The effect of dispersed rock pieces on the stability of a slope made of soil-rock mixtures

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Abstract

Many natural slopes are made of mixtures of soil and rocks. Previous direct shear, ring shear and tri-axial compression tests on soil-rock mixtures have indicated that: (a) the shear strength of the mixtures was totally controlled by the shear strength of the soil matrix (zero influence on the strength by the rock pieces), if the rock pieces in the mixture had a volume concentration, C, smaller than 31%; (b) the shear strength of the mixtures was partially controlled by by the frictional strength between the rock particles if C varied between 31% and 40%; and (c) the shear strength of the mixtures was completely controlled by the frictional shear strength between the rock pieces if the C of the rock pieces was greater than 40%. This study was designed to validate the results of the previous shear strength tests on soil-rock mixtures using the stability analysis of a slope made of different volume concentration of the rock pieces, C. To accomplish this, the stability of a vertical slope made of a simulated soil-rock mixtures with values of $C \geq 0\%$ but $\leq 40\%$, was evaluated in order to determine how the C of the rock pieces in the mixture influenced the factor of safety (FOS) values. The stability analysis was made using the shear strength reduction method and the Finite Element Method (FEM). From the stability analysis it was found that the limits of shear strength obtained from the laboratory shear strength tests at which the volume concentration (C) of rock pieces has zero, partial and total influence on the FOS were found to be lower than the limits provided by the laboratory shear strength tests. From the stability analysis, if $C \leq 24\%$, the factor of safety (FOS) of the slope remained unchanged (the frictional strength of the rock pieces has zero influence on the stability of the slope). When the value of $C > 24\%$ but $\leq 32\%$, the FOS increased substantially (the frictional strength between rock pieces partially controlled the stability). When the value of $C > 32\%$, the FOS remained unchaged and the stability of the slope was completely controlled by the frictional strength between the rock pieces.

1 INTRODUCTION

Direct and ring shear tests as well as tri-axial compression tests conducted by Holtz and Gibbs (1956), Holtz and Ellis (1961), Paduana (1966), Kurata and Fujishita (1960), Doddiah et al., (1969), Vasileva et al. (1971), Marsal and Fuentes de la Rosa (1976), Lupini et al. (1981), Fragaszy et al. (1992), Vallejo and Mawby (2000) and Vallejo (2001) on mixtures of cohesive soils with dispersed (not touching) oversized rock particles as well as on mixtures of granular materials with dispersed (floating) oversized rock particles have indicated that that the shear strength of the mixtures depends upon the relative concentration by volume (or weight) of the oversized particles in the mixtures. These researchers found that if the concentration by volume was greater than 40% (62% by weight), the shear strength of the mixtures was basically that of the large particles alone. If the concentration by volume of the large particles in the mixtures was between 40% and 31 % (62% and 48% by weight), the shear strength of the mixtures was partially controlled by the friction between the large particles. If the concentration by volume of the large particles was less than 31% (<48% by weight), the shear strength of the mixtures was that of the soil matrix in the mixtures.

The objective of this study was to make a slope stability analysis of a slope with a vertical face (Fig. 1) made of a soil-rock mixture. The stability analysis of the slope was made using a soil-rock mixture that contained different volume concentrations, C, of the large dispersed (not touching) rock particles in the mixture. The value of C was varied between 0% and 40%. If the volume concentration of the large particles in the soil-rock mixture increases between 0% and 31%, the Factor of Safety (FOS) of the slope should remain constant. If this is the case, the results of the direct shear, ring shear and tri-axial compression tests on soil-rock mixtures with C ≤ 31% will be validated. The stability analysis was made using the Strength Reduction Factor (SRF) that was implemented into the Finite Element Method (ABACUS, 2006) assuming it to be a continuously changing variable.

Figure 1. Vertical slope made of a soil-rock mixture and located on Cape Breton Island, Canada (public domain photo from NASA's Earth Science Division; height of slope 6.1 meters)

2 FINITE ELEMENT ANALYSIS

2.1 The strength reduction factor method

In the strength reduction factor (SRF) technique, the factor of safety (FOS) of a slope against failure can be evaluated by reducing the soil-rock mixture shear parameters in a sequence of analyses until collapse occurs. Collapse represents large displacements in the soil-rock mixture. This technique was introduced by Zienkiewicz et al. (1975) and has undergone extensive development since then (Griffiths and Lane, 1999).

In a finite element analysis, the analysis commences before failure is initiated (FOS>1). In this case the mobilized shear stress in the soil-rock mixture is less than its shear strength. The resisting forces and moments can be reduced by reducing the shear strength parameters. This can be achieved systematically in a finite element analysis by reducing the nominal cohesion, c, and friction angle, ϕ, of the soil by a reduction factor, SRF [Eqs. (1) and (2)]. The strength parameters used in the analysis will therefore be:

$$c_f = \frac{c}{SRF} \quad (1)$$

$$\tan\phi_f = \frac{\tan\phi}{SRF} \quad (2)$$

where c_f and ϕ_f are the reduced shear strength parameters and SRF is the shear strength reduction factor. When the strength parameters are reduced to such an extent that the resisting forces or moments become marginally less than the disturbing forces or moments, failure will be initiated. At failure, the SRF value will be equal to the Factor of Safety (FOS) against failure and the displacements in the slope will be large (Snitbhan and Chen, 1976). This method can be used with any elasto-plastic soil model and with any nominal shear strength parameters.

2.2 Application of the strength reduction factor method to a slope

The strength reduction technique will be applied to the slope with a vertical face shown in Figs.1 and 2. The slope has a height of 6.1 m and a depth also equal to 6.1 m (Fig. 2). According to Terzaghi (1943), the failure surface in a vertical slope has a maximum depth equal to half the height of the slope (3.05 m for the case of the slope in Fig. 2). This maximum depth of the failure surface occurs at the top of the slope. Thus, all the deformations and possible failure surface in the slope shown in Fig. 2 will be located well within the depth of 6.1 m. The slope was assumed fixed at a depth of 6.1 m and at the base of the slope as shown in Fig. 2. The slope was made of a soil matrix and dispersed large rock particles *that were assumed to be welded to the soil matrix*. The concentration and size of this dispersed large rock particles changed in value as shown in Figs 3 and Tables 1 and 2. The slope was partitioned with the mesh generation technique built in ABAQUS (2006) and assigned element type as four-node or three-node bilinear plane strain quadrilateral elements (CPE4 or CPE3) as shown in Fig.4. The material properties of the soil matrix and rock particles are shown in Table 3. The volume concentration of the rocks, C can be defined as,

$$C = \frac{\sum S_{rock}}{S} = \frac{\sum_{i=1}^{n} \pi r_i^2}{S} \tag{1}$$

where S is the area of the whole square section (37.21 m^2); $\sum Srock$ is the total area of the rocks and n is the number of the rocks. The rock pieces are assumed circular with a radii equal to r.

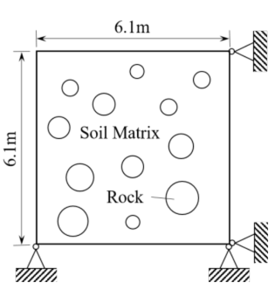


Figure 2. Slope used for the finite element analysis

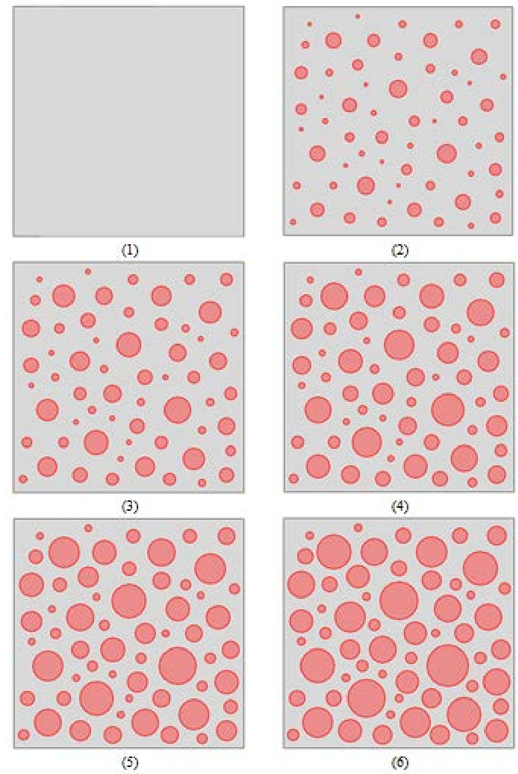


Figure 3. Slope with six different concentrations by volume, *C*, of the large dispersed rock pieces that were assumed to be welded to the soil matrix and were randomly distributed according to their sizes.

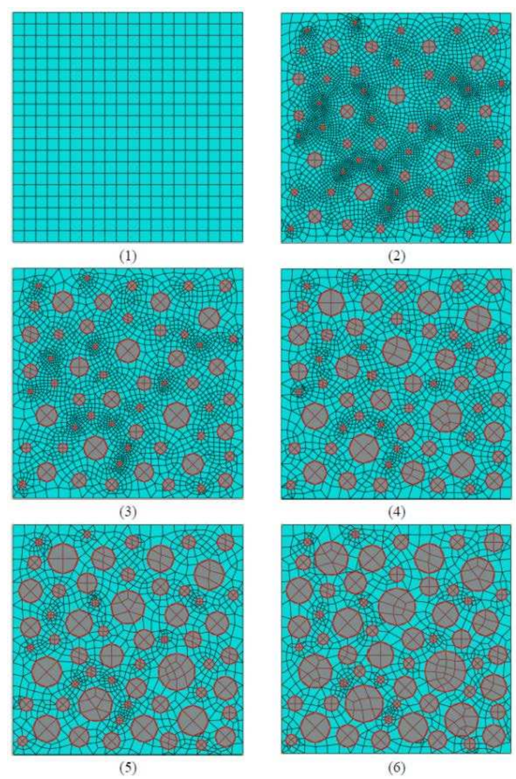


Figure 4. Mesh plan for the vertical slope and the six cases with different volumen concentration, C, of rocks. The rocks were assumed to be welded to the soil matrix and were randomly distributed according to their sizes

Table 1. Numer and raddi of rock pieces in different cases as shown in Fig. 3.

Number of rocks*	Case 2*	Case 3	Case 4	Case 5	Case 6
	Radii of rock pieces in each case , r (m)				
1	0.246	0.348	0.426	0.492	0.55
2	0.224	0.316	0.387	0.447	0.50
4	0.201	0.285	0.349	0.402	0.45
4	0.179	0.253	0.310	0.358	0.40
6	0.157	0.221	0.271	0.313	0.35
6	0.134	0.190	0.232	0.268	0.30
8	0.112	0.158	0.194	0.224	0.25
8	0.089	0.126	0.155	0.179	0.20
10	0.067	0.095	0.116	0.134	0.15
11	0.045	0.063	0.077	0.089	0.10

* Case 1 has zero number of rock pieces

Table 2. Volume concetration,C, of rock pieces in Fig. 3

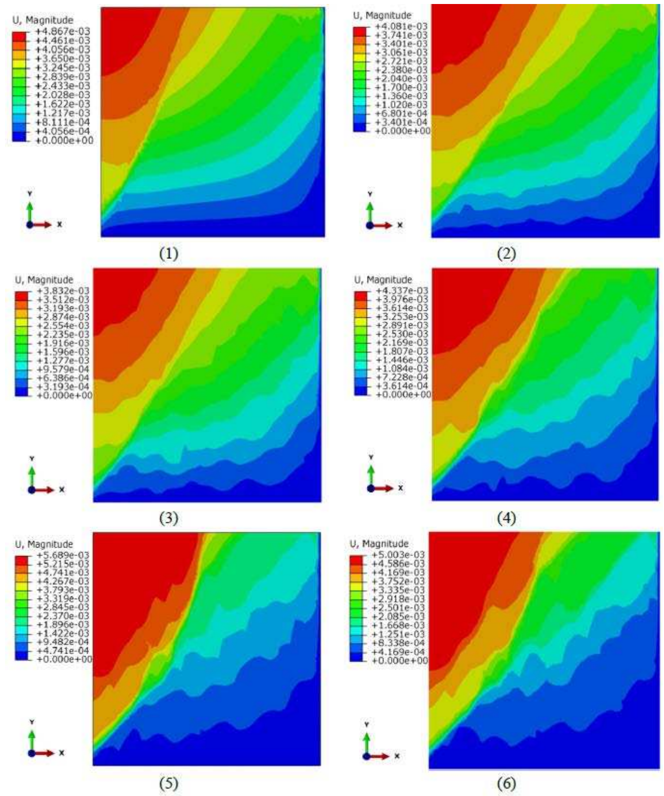
Cases	Volume concentration, C (%)
1	0
2	7.92
3	15.83
4	23.75
5	31.67
6	40.00

Table 3. Material properties

Material	γ (kN.m^3)	E (kPa)	ν	c (kPa)	ϕ (deg.)
Soil	20	10^4	0.3	20	36
Rocks	24	$3x10^7$	0.2	1000	55

2.3 Analysis of the simulation results

In order to obtain the factor of safety of the slope shown in Fig. 2 containing different concentration of rock pieces, C, the total displacement, U, of the left corner of the slope was evaluated using ABAQUS (2006). The values of the toal displacement U in meters are indicated in Fig. 5. The value of these maximum displacements U were then correlated with the associated streng reduction factors (SRF) used to



obtain the factor of safety (Figs. 6 and 7)

Figure 5. Contours graphs of total displacement magnitude, U (m) for the in six cases shown in Fig. 3.

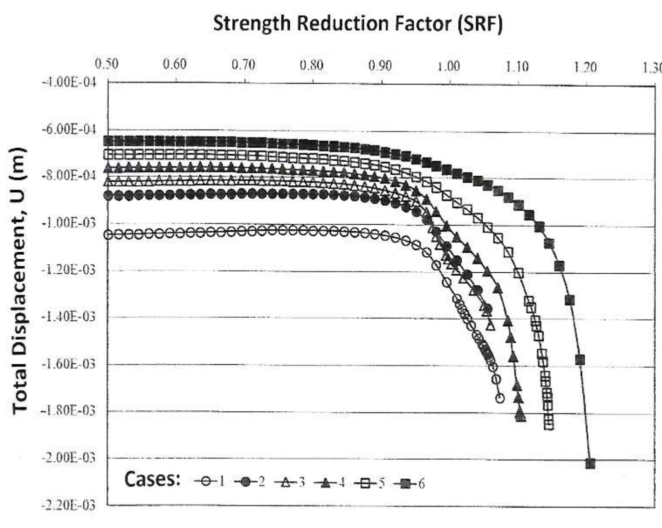


Figure 6. Relationship between the total displacement U and the strength reduction factor (SRF) used to obtain the FOS.

The factor of safety (FOS) is determined from Fig. 6 as the critical SRF related to the point of maximum curvature of the curves shown in Fig. 6. If the point of maxium curvature is difficult to obtain in Fig. 6, the left and staright portions of the curves are extended, the points at which these extended portions of the curves meet are related to critical values of the SRF that represent the FOS for the cases analyzed. Table 4 shows the FOS for each case (Fig. 3), the associated volume concentrations, C, and the values of c_f and ϕ_f related to the FOS. The plot relating the FOS with C is shown in Fig.7.

Table 4. Cases and the related values of C, FOS, and the critical values of c_f and ϕ_f.

Case Number	C (%)	FOS	c_f (kPa)	ϕ_f (deg.)
1	0	0.96	37.41	21.05
2	7.92	0.96	37.41	21.05
3	15.83	0.96	37.41	21.05
4	24	0.965	37.00	21.00
5	32	1.14	34.18	18.70
6	40	1.145	32.40	17.50

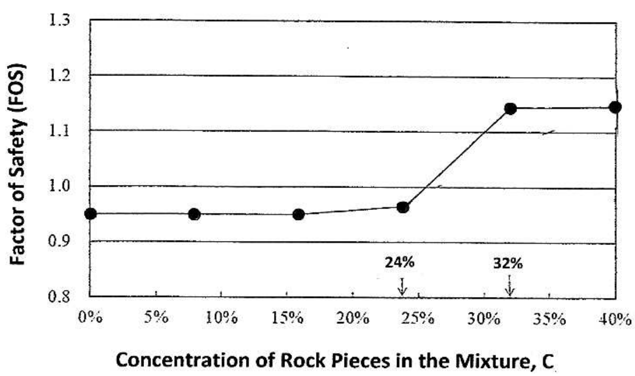


Figure 7. Relationship between the FOS and C for the six different cases shown in Fig. 3

An analysis of the stability analysis shown in Fig. 7 and Table 4 indicates that if $C \leq 24\%$, the factor of safety (FOS) of the slope remained unchanged (the frictional strength of the rock pieces has zero influence on the stability of the slope). When the value of C > 24% but ≤ 32%, the FOS increased greatly (the frictional strength between rock pieces partially controlled the stability). When the value of C > 32%, the FOS remained relatively unchaged and the stability of the slope was completely controlled by the frictional strength between the rock pieces. The limiting FOS values at which these limits of C were obtained were smaller than the limits of C obtained from the shear strength tests.

3 CONCLUSIONS

In this study the influence of the volume concentration of rock pieces, C, on the factor of safety (FOS) of a slope made of soil-rock mixtures was carried out using a finite element (FE) analysis. From this study the following conclusions were obtained:

(1) If $C \leq 24\%$, the FOS of the slope remained unchanged (the frictional strength of the rock pieces has zero influence on the stability of the slope). When the value of C > 24% but ≤ 32%, the FOS increased substantially (the frictional strength between rock pieces partially controlled the stability). When the value of C > 32%, the FOS remained unchaged and the stability of the slope was completely controlled by the frictional strength between the rock pieces.

(2) The limits at which the FOS changed with C obtained from the stability analysis were lower than the limits obtained using laboratory shear strength tests.

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