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Effect of Reinforcement on Stability of Slopes using GEOSLOPE

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ABSTRACT

This paper deals with slope stability evolutions by limit equilibrium (LE) methods and compared with the results from GEOSLOPE software. The LE based methods are compared based on the factor of safety (FOS) obtained from various conditions with simplified slope geometry and assumed input parameters. The Bishop simplified Method (BSM) and Janbu simplified Method (JSM) is compared with Morgenstern-Price method (M-PM) and it is seen that the prediction of the most critical slip surface is influenced by the search technique. The comparative study among the LE methods showed that BSM is as good as M-PM for normal condition in circular shear surface (CSS) analysis whereas simplified Janbu (JSM) method gives the most conservative value of the FOS.

1. INTRODUCTION

Slope stability analysis using computers is not a tough job for engineers provided the slope configuration and soil parameters are well known. However, the selection of method of analysis is a difficult task. Therefore, efforts should be made to collect the field data and the failure observations in order to understand the failure mechanism, which determines the slope stability method applicable for analysis.

Presently, stability of slope can be analyzed using several geotechnical-software. *GEOSLOPE* is one them, developed by *GEO-SLOPE* International, Canada, based on limit equilibrium principles which also incorporates a finite element package, developed specifically for the analysis of deformation and stability of geotechnical structures. It includes stability modeling (*SLOPE/W*), seepage modeling (*SEEP/W*), stress and deformation modeling (*SIGMA/W*), dynamic modeling (*QUAKE/W*), thermal modeling (*TEMP/W*), containment modeling (*CTRAN/W*) and vadose zone modeling (*VADOSE/W*).

SLOPE/W is a component of a complete suite of geotechnical products called GeoStudio. SLOPE/W has been designed and developed to be a general software tool for the stability analysis of earth structures. SLOPE/W has five sub routines: 1) Geometry – description of stratigraphy and shapes of potential slip surfaces, 2) Soil strength – parameters used to define the soil (material) strength, 3) Pore water pressure – means of defining the pore water pressure conditions, 4) Reinforcement or soil-structure interaction – fabric, nails, anchors, piles, walls, and so forth, and 5) Imposed loading – surcharges or dynamic earthquake loads.

2. METHODOLOGY

In this study, *SLOPE/W* has been applied separately and together with *SEEP/W*. Three types of *CSS* searching techniques: *Grid-radius*, *Entry-exit*, and *Auto-locate* were used. The most common *LE* based methods (*BSM*, *JSM* and *M-PM*), which are incorporated in *SLOPE/W*, were considered for comparison purposes.

A total of six situations were studied:

(i) Stability analysis of an unreinforced dry slope,

(ii) Stability analysis of a reinforced dry slope,

(iii) Stability analysis of an unreinforced wet slope,

(iv) Stability analysis of a reinforced wet slope,

(v) Stability analysis of an unreinforced wet slope using *SEEP/W* generated pore pressures, and

(vi) Stability analysis of a reinforced wet slope using *SEEP/W* generated pore pressures.

2.1 Stability Analysis of an Unreinforced Dry Slope

The objective of the analysis was to compute the minimum factor of safety and locate the critical slip surface. Figure 1 presents the schematic diagram of the dry slope considered for the present study. The slope (2-horizontal: 1-vertical) is having total height of 10 m over rock at 5 m below the base of the cut.

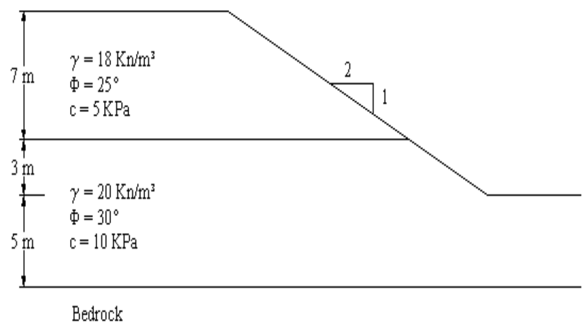

Fig. 1 Schematic diagram of a dry slope

The problem was first modeled in *SLOPE/W* using a Mohr-Coulomb soil model without tension cracks and solved using *JSM*, *BSM* and *M-PM* with half-sine inter-slice force function. The *CSS* is searched by *grid-radius*, *entry-exit* and *auto-locate* options and the corresponding *FOS*s were computed (Table 1). The *CSS* corresponding to lowest *FOS* obtained is shown in Fig. 2.

Table 1 *FOS* of an unreinforced dry slope

GEOSLOPE (SLOPE/W)			
Slope stability method used	*CSS* Searching Method Used		
	Auto-locate	Entry-exit	Grid-radius
JSM	***1.470***	1.672	1.806
BSM	1.513	1.734	1.983
M-PM	1.515	1.745	1.990

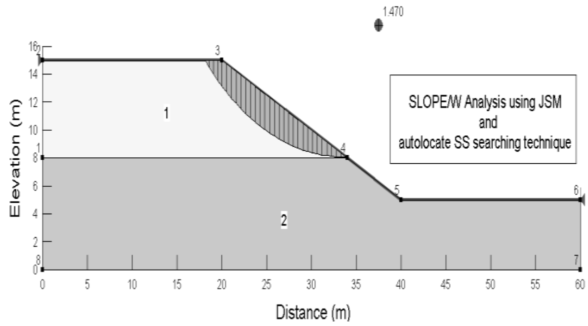

Fig. 2 *CSS* for *SLOPE/W* Analysis using *JSM* and *auto-locate SS* for a dry unreinforced slope

2.2 Stability Analysis of a Reinforced Dry Slope

The same dry slope was considered to be reinforced with geotextile. A woven geotextile having tensile strength of 400 t/m with a contact 'c' of 3 kPa and a contact 'φ' of 38° was used as reinforcement. *Strip Tensile Test* was conducted to determine the tensile strength of the geotextile. A test specimen was clamped in a tensile testing machine (Fig. 3) and forced it until it fails. The specimen was of size 50 mm × 300 mm with the longer side parallel to the test direction. The tensile strength of the geotextile was found to be 400 t/m at 25% of strain. This properties was used in model (Fig. 4) in *SLOPE/W* in a similar manner using a Mohr-Coulomb soil model without tension cracks and solved using *JSM, BSM* and *M-PM* with half-sine inter-slice force function. The *CSS* was searched with *grid-radius, entry-exit* and *auto-locate* and the corresponding *FOS*s were computed (Table 2).

Fig. 3 Strip tensile test of geotextile

Table 2 *FOS* of a reinforced dry slope

GEOSLOPE (SLOPE/W)			
Slope stability method used	*CSS* Searching Method Used		
	Auto-locate	Entry-exit	Grid-radius
JSM	***1.865***	2.020	2.216
BSM	1.953	2.240	2.345
M-PM	1.943	2.245	2.348

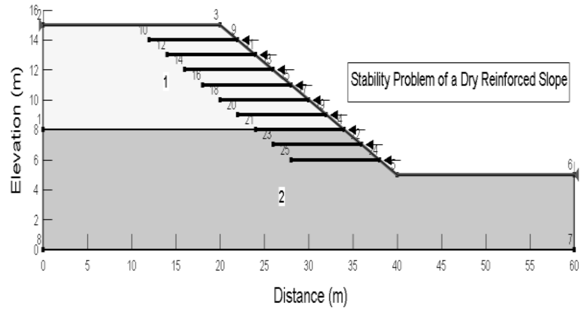

Fig. 4 Geometric model of a dry reinforced slope

2.3 Stability Analysis of an Unreinforced Wet Slope

The presence of water in slope was considered as wet slope. Two cases were considered; 1) The water table was assumed to be located at an elevation of 10 m from bedrock and the pore pressure condition was assumed to be hydrostatic and 2) Downstream water table is assumed to be at elevation of 5 m. Here the pore pressure profile is obtained from the seepage analyses using SEEP/W. Figure 5 shows the schematic diagram of the wet slope. The problem was modeled in *SLOPE/W* using Mohr-Coulomb soil model without tension cracks and solved using *JSM*, *BSM* and *M-PM* with half-sine inter-slice force function. The *CSS* was similarly searched with *grid-radius*, *entry-exit* and *auto-locate* and the corresponding *FOS*s were computed (Table 3).

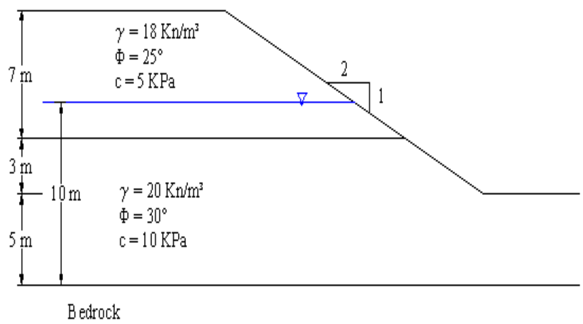

Fig. 5 Schematic diagram of the wet slope

Table 3 *FOS* of an unreinforced wet slope

GEOSLOPE (SLOPE/W)			
Slope stability method used	*CSS* Searching Method Used		
	Auto-locate	Entry-exit	Grid-radius
JSM	***1.295***	1.501	1.623
BSM	1.390	1.571	1.787
M-PM	1.374	1.583	1.795

2.4 Stability Analysis of a Reinforced Wet Slope

The same wet slope was considered to be reinforced with the same geotextile and it was modeled in *SLOPE/W* in similar manner using Mohr-Coulomb model without tension cracks and solved using *JSM, BSM* and *M-PM* with half-sine inter-slice force function. The *CSS* was searched by *grid-radius, entry-exit* and *auto-locate* and corresponding *FOS*s were computed (Table 4). The *CSS* corresponding to lowest *FOS* obtained is shown in Fig. 6.

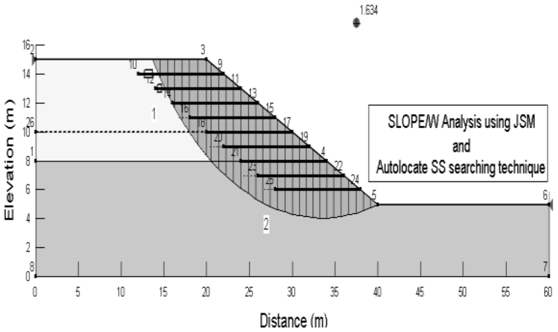

Fig. 6 *CSS* for *SLOPE/W* analysis using *JSM* and auto-locate *SS* for a wet reinforced slope

Table 4 *FOS* of a reinforced wet slope

GEOSLOPE (SLOPE/W)			
Slope stability method used	*CSS* Searching Method Used		
	Auto-locate	Entry-exit	Grid-radius
JSM	***1.634***	1.661	1.964
BSM	1.751	1.832	2.106
M-PM	1.719	1.840	2.110

2.5 Stability Analysis of a Wet Unreinforced Slope Using *SEEP/W* Generated Pore Pressure

The problem geometry of the dry slope discussed in earlier section is considered here also. Downstream water table was assumed to be at elevation of 5 m. Here the pore pressure profile was obtained from the seepage analysis. The pore pressure distributions were first analyzed separately in *SEEP/W*. The *SEEP/W* software computes the pore pressure using finite element mesh. *SEEP/W* uses a *steady-state two dimensional* analysis. Assumed K_{sat} of upper and lower soil were 10^{-3} m/day and 10^{-5} m/day respectively. Each hydraulic conductivity function were defined as a two point function with Point#1 was at P = 0 and K_{sat} while Point #2 was at P = -100 and $K_{sat}/100$. Steady-state infiltration rate, $q = 5.0 \times 10^{-5}$ m/day was assumed over the surface. *Potential seepage review* along the face of the slope was used. The analyzed pore pressure was stored in an internal *SIGMA/W* file and was used in *SLOPE/W* (Fig.7) analysis for computation of the corresponding *FOS*. This internal *SIGMA/W* file was flagged in the *Keyin analysis settings* menu of *SLOPE/W* environment. The *CSS* was searched by *grid-radius, entry-exit* and *auto-locate* and the corresponding *FOS*s were computed (Table 5). The *CSS* corresponding to lowest *FOS* obtained is shown in Fig. 8.

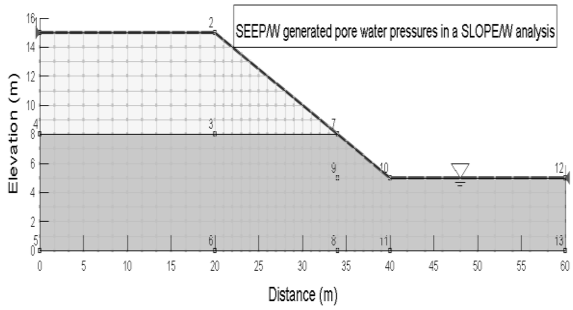

Fig. 7 *SEEP/W* generated pore water pressures in a *SLOPE/W* analysis

Table 5 *FOS* of an unreinforced wet slope using *SEEP/W* generated pore pressures

GEOSLOPE (SLOPE/W + SEEP/W)			
Slope stability method used	*CSS* Searching Method Used		
	Auto-locate	Entry-exit	Grid-radius
JSM	***0.929***	1.009	1.116
BSM	0.992	1.127	1.213
M-PM	0.984	1.146	1.229

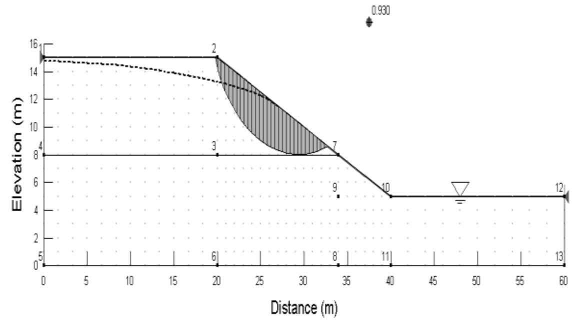

Fig. 8 *CSS* for *SEEP/W* generated pore water pressures in a *SLOPE/W* analysis using *JSM* and auto-locate *SS* searching technique for an unreinforced slope

2.6 Stability Analysis of a Wet Reinforced Slope Using *SEEP/W* Generated Pore Pressure

The problem presented in previous case is now considered to be reinforced with geotextile having tensile strength of 400 t/m with a contact 'c' of 3 kPa and a contact 'φ' of 38^0. The pore pressure profile is obtained from the *SEEP/W* analysis carried out for the previous section and used in *SLOPE/W* analysis for computation of the corresponding *FOS*s. The *CSS* was searched by *grid-radius, entry-exit* and *auto-locate* and the corresponding *FOS*s were computed (Table 6). The CSS corresponding to lowest *FOS* obtained is shown in Fig. 9.

Table 6 *FOS* of an unreinforced wet slope using SEEP/W generated pore pressures

GEOSLOPE (SLOPE/W + SEEP/W)			
Slope stability method used	*CSS* Searching Method Used		
	Auto-locate	Entry-exit	Grid-radius
JSM	***1.143***	1.183	1.406
BSM	1.193	1.306	1.529
M-PM	1.195	1.329	1.541

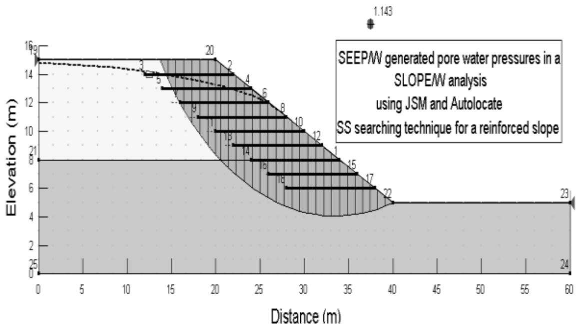

Fig. 9 *CSS* for *SEEP/W* generated pore water pressures in a *SLOPE/W* analysis using *JSM* and auto-locate *SS* searching technique for a reinforced slope

3. CONCLUSIONS

The scope of this study was to compare various stability evaluation methods using *GEOSLOPE*. Accordingly, most common *LE* approaches were compared with the advanced *LE* (*M-PM*) method. The main findings from the studies are summarized as follows:

1. Prediction of the most critical slip surface is influenced by the search technique.
2. The *BSM* method either over or underestimates the *FOS*.
3. The simplified Janbu (*JSM*) method gives the most conservative value of the *FOS*.
4. The Auto-locate *SS* searching method is recommended for use in *LE* methods of slope stability.
5. Inclusion of reinforcement improves the FOS by 12-30%.
6. *SEEP/W* generated pore pressure conditions are recommended to use while analyzing wet slopes.

In future, further research on slope stability analysis in unsaturated soils can be done, focusing on particular measures that can increase or maintain suction during rainfall infiltration. The FE methods are best suited for external loads, complicated geometry and more realistic normal stress distributions and resulting FOS. Hence, further research on the FE analysis can also be done using the stability evaluations with investigated relevant soil parameters. 3-D solution is always better than 2-D solutions. Thus, slope stability analyses results obtained from 2D analyses, can be compared with 3-D results which would be more efficient and cost effective. A detailed study on dynamic response is a good future research option by conducting resonance column test for site specific damping ratio.

4. REFERENCES

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