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Stability analysis of side slope by using stone column and tieback support

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Abstracted- Geotechnical engineers have always been concern with the stabilization of slopes. For this purpose, various methods such as retaining walls, piles, and geosynthetics may be used to increase the safety factor of slopes prone to failure. The application of stone columns may also be another potential alternative for slope stabilization. Such columns have normally been used for cohesive soil improvement. In this paper, limit equilibrium method has been presented by **SLIDE V.5.00** program to investigate the stability of slopes reinforced with multi-rows of stone columns, and reinforced by using tieback support. The results have shown that the safety factor of slope-reinforced with stone columns and Tieback generally 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 of the slope and around it. Further parametric studies have been carried out to determine the influencing factors such as stone column diameter, friction angle of stone column material, and distance between stone columns.

Index Terms- side slope, stone columns, stability analysis, SLIDE V.5.0, factors of safety, cohesive soil.

1. INTRODUCTION

Slope stability is one of the fundamental problems faced on a consistent basis by the majority of practicing Geotechnical Engineers. This is why stability analysis isemphasized both at the undergraduate slope and more so at the graduate level of Geotechnicalstudies.

It is a very well-known fact that earthen dam slopes and other slopes fail. They fail for a variety of reasons. One reason may be excavation of the toe of an embankment, resulting in removing the balancing moment of the slope and causing failure. Another could be an increase in pore pressure along the failure plane during rapid drawdown condition and a corresponding decrease in vertical effective stress and a loss of strength [**Yaeger, 2002]**.

There have been methods developed to help in stabilizing failing slopes and reinforce slopes that could fail. These methods are listed below [**Yaeger, 2002]:**

- End anchored support, (e.g., mechanically end anchored rock bolts).
- Geotextiles (Strip reinforcement).
- Grouted tiebacks / Ground anchors.
- Micro piles.
- Soil nails.
- Stone columns

This paper adopted to discuss two techniques that are used to reinforce existing failures, installation of tiebacks and the installation of stone columns. It will be seen that these methods can be very effective, if utilized correctly, stabilizing existing failures and increasing the strength of slopes on the verge of failing.

2. Limitation of using tieback and stone column methods

2.1 Tiebacks

The concept of tiebacks is basically that one carries the lateral earth pressure with a "tie". The tie transfers the lateral load of the soil to a zone of soil or rock located beyond the failure plane as can be seen in Figure (1).

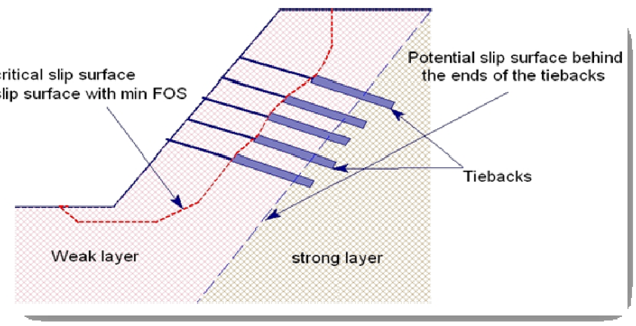

Figure (1) details of Tiebacks support

International Journal of Scientific & Engineering Research Volume 5, Issue 9, September-2014
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The following design guideline should be used when working with tiebacks,[**Yaeger, 2002]**

- Tiebacks are typically installed in cohesion less soils
- The length if the tieback should be selected such that the anchorage zone is beyond the original failure plane.
- Shallow failure surfaces typically only require one row of tiebacks.
- The inclination of the tiebacks should be between 10 and 30 degrees from the horizontal.
- There should be a minimum of 15 feet of overburden above the zone of embedment.
- All permanent tiebacks should be corrosion resistant.

2.2 Stone Columns

Stone columns increase the factor of safety by two means:

1. Increases the average shear resistance of a soil by displacing or replacing the soil with a series of gravel columns. (Reference Figure 2)
2. Columns act as a drain to decrease the effective stress in the soil and thereby increase the strength along the failure surface.

According to **Abramson et al. (1996)** stone columns should be used in soils with shear strengths in the range of 200-1000(lb/ft²). Soils in the lower range of these limits may not provide enough lateral support and thus the soil will consume too much stone to make the method cost effective. Soils in the higher range may not benefit from the placement of stone columns.

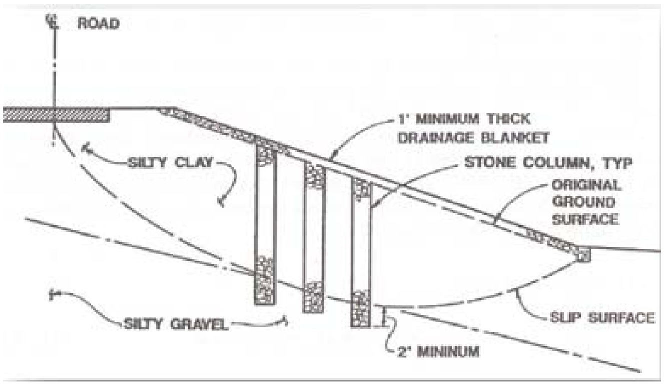

Figure (2) details of stone column support, [Yaeger, 2002]

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3. Stability Analysis of Side Slope by Using Stone Column Technique

Tables 1 and 2 show soil and stone column material properties used for two examples and further in parametric study for this technique.**[Ghazavi, and Shahmandi,2008]**.

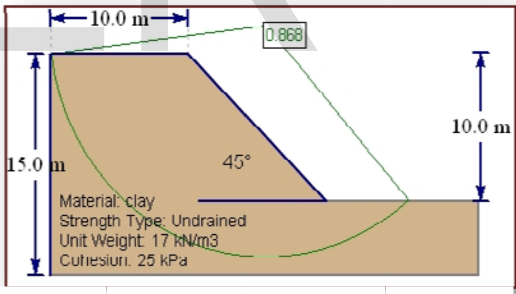
Slope profiles and position of most critical slip surface for two angles of slopes are shown in the figure (3).

Table 1. Geotechnical properties of clayey soil.

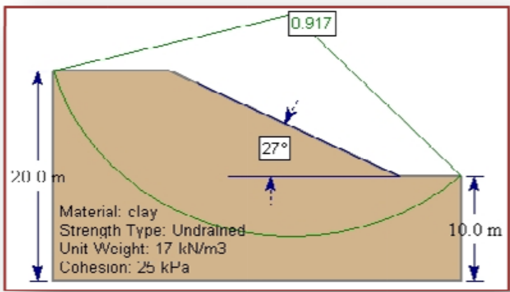
Modulus of elasticity [kN/m²]	Poisson's ratio	Undrained cohesion [kN/m²]	Friction angle [degree]	Saturated unit weight [kN/m³]
5000	0.48	25, 30, 40	0	15, 16, 17

Table 2. Geotechnical and geometrical properties of stone column materials.

Modulus of elasticity [kN/m²]	Poisson's ratio	cohesion [kN/m²]	Friction angle [degree]	Saturated unit weight [kN/m³]	equivalent strip width [m]
50000	0.30	0	35, 40, 45	22	0.50, 0.65, 0.80



(A) Slope angle = 45°, FOS = 0.868



(B) Slope angle = 27°, FOS = 0.917

Figure (3) Geometrical specification of two samples for slopes, before adding stone column.

International Journal of Scientific & Engineering Research Volume 5, Issue 9, September-2015
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In order to understand the techniques of determining the value of safety factor for reinforced slope with a row of stone column, some of limitation had been taken for analysis.
Based on two-dimensional analysis of slopes, a 3-D stone column must be changed to 2-D.Figure 4a shows a sample of grouped stone column arrangement. With respect to this figure, one row of successively stone columns with center to center spacing of **S** is replaced with an equivalent column. The volumes of stone column materials are identical in both two and three dimensional conditions. On the basis of equality of volumes, equivalent strip width for each row of the stone columns is obtained from [Barksdale &Bachus, 1983; Cheung, 1998], quoted from **(Ghazavi, and Shahmandi,2008)**.

$$\boxed{\frac{\pi R^2}{s}} \quad \ldots\ldots\ldots\ldots..(1)$$

Where:
R is radius of 3-D stone columns
S is distance between centers of stone columns in each row.
Figure (4b) shows a slope reinforced by a row of stone columns which in this figures is horizontal distance of column from topmost of the slope. The slope is assumed to be homogeneous and consist of saturated clay in un-drained conditions (Φ = 0).

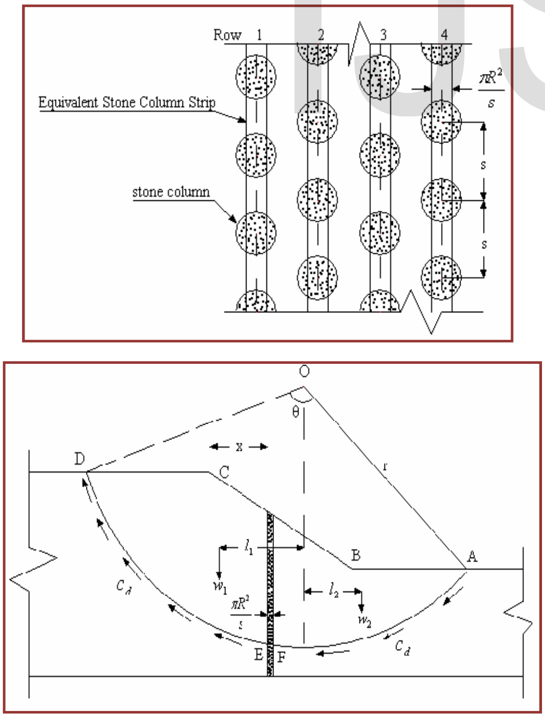

Figure 4. (a) Plan of grouped stone columns (Barksdale &Bachus, 1983); (b) Static slope stability analysis of homogeneous saturated clay (Φ = 0) reinforced with a row of column

In this section, one row of stone columns are used to reinforce the slope and parametric studies have been performed to determine the effects of contributing parameters such as geotechnical properties of slope soil materials and stone column materials, geometrical specifications of the slope (height and angle of the slope) and diameter of the stone columns.
The following tables represent summary results of **SLIDE V.5.0** computer program of two examples in case of using stone column supports.

Table (3)Safety factors related to slope in figure (5a) when a row of column is located at x = 0, for different values of column width.

Friction angle of stone column materials [degree]	No Column	(equivalent strip width of column)		
		0.65 m	0.8 m	1.0 m
35	0.917	0.963	0.984	1.00
40	0.917	0.974	0.999	1.02
45	0.917	0.985	1.081	1.04

Table (4)Safety factors related to slope in figure (5b) when a row of column is located at x = 0,for different values of column width.

Friction angle of stone column materials [degree]	No column	(equivalent strip width of column)		
		0.65m	0.8m	1.0m
35	0.868	0.937	0.951	0.965
40	0.868	0.952	0.970	0.987
45	0.868	0.969	0.986	1.013

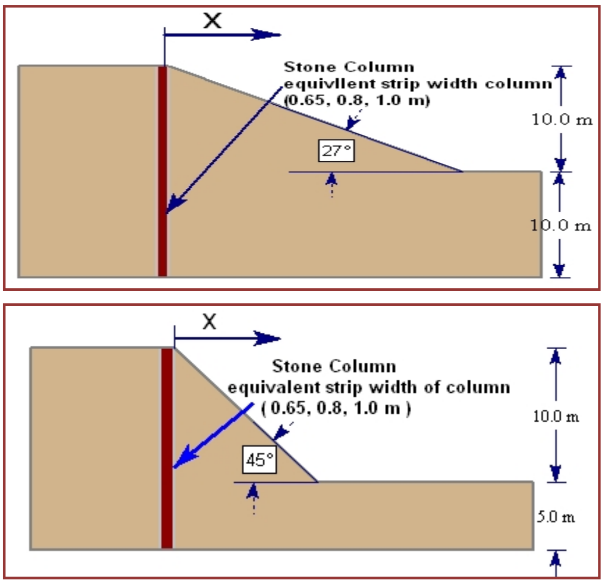

Figure (5) slope profiles for two cases used in parametric study, X= 0 for two cases

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International Journal of Scientific & Engineering Research Volume 5, Issue 9, September-2014
ISSN 2229-5518

About optimum location, first it is obvious that the best location of stone columns for achievement the greatest safety factor is unknown. Thus initially, limit equilibrium method presented by SLIDE program is used to determine the safety factor and slip surface for unreinforced slope. Upon finding this critical slip surface, the stone column is displaced through the slope face and the variation of safety factors is found. Among these factors, the best location of the column is captured.
Apart from using parameters given in Tables 1 and 2, two values of 27°, and 45° for slope angles and two values of 5 and 10 m for slope heights are also used and the variation of safety factor is determined by moving the location of a row of columns along the slope. It has been found that when the stone column is located on the topmost of the slope (column at x = 0), the greatest safety factor is achieved. In addition, this factor decreases by moving the column from the slope crest toward the slope toe. The same trend has been observed in all analyses. The variation of FOS with respect to the stone location is shown in Figure 6. As seen, steep straight lines represent this variation.

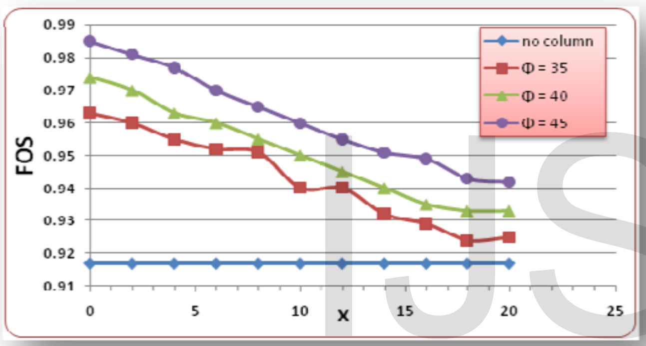

Figure (6) Variations of safety factor versus location of column from the topmost of the slope, for slope profiles in figure (5a).

5. Reinforcing side slope (Tieback method)

5.1 Factor of Safety for Reinforcing Forces and Soil Strengths

Two methods have been used for limit state equilibrium analyses of reinforced slopes based on allowed reinforcing forces and a specified ultimate reinforcing force [**Duncan ,and Wright (2005)**].A global Factor of Safety should be multiplied by the allowed tensile strength to get the ultimate strength required. Usually a computer program **(SLIDE V.5.0**) is used to achieve a target value of factor of safety by conducting repeated trials by varying applied forces.
The amount of force required to achieve a target value of factor of safety can be determined using repeated trials, varying the magnitude of the force until the factor of safety computed is the one desired. Some computer programs can perform this operation automatically. The input is the desired factor of safety, and the output is the required reinforcement force. This type of program is better adapted to design of reinforced slopes, since there is no need for repeated analyses.
The Factor of safety can be defined with respect to shear strength, load and moment. These different types of definition lead to different values of Factor of safety. The most frequently used definition of FOS is one based on moments. In this case the factor of safety is defined as ratio the ratio of the available resisting moment divided by the actual driving moment as shown in Equation 1

$$\mathrm{FOS} = \frac{\text{availabel resisiting moment}}{\text{actual driving moment}} = \frac{MR}{MD} \quad \ldots(1)$$

The equilibrium Equation shows the balance between the driving moment (MD) and the pseudo resisting moment which is developed by the available resisting moment (M**R**) reduced by the factor of safety. If the resisting moment is due entirely to the shear strength of the soil alone, then the factor of safety applied to the resisting moment is the same as the factor of safety defined with respect to shear strength.
Two methods have been used for limit state equilibrium analyses and as follow **[Duncan ,and Wright (2005)]:**

Method A. The reinforcement forces used in the analysis are allowable forces and are not divided by the factor of safety calculated during the slope stability analysis. Only the soil strength is divided by the factor of safety calculated in the slope stability analysis.
If the factor of safety for circular slip surfaces is defined by an equation of the form

$$F = \frac{\text{shear streangth}}{\text{shear stress required for equilibrium - reinforcement resistance}}$$

- **Method B**. The reinforcement forces used in the analysis are ultimate forces, and are divided by the factor of safety calculated in the slope stability analysis. Both the reinforcing force and the soil strength are divided by the factor of safety calculated in the slope stability analysis.

$$\mathbf{F} = \frac{\textbf{shear strength + reinforcement resistance}}{\textbf{shear stress requried for equilibrium}}$$

Method B is preferable, because the soil strength and the reinforcement forces have different sources of uncertainty, and they therefore involve different amounts of uncertainty. Factoring them separately makes it possible to reflect these differences**[Duncan ,and Wright (2005)]**.

5.2 Reinforced Embankment on the Soft Ground

Depending on how the reinforcement force incorporated in Equation 1 and whether the factor of safety is applied to a resisting or disturbing moments the results calculated using these traditional methods give different results except if factor of safety is unity[**Mwasha, 2009].**

International Journal of Scientific & Engineering Research Volume 5, Issue 9, September-2014
ISSN 2229-5518

$$M_D = \frac{M_R}{FOS_G} + \frac{M_{TR}}{FOS_G} \ldots\ldots\ldots (2)$$

$$M_D = \frac{M_R}{FOS_G} + M_{TR} \ldots\ldots\ldots (3)$$

If global FOS_G is unity then both equations can be represented by Equation 3

$$M_D = M_R + M_{TR} \ldots\ldots\ldots\ldots (4)$$

Equation 4 can be rewritten as shown in Equation 5

$$FOS_G = FOS_U + \frac{Y T_{RM}}{R \sum W \text{SIN}\,\alpha} \ldots\ldots\ldots (5)$$

Therefore the Global Factor of Safety (FOS_G) can be considered to comprise two components i.e. that due to the soil shear strength alone (FOS_U) and Factor of Safety due to reinforcement (FOS_{TR}) Equation 6.

$$FOS_G = FOS_U + FOS_{TR} \ldots\ldots (6)$$

And

$$\frac{Y}{R} \frac{1}{\sum W \text{SIN}\,\alpha} = A^* \ldots\ldots\ldots\ldots (7)$$

.

In Equation 7 the value of A* depends on the driving moment and the critical slip circle parameters Y.
Then expression 5 can be re-written as shown in Equation 8, Where **TRM** is the mobilized tensile strength (Tensile strength at given global FOS).

$$1 = \frac{FOS_U}{FOS_G} + T_{RM}\ A^* \quad \ldots (8)$$

In order to achieve a specific FOS both soil shear strength and tensile strength from the incorporated reinforcements should work together to generate a global Factor of Safety. Since the addition of reinforcement to a slope can change the position of the critical circle (from that of an unreinforced slope FOS_U) it is useful to define a parameter (FOS_{SR}), which is the contribution to Factor of Safety, of the tensile force within a reinforced soil. Therefore Equation 8 can be written in the more general form as Equation 9.

$$1 = \frac{FOS_{SR}}{FOS_G} + \frac{T_R}{FOS_G} A^* \ldots\ldots\ldots (9)$$

Relation between different types of factor of Safety used is shown in Equation 10.

If T**R**=0 and FOS_G=1, then

$$FOS_{SR} = FOS_U \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ .(10)$$

5.3 Parametric study (Tieback support)

A parametric study was conducted in order to review typical engineering properties for existing free drained embankment and soft clay soils. The result of this analysis, 4 types of slopes and mechanical properties for free drained embankments and foundation soils were tabulated as shown in Table 5.

Table 5: Typical value of the relevant parameters extracted from filed data[**Mwasha, 2009]**.

Embankment	Typical steepest slope(V: H)	Slope range chosen for analysis V: H
	1:1 to 1:5	1:2 to1:5
	Typical shear strength parameters c′ = 0(kN/m²) , φ′ = 35 to 41	Selected shear strength parameters c′(kN/m²) = 0 , φ′ = 35 and 41
	Range of bulk unit weight 18 to 20(kN/m³)	Selected bulk unit weight 18(kN/m³)
Soft soil	Typical shear strength parameters c′ = 0 , φ′ = 14 to 26	Selected shear strength parameters c′ = 0 , φ′ = 14 to 26
	Range of bulk unit weight 15 to 20(kN/m³)	Selected bulk unit weight 15 to 22(kN/m³)

6. Back-Analysis Approaches

Formulations of equation (9) can be used effectively if the critical slip circle parameter A* for reinforced slope is known. A computer program SLIDE V.5.0 was used to analyze simple self drain slopes erected on homogenous soft soil. Slopes having Vertical:

International Journal of Scientific & Engineering Research Volume 5, Issue 9, September-2014
ISSN 2229-5518

Height (V:H) = 1:2, 1:3, 1:4. 1:5 were analyzed based on data from parametric study.. For demonstration the foundation depth (D) was 3m to an embankment height (He) of 3m. The investigation was conducted at the end of construction. Effective angles of internal friction for foundation varied from 15, 20, 23 and 26 degrees and for an embankment varied from 35to 41 degrees.

The back-analysis process was conducted using SLIDE program by incorporating reinforcement parameters at the base of an embankment. A method of trial and error was formulated in order to estimate the tensile strength required to achieve specific FOS. The global Factors of Safety estimated were 1.0, 1.2, 1.5 and 2.0

.

Table 6: Estimation of required reinforcement (Tieback) to achieve specific FOS using back analysis methods

Slopes V:H	Embankment and Foundation parameters	FOS	FOS_{SR}	FP (KN/m)	FA (KN/m)	TR (KN/m)	TR (KN/m)	TR (KN/m)	TR (KN/m)
1:2	For embankment γ = 18kN/m^3 ϕ = 41^o C = 0 For foundation γ=20kN/m^3 ϕ = 15^o C = 0	0.527	0.527	0	0	Un reinforced			
		1.00	0.527	30.25	30.25	30.25			
		1.20	0.527	44.88	37.40		37.40		
		1.50	0.527	68.00	45.31			45.31	
		2.0	0.527	108.545	54.27				54.27
1:3		0.573	0.573	0	0	Un reinforced			
		1.00	0.573	26.30	26.33	26.33			
		1.20	0.573	39.43	32.86		32.86		
		1.50	0.573	60.232	40.155			40.155	
		2.0	0.573	96.89	48.44				48.44
1:4		0.752	0.752	0	0	Un reinforced			
		1.00	0.752	9.75	9.75	9.75			
		1.20	0.752	17.46	14.55		14.55		
		1.50	0.752	29.44	19.63			19.63	
		2.0	0.752	50.34	25.17				25.175
1:5		0.88	0.88	0	0	Un reinforced			
		1.00	0.88	6.04	6.04	6.04			
		1.20	0.88	15.55	13.0		13.0		
		1.50	0.88	29.38	19.6			19.6	
		2.0	0.88	52.77	26.38				26.38

TR (kN/m) – Tensile strength required to achieve a specified global FOS in kN per meter.
FP (kN/m) –Passive force kilo Newton/meter
FA (kN/m) –Active Force kilo Newton/Meter
FOS_{SR} – Factor of safety due to shear strength parameters

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International Journal of Scientific & Engineering Research Volume 5, Issue 9, September-2014
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7. Effect height of embankments on the values of Tensile strength

By Using back analysis method to calculated the amount of required reinforcement for different values of height 1, 2, 3, 4,5,6 and 7m for slopes V: H 1:3, 1:4 and 1:5 were investigated. It was found that on increasing on embankment height there was exponential increase in amount of reinforcement required to achieve a global FOS of unity. A chart for slopes 1:3, 1:4 and 1:5 is shown in Figure 7.

For Slope V:H = 1:3

TR = 2.9656 He2 + 0.3804He – 0.4142 . . . . .(11)
R2= 0.9993

For Slope V:H = 1:4

TR = 1.4635 He2 –0.098He – 0.0571 . . . . (12)
R2= 0.9965

For Slope V:H = 1:5

TR = 0.6876 He2 + 0.3041He + 0.5696 . . . . (13)
R2= 0.9996

Displayed R- squared values for chart on equations were relatively high.

He- height of side slope of embankments.

8. Comparing with traditional methods

Table 6 contains a summary of tensile force predicted using traditional methods had been published by different researcher. The results are also compared with the results of back-analysis using computer program SLIDE V.5.0. The data for these analyses were obtained after conducting back-analysis using computer program SLIDE V.5.0. Differences between these values according in deferent in using

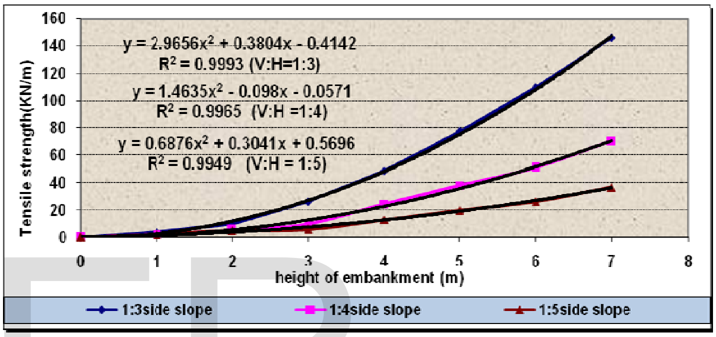

Figure7: Effect height of embankment on value of reinforcement

Table (6) tensile force estimation to achieve specific global FOS (comparison)

Authors	Reinforcement required TR (kN/m) at given global FOS_G V:H 1:2			
	1.00	1.20	1.50	2.00
Proposed Equation (**Mwasha,2009**)*	**92.00**	**146**	**227**	**362.0**
USA-Technical Manual TM 5-818-8(1995) Duncan and Wright (2005)**	**30.00**	**37.69**	**46.37**	**55.27**
Morris(1998) Duncan and Wright (2005)**	**30.00**	**45.23**	**69.56**	**110.5**
Computer program GEO5 Back analyses ((**Mwasha,2008**)*	**90**	**140**	**215.0**	**348**
Computer program SLIDE V.5.0) **	**30.25**	**37.40**	**45.30**	**54.27**

* passive forcesare usedfor reinforcement
** active forcesare used for reinforcement

International Journal of Scientific & Engineering Research Volume 5, Issue 9, September-2014
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9. CONCLUSION

In this research, increasing the stability of side slope had been investigated by two analysis approaches, reinforced with **stone columns**, and reinforced with **Tieback** support. Several parametric analyses have been performed using the limit equilibrium method. The following conclusions are drawn based on this study:

In case of using stone columns,

- The safety factor values of stone column-reinforced slopes are influenced by various parameters including geometrical specifications of slope, geotechnical properties of soil and stone column materials, center to center spacing of columns, location of columns, number of column rows and etc.
- If slope is reinforced by a row of column, the maximum safety factor is achieved when the column is located on the topmost of slope. With further moving the column toward the slope toe, the factor of safety decreases.
- With increasing the sliding active force, for example due to low untrained shear strength of slope soil, increasing the slope height or the slope angle, the influence of column on safety factor values increases.
- With increasing equivalent width of stone columns and friction angle of column materials, safety factor values increase dramatically.

In case of using Tieback support,

It has been found that the proposed equations used for estimating amount of required reinforcement to achieve a specific FOS underestimate the value of required reinforcement by a large amount. The proposed equations can be used for preliminary assessment of reinforcement required to achieve a specific FOS. It is strongly recommended that the future work on this topic to be conducted

by varying foundation depth as well as embankment height for different soil parameters. These different parameters will be used to create wider applicable solution for this problem.

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