only vertical strains were used as input to the FLAC model.

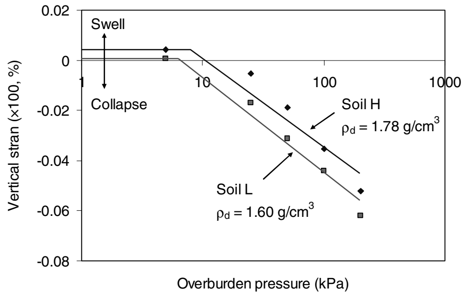

Figure 9. Measured collapse potentials (soils H and L) and the best-fit logarithmic functions (after Rorie, 2006)

3.3.4 *Step4: Superposition of the results*

As a final step, the results (lateral and vertical displacements within the solution domain and axial strain in the reinforcement) from the two numerical simulations described in step 3 were combined.

4 RESULTS

The matric suction distributions of backfills during rainfall periods from the seepage analysis are shown in Figure 10. It is clearly shown that there is a substantial difference between the infiltration depths in the poorly and well compacted zones. From the results as shown in Figure 10, the infiltration depth in the poor quality compaction zone is about 3m after the 12-days of surface water, while a relative shallow advancing "wetting front" (less than 1m) is developed in the well compacted zone, due to the lower water permeability of the denser material.

The "total" displacements are estimated by summing up the displacements induced by (1) decreases of shear strength and (2) volumetric strain of backfill soils due to wetting. Figure 11 shows the face-deflection and vertical-displacement profiles during the 12-day rainfall from the end of the construction condition. It can be seen that the magnitude of the increased displacements become larger from the top of the wall (ground surface), and that the zone of significant displacement increases in depth. After 12-days of rainfall, the maximum values of the wall-face deflection and vertical displacements are predicted to be 33 mm and 74 mm, respectively. The locations of these maximum values are found at 0.6h and 0.8h, respectively (where h is the height of the MSE wall), which are higher than those at the end of construction (approximately 0.5h).

As the reinforcement is modeled with a cable element, the compressive yield strength is set to a very small value (*ycomp* = 0.01kN). This maintains the minimal compressive forces believed to exist in the actual wall. In the simulations, the axial strains produced within each reinforcement layer, for each simulation step, are superimposed and then converted to the resulting tension force using the reinforcement stiffness and

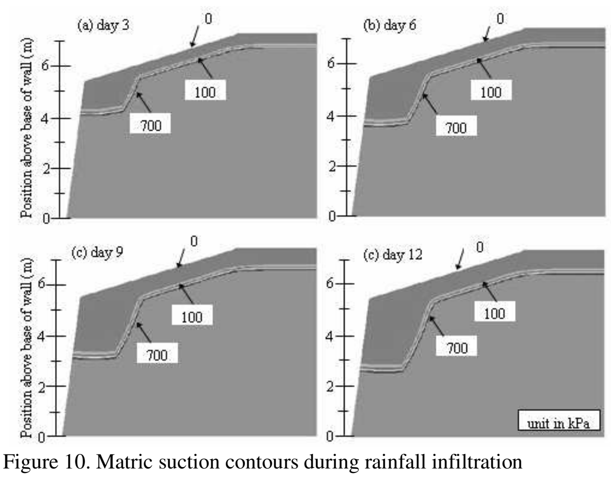

Figure 10. Matric suction contours during rainfall infiltration

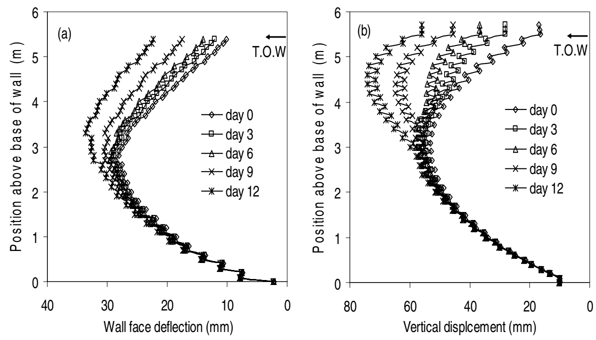

Figure 11. Variation of wall movement during rainfall infiltration: (a) Wall face lateral deflection and (b) Vertical displacement at section-I

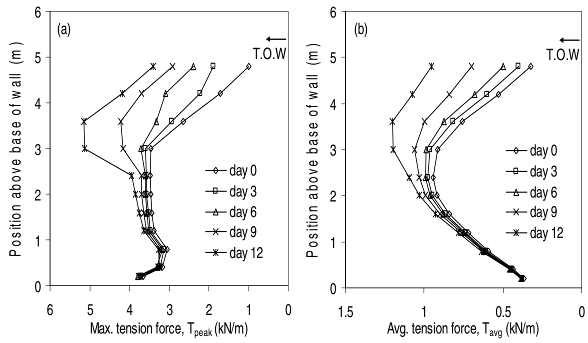

Figure 12. Variation of reinforcement tension during rainfall infiltration: (a) Maximum tension, T_{peak} and (b) Average tension, T_{avg}

cross-sectional area. The maximum tension forces, T_{peak}, and the average tension forces, T_{avg}, for each layer along the wall height are shown in Figures 12(a) and (b), respectively. After 12-days of infiltration, the maximum values of T_{peak} and T_{avg} of all layers inside the MSE wall (defined as T_{peak_max} and T_{avg_max}, respectively) are computed to be 5.1kN and 1.2kN, respectively, and both are found in the third layer down from the top of wall.

5 CONCLUSIONS

In order to predict the MSE wall behavior induced by rainfall or ground surface water infiltration, a series of numerical analyses that included transient flow analysis and stress-deformation analysis were performed using the finite difference code FLAC. The simulation results showed the wall displacement and reinforcement tension increased at an increasing rate as the infiltration depth increased.

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