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Static analysis of slopes reinforced with stone columns

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ABSTRACT: The stabilization of slopes has been of great concern to geotechnical engineers. Various methods may be used to increase the safety factor of slopes prone to failure. These include retaining walls, piles, and geosynthetics, etc. An alternative solution is the use of stone columns. Such columns have been used since 1950 normally for cohesive soil improvement. A potential application of stone columns may be to stabilize slopes against instability. In this paper, a numerical approach in conjunction with an analytical approach is used to investigate the stability of slopes reinforced with stone columns. The slope soil is assumed to be soft, cohesive, and undrained. The present solution has been verified using the finite element method (FEM) as coded into GEO-OFFICE software. The results obtained from the developed method have shown that the factor of safety of slope-reinforced with stone columns increases. Moreover, it has been found that to achieve the greatest safety factor for slopes, the best location of the column is at the top the slope. Parametric studies have been performed to determine the best location of stone columns in the slope to achieve the maximum factor of safety. Further parametric studies have been performed to determine the influencing factors such as stone column diameter, friction angle of stone column material, distance between stone columns.

1 INTRODUCTION

Many parameters are effective on slope stability. Among these, the most important ones are soil unit weight, slope geometry, tectonic, earthquake, vibration, heterogeneousness of soil, strength parameters of soil, and pore water pressures.

Engineering stabilizing is generally referred to stop or return the instability process. Preventing the movement of a slope or increasing the safety factor (SF) is possible by using structural or geotechnical methods. Among techniques which increase resisting forces and basically act externally on the soils or rocks sliding are geometrical methods, structural barriers such as rigid walls and piles, permeable or impermeable coverage at surface, hydraulic improvement, physical improvement, chemical improvement, mechanical improvement, reinforcing with geosynthetics, an soil nailing, etc. (Jorge & Zornberg, 2002; Komak and Panah, 1994; Ausilio et al., 2001; Hassiotis et al., 1997; Jorge & Zornberg, 2002).

Stone column is another method for slope stabilization. It is a hole with circular section which is filled by gravel, rubble and etc and is an effective method to increase the shear strength on the slip surface of clayey slopes. The most important cases for utilizing stone columns (School of Civil Engineering Georgia Institute of Technology Atlanta, 1983) are:

1. Slopes stabilization
2. Stabilizing the retaining walls
3. Decreasing the liquefaction potential of sandy soils
4. Increasing the bearing capacity of shallow foundations situated on soft soils.

The performance of stone columns for reinforced and improved soil is easier and cheaper in comparison to other methods such as geotextile, grouting, compaction, etc. In some cases, it offers better results than other methods. Usually the diameter of stone column varies between 0.3 to 1.2 m and their intervals between 1.5 to 3 m. Stone columns are often performed in multiple rows (depending on soil condition).

In this paper, two rows of stone columns have been located within the slope. A two-dimensional finite element software (Geo-Slope software version 5.04) has been used for slope stability analysis, therefore, 3-D stone columns must be changed to 2-D. To do this, an equivalent column is replaced with one row successively and with distance s between two neighboring columns. Thus their centers are replaced by a continuous stone strip with equivalent width W. The volumes of stone column materials are identical in both two and three dimensional conditions. On the basis of equality of volume, equivalent strip width for each row of the stone columns is obtained from (Cheung, 1998):

$$W = \frac{\pi R^2}{s} \qquad (1)$$

where R = radius of 3-D stone columns and s = distance between centers of 3-D stone columns in each row.

2 ANALYSIS METHOD

The SF of slope reinforced with stone columns varies with changing the column location within the slope. Therefore, it is necessary to change the column location along the slope to determine the greatest SF. To achieve this, first, by the use of Taylor method, the SF and the critical slip surface of the slope is found and then this normal slope is simulated using Geo-Slope software. The value of nH is then found, where H is slope height and n is a factor representing the location of toe of slip surface in Taylor method. By the use of same nH in Geo-Slope, the same slip surface with the same SF is obtained. When this critical surface is found, the stone column is displaced along the slope and the variation of SF is determined.

3 SLOPE STABILITY ANALYSIS REINFORCED BY A ROW OF STONE COLUMN

Figure 1 shows the geometry of a slope reinforced with a row of stone columns. Tables 1 and 2 show the geotechnical properties of clayey soil and stone column materials, respectively. The critical slip surface is first determined with displacing the row of stone columns in the horizontal direction along the slope. The variation of SF is captured.

In Figure 1, x = horizontal distance of stone column from the slope crest and h = slope height.

Using parameters shown in Tables 1 and 2 in conjunction with three values of 27, 38 and 45° for slope angles, and three values of .50, 0.65, and 0.80 m for the column diameter, the variation of SF was determined with respect to the varying location of the column along the slope. Figure 2 shows that when the stone column is located at the upper part of the slope, the greatest SF is achieved. With moving the column toward down the slope, the column effect on the slope stability decreases.

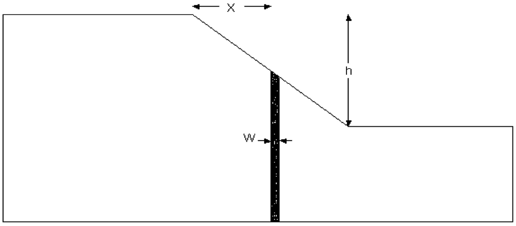

Figure 1. Geometry of slope reinforced with stone column.

4 SLOPE STABILITY ANALYSIS REINFORCED BY TOW ROWS OF STONE COLUMNS

It is customary to use several rows of stone columns for slope reinforcement. In this section, the influence of other contributing parameters such as number of rows of columns, location of columns, and the distance between two subsequent rows are investigated.

Table 1. Geotechnical properties of clayey soil.

Elastic modulus	4000 kN/m^2 4500 kN/m^2 5000 kN/m^2
Undrained cohesion	25 kN/m^2 40 kN/m^2
Unit weight	17 kN/m^3 18 kN/m^3
Friction angle	0.0 degree
Poisson's ratio	0.48

Table 2. Geotechnical properties of stone columns materials.

Elastic modulus	40000 kN/m^2 50000 kN/m^2 55000 kN/m^2
Cohesion	0.0
Unit weight	22 kN/m^3
Friction angle	35 degree 40 degree 45 degree
Poisson's ratio	0.25 0.30

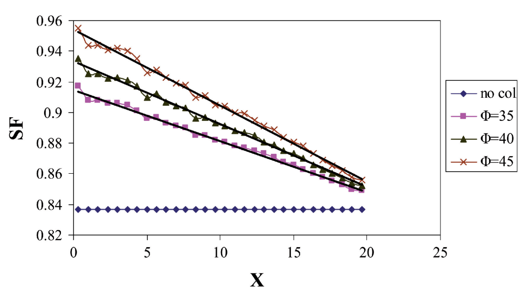

Figure 2. Variation of SF in terms of location of column from the sloe crest (Φ = friction angle of stone column materials).

For brevity, only some analyses are presented herein. The results of these limited analyses have shown that generally when the stones in rows are located close to the slope crest, the greatest SF is achieved. It was found that the location of two rows of columns is very effective on SF and when two rows of columns are placed in upper half slope face, the greater SF. With moving rows of columns toward the middle of the slope face and toward down the slope, the value of SF and the stability decreases.

It was further investigated that by the use of both one and two rows of columns, the stability increases markedly. Furthermore, it was observed that with increase equivalent width of stone column and friction angle of column materials, SF increases. In addition, with increasing the undrained cohesion of the slope soil, the effect of column on increasing the SF decreases.

5 STONE COLUMN EFFECT ON SLOPE STABILITY

Stone columns have two impacts on increasing slope stability:

1. Reduction of pore water pressure by dissipation
2. Increasing the shear strength on the slip surface due to high friction angle of stone column materials.

Stone columns can drain well and reduce pore water pressure with time elapse. However, in short time, columns are unable to perform this mechanism. The presence of the column causes pore pressures dissipate considerably on the slip surface-column intersection. The pore water pressure at each level in column is approximately equal to $u = \gamma_w$ h where γ_w = water unit weight and h=water depth from the slope surface at the column location.

The main reason for SF increase is high column material friction angle, which is offered at the failure surface. The presence of stone column causes the SF value suddenly increases for the slip surface. This surface passes the column material.

With accuracy to this mechanism a new analytical equation has been found.

6 CLOSED-FORM SOLUTION FOR STONE COLUMN-REINFORCED SLOPE

6.1 *Normal slope*

Taylor (1937, according to Das, 1941) presented an equation to determine SF of homogenous undrained ($\Phi = 0$) clayey slopes (Figure 3):

From Figure 3, it is seen that the average shear strength of the soil is $\tau_f = c_u$ where c_u = undrained shear strength of clay, τ_f = shear strength.

The mobilized shear strength on the slip surface is $\tau_d = c_d$. Therefore, the sliding moment is given by:

$$M_d = w_1 x_1 - w_2 x_2 \qquad (2)$$

The resisting moment is expresses as:

$$M_R = c_d R^2 \theta \qquad (3)$$

Using equations (2) and (3) gives SF as:

$$SF = \frac{M_R}{M_d} = \frac{c_d R^2 \theta}{w_1 x_1 - w_2 x_2} \qquad (4)$$

6.2 *Reinforced slope by a row of column*

With the presence of column on the slope face, the shear strength on the slip surface is mobilized. Thus from Figure 4, following equations are expressed:

DE = L_1; EF = L_2; FA = L_3; and DEFA = L.

Figure 5 shows exerted forces on the equivalent strip stone column between surface of slope and slip surface.

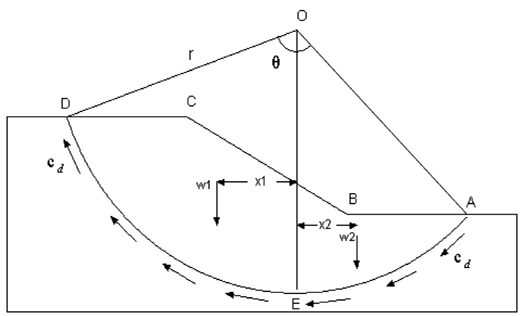

Figure 3. Slope stability analysis of homogenous saturated clay ($\Phi = 0$).

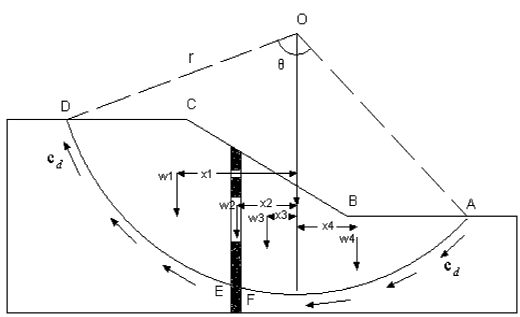

Figure 4. Slope stability analysis of homogenous saturated clay ($\Phi = 0$) reinforced by a row of column.

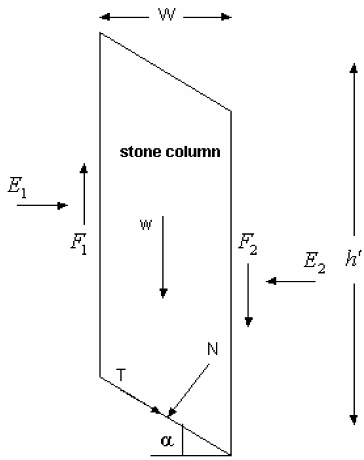

Figure 5. Exerted forces on strip stone column.

With respect to Figures 4 and 5 and assuming that $E_1 = E_2$ and $F_1 = F_2$:

$$w = \gamma_{sat} W h' \tag{5}$$

where w = weight of strip stone column; γ_{sat} = saturated unit weight of strip stone column; and h' = height of strip stone column between surface of slope and slip surface.

$$N = w\cos\alpha = \gamma_{sat} W h' \cos\alpha \tag{6}$$

$$T = w\sin\alpha = \gamma_{sat} W h' \sin\alpha \tag{7}$$

$$L_2 = W/\cos\alpha$$

The total normal stress on the base of stone column is:

$$\delta = N/(W/\cos\alpha) = \gamma_{sat} h' \cos^2\alpha \tag{8}$$

The shear strength on the base of the stone column is given as:

$$\tau = T/(W/\cos\alpha) = \gamma_{sat} h' \cos\alpha \sin\alpha \tag{9}$$

The shear strength on the slip surface of slope-column system is determined from:

$$\tau_f = c_u + \Delta\tau_f = c_u + \delta' \tan\phi = c_u + (\delta - u)\tan\phi$$

$$= c_u + \gamma' h' \cos^2\alpha \tan\phi \tag{10}$$

The shear strength mobilized on the slip surface with the presence of the column is expresses as:

$$\tau_d = c_d + \gamma' h' \cos^2\alpha \tan\phi_d \tag{11}$$

The sliding moment is computed from:

$$M_d = w_1 x_1 + w_2 x_2 + w_3 x_3 - w_4 x_4 \tag{12}$$

The resisting moment is given by:

$$M_R = c_d L_1 r + \gamma' h' \cos^2\alpha \tan\phi_d L_2 r + c_d L_3 r$$

$$= c_d r(L_1 + L_3) + r\gamma' h' \cos\alpha W \tan\phi_d \tag{13}$$

The SF value for unreinforced slope can be determined using:

$$(SF)_{col} = \frac{c_u r(L - L_2) + r\gamma' h' W \cos\alpha \tan\phi}{w_1 x_1 + w_2 x_2 + w_3 x_3 - w_4 x_4} \tag{14}$$

Similarly, SF of reinforced slope by a row of stone column is obtained from:

$$(SF)_{col} = \frac{c_u r(r\theta - \frac{W}{\cos\alpha}) + r\gamma' h' W \cos\alpha \tan\phi}{w_1 x_1 + w_2 x_2 + w_3 x_3 - w_4 x_4} \tag{15}$$

where α = angle of stone column failure with horizontal direction on the slip surface and γ' = buoyant unit weight of stone column materials.

With use geometrical method and with obtained equation we can determine SF of slope.

By splitting Equation (15), the ratio of SF for reinforced slope to SF for un-reinforced slope, SF_{ratio}, is determined from:

$$SF_{ratio} = \frac{(SF)_{col}}{(SF)_{no-col}} = 1 - \frac{W}{r\theta\cos\alpha} + \frac{\gamma' h' W \cos\alpha \tan\phi}{c_u r\theta} \tag{16}$$

Equation (16) may be converted to:

$$SF_{ratio} = \frac{(SF)_{col}}{(SF)_{no-col}} = 1 - \frac{\pi R^2}{s r\theta\cos\alpha} + \frac{\gamma' h' \pi R^2 \cos\alpha \tan\phi}{s c_u r\theta} \tag{17}$$

Similarly, SF_{ratio} can be computed for reinforced slopes with several rows of columns.

7 VERIFICATION OF DEVELOPED CLOSED-FORM SOLUTION

Parametric studies were performed using Geo-Slope software to verify the new developed closed-form solution. The results obtained from closed-form solution are comparable with those obtained from Equation (16), as shown in Figures 6 and 7. Figure 6 illustrates SF_{ratio} values with respect to column location.

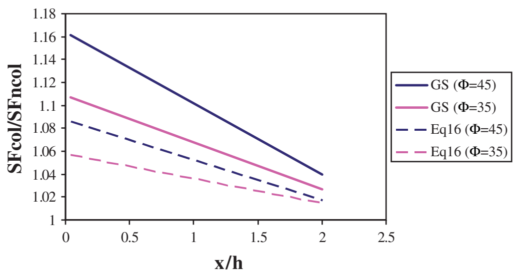

Figure 6. Comparison between relative safety factors given by Equation (16) and those given by Geo-Slope (GS stands for Geo-Slope).

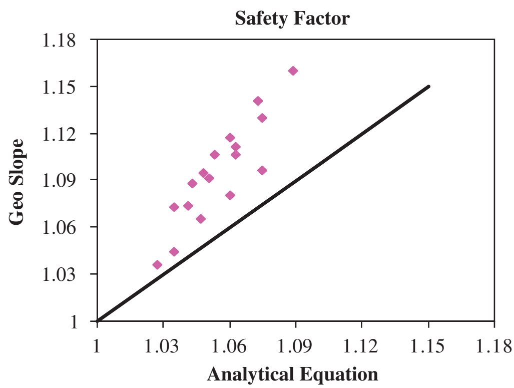

Figure 7. Comparison of SF values from closed-form solution and Geo-Slope.

Figures 6 and 7 show that the maximum difference between the results of two methods is less than 10%. The closed-form solution gives lower SF_{ratio} than Geo-Slope software, and this is on the safe side. This difference may be partly attributed to ignoring total external forces exerted on the strip stone column.

8 CONCLUSIONS

The results of analyses performed in this paper indicate that:

1. The SF values of stone column-reinforced slopes are influenced by various parameters including geometrical specifications of slope, slip surface, geotechnical properties of soil and stone column materials, center to center of columns, location of columns , number of column rows.
2. If the slope is reinforced by a row of column, the maximum SF is achieved when the column is located in the upper slope head.
3. The SF decreases with moving the column from the slope crest toward the slope toe.
4. With increasing sliding active force, for example due to low undrained shear strength of slope soil, increasing the slope height, or the slope angle, the influence of column on SF values increases.
5. With increasing equivalent width of stone columns and friction angle of column material, SF values increase remarkably.
6. An analytical equation verified by Geo-Slope was developed to determine the SF accurately for practical purposes.
7. The SF values for slopes reinforced with two rows of columns are higher for cases when columns are located in the upper slope part and column rows are very close.

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