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Analysis for Stabilization of Soil Slope in Silty Soil with Replacement of Soil Cement

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Abstract

The slope instability may result due to change in stress conditions, rise in groundwater and rainfall. Similarly, many slopes that have been stable for many years may suddenly fail due to loss of soil shear strength, and external forces. This is a crucial problem as it may destroy buildings, damage roads, and even leads to loss of human life. So it is imperative to understand failure mechanism and adopt safety measures to prevent such failures. The objective of this study is to analyze the slope at different angles (at 30^0, 35^0, 45^0 & 60^0) in silty soil and propose a method to stabilize it. The proposed methods to stabilize the existing slope are replacing soil-cement (7% by weight) by vertical layering and layering along the slope. Limit equilibrium method was used to analyze the slopes. The existing slopes were likely to be failed because values of minimum FOS was computed less than 1.5. The FOS improved significantly after replacing soil cement by both methods. Among the two methods, it was revealed that the layering along slope method of soil replacement was most economical and easy to be executed at the site.

Keywords: Slope Stability Analysis; Soil Cement Replacement; Slope Stabilization; Limit Equilibrium Analysis.

1. Introduction

Slope instability problems in natural and manmade slopes are most common challenges for civil engineers. The slope instability may result due to change in stress conditions, rise in groundwater table and rainfall. Similarly, many slopes that have been stable for many years may suddenly fail due to changes in the slope geometry, loss of soil shear strength, and external forces effect [1]. Earthquakes are the greatest threat to the long term stability of slopes in active seismic zones [2]. Additionally, the long-term slope stability is also affiliated with the chemical influence and weathering action that can lessen the soil shear strength and produce tension cracks. In these conditions, the slope stability evaluation turns a basic interest all over.

The technical solutions to slope failure problems demand expert understanding of analysis methods, stabilization measures and investigative tools [1]. According to Nash [3], a quantitative evaluation of the safety factor is most significant when decisions are made. According to Chowdhury [4], the primary aim of stability analyses of a slope is to impart a secure and economical design of embankments, earth dams and excavations. Developing activities may face challenges due to the instability of earth surfaces. Likewise, the slope instability can disturb the accomplished essential servings as traffic movement, electricity production, water supply system and many other basic facilities. Therein, the

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primary motive of slope stability analyses is to preserve lives, scale down structural collapse and supply uninterrupted basic facilities.

Hence, the most appropriate and authentic slope stability methods have large scope and so, it is more and more demanding. The selected method of analysis should be capable to distinguish the existing safety situations and propose for economically feasible and technically executable solutions.

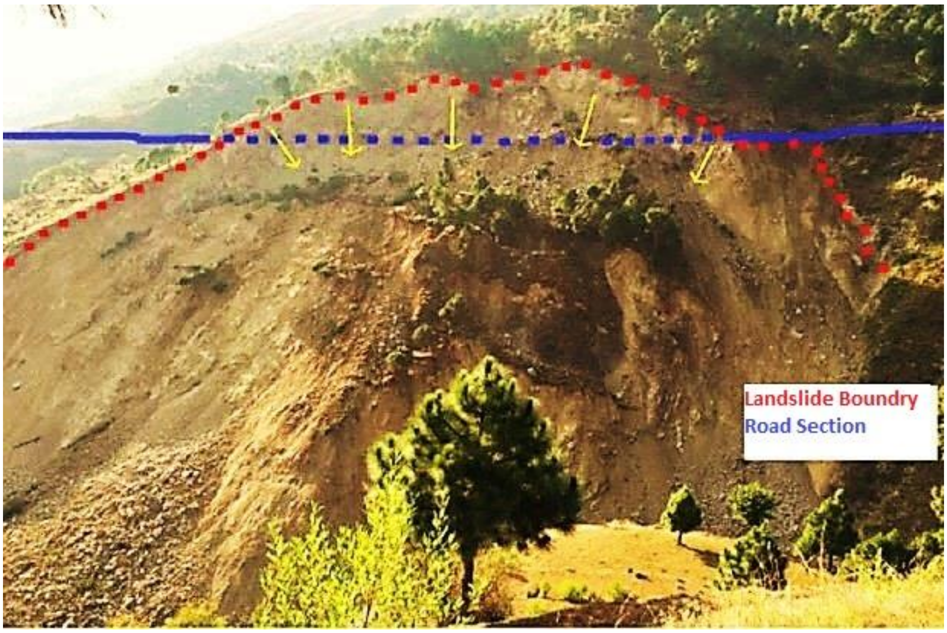


Figure 1. Failure surface of Havelian Landslide, the collapsed section of the road is shown [5]

The aim of this research study was to analyze the slope stability at different angles in silty soil and propose a method to stabilize the slope.

The specific objectives of the research are:

- To investigate the factor of safety of the slopes at different angles (i.e. 30°, 35°, 45°, 60°).
- To investigate the stability of the slope with the replacement of soil cement by using different techniques.

2. Review of Methods of Analysis

Generally, the LEM is adopted for two-dimensional (2D) slope stability analysis [6]. About the basic concept of LEM, the soil volume above the sliding surface is divided into number of slices to find a factor of safety (FOS) for a slope failure surface, which is recognized as a method of slices. Equilibrium conditions are used for each slice to calculate moment, resisting and driving forces. For the computation of total FOS, the sum of all the resisting and driving forces and moments is calculated. The ratio of these resisting to driving sums is known as a factor of safety, FOS:

$$FOS = \frac{\sum(resistingforces)}{\sum(derivingforces)} = \frac{\sum(resistingmoments)}{\sum(derivingmoments)} \quad (1)$$

Based on this FOS equation the stability of the slope is clearly computed by a numeric value. The failure of a slope is possible when the FOS value is lower than 1.5, computed by many slip failure surfaces, which shows that the soil slope may fail or in a state of impending failure. Normally the constant FOS is obtained along the slip surface, based on definitive concepts of slope stability. Therefore, the mean value is employed rather than the real value, which may vacillate along the failure surface. Chugh [7] proposed a method based on the model of limit equilibrium for finding a varying safety factor for analyzing the slope stability. However, this model adopts a procedure that uses various suppositions which have no solid theoretic background.

Commonly failure computing is placed on the supposition which specifies a circular failure surface, though this assumption is precise for many homogenous types of soils the assumption can't be precise in several real-life conditions where soil type is heterogeneous or a composite shape is conceived. In these conditions, non-circular slip failures are most expected. Many methods of analysis have been formulated for computing the factor of safety by using the method of slices. The LEM used by different research workers including of Agam et al [8] who specified the effect of changing parameters upon the FOS by applying Spencer's method and LEM of slices and Mohr-Coulomb soil parameters. Zhou [9] analyzed the stability of three dimensional slopes by applying a new displacement method based on rigorous LEM.

A new method combination of pseudo-dynamic and the rigorous LEM was suggested by Zhou [10] to determine the three dimensional stability of seismic landslides, which satisfied all forces equilibrium conditions around 3 align axes and all moment conditions of equilibrium about 3 align axes. Earlier, Zhou [11] applied inter-column forces based upon 6 conditions of equilibrium to get the rigorous LEM, which includes both three directional moment and force conditions of equilibrium about three align axes. A modern pseudo-static LEM for analysis of cantilevered retaining walls was described by Conti and Viggiani [12] for seismic loading, while by applying the method of slices Shamsabadi [13] calculated seismic earth pressure due to earthquake-induced pseudo-static body forces.

Wei and cheng [14] practiced the LEM and the strength reduction method to study three dimensional stability of slope for many examples, Limit equilibrium methods can be split up into 3 primary methods, which are methods of slices, Swedish circle method (SCM) and noncircular methods. But there is a no thumb rule to manifest which technique is the Safest; however, it's by and large accepted that noncircular analysis methods are safer as they take internal forces more cautiously. There is a common instruction that the noncircular methods are normally better than the other methods as they take the internal forces more cautiously. In spite of a couple of deviations in these methods of analysis, many research workers have accepted that computed results are more or less equal [15,16].

Method of slices is the basic method applied to analyze the slope stability. This is because there are numbers of comparatively cheap computer software's which use this type of analysis. The method of slices is usually the acceptable method among geotechnical engineers. These computer software's enable the user to easily change soil parameters, pore water pressure condition, and failure surface geometries. The theoretic base for the method of slices represents that the normal stress acting at a point on a potential slip surface should be influenced primarily by the burden of the soil resting above that point. The expected slip surface bulk is then split up into various vertical slices and then equilibrium for each one slice is computed in conditions of forces and moments. This provides the minimal safety factor to be computed for that slip surface bulk. Presently most of the computer software's which apply LEM have search engines that facilitate in discovering the critical slip surface bulk and later on generates the minimum safety factor for that slip surface [17]. Figure 2 vertical slices in a slope slip surface.

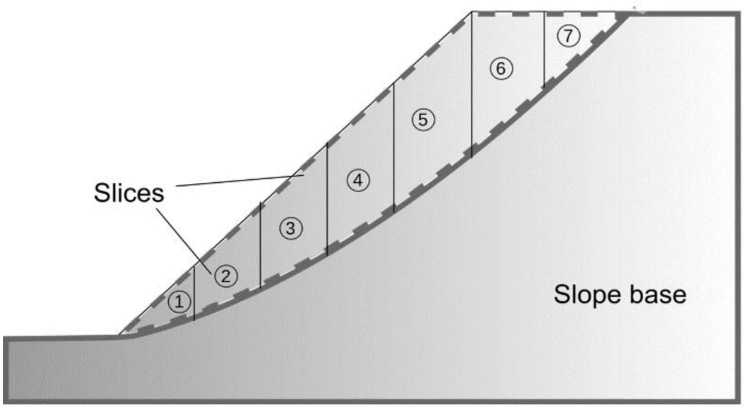


Figure 2. Vertical Slices in a slope slip surface

Ordinary method is also recognized as the Swedish method of slices. This method ignores all the interslice forces and neglects to satisfy force equilibrium for both the slide mass and for individual slices. This is one of the simplest method based on the method of slices [18]. Simplified bishop method was suggested by Bishop [19], this method assumes that the vertical interslice shear force doesn't exist hence the resulting interslice force is horizontal. This method only satisfies the moment equilibrium.

Janbu simplified method uses the horizontal forces equilibrium equation to find out the FOS. This method doesn't include interslice forces in the computation but describes its effect by applying a correction factor. The correction factor is concerned with the internal friction angle, cohesion and pattern of the slope failure slip surface [20]. Spencer's method was firstly formulated for the circular slip surfaces, which satisfies all equilibrium conditions, including horizontal, vertical force and moment. Spencer method carries to simulate noncircular slip surfaces and presumes that total forces on the sides of the slice are parallel. This method individually applies the horizontal force equilibrium condition and moment equilibrium condition to find out multiple factors of safeties. The factors of safety obtained by the moment equilibrium condition are same as it is from the Janbu's simplified method and the simplified Bishop method [21].

In Morgenstern Price method (MPM), for each slice, all tangential, moment and normal equilibrium conditions are considered for both circular and noncircular slip surfaces. Similar to Spencer's method this method also generates two factors of safeties on the basis of moment and force equilibrium. As the MPM allows moment and force equilibrium and also forces on sides of a slice, the analysis results of slope stability are more robust [22].

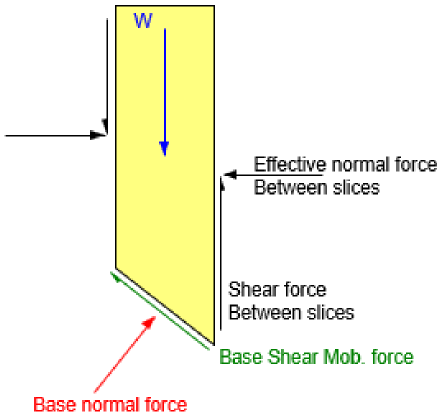


Figure 3. Morgenstern and Price Method Effecting Forces

3. Research Methodology

Figure 4 shows the flow chart of the methodology which was adopted in this study. After the selection of the geometry, the model parameters (i.e. c' and ϕ') were taken from the literature [26]. In the subsequent stage, the geometry of slope was created in Slope/W. After assigning soil properties and defining slip surface, the model was submitted in the software for analysis. After successful completion of the numerical model analysis, the required results such as critical factor of safety of slope and failure pattern were extracted from Slope/W. In final stage of the study, the computed results obtained from the numerical modelling were discussed and interpreted.

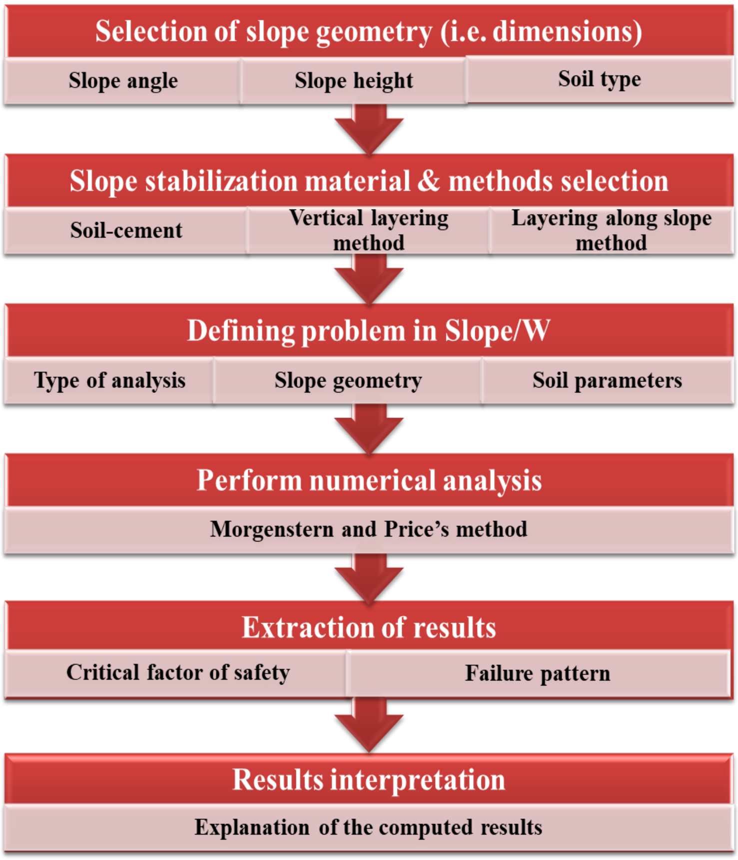


Figure 4. Flow chart showing research methodology adopted in this study

Figure 5 shows the typical section of a slope in silty soil of 7m height with an angle 35° and Figure 6 shows typical sections of upgraded slopes by (a) vertical layering and (b) layering along the slope

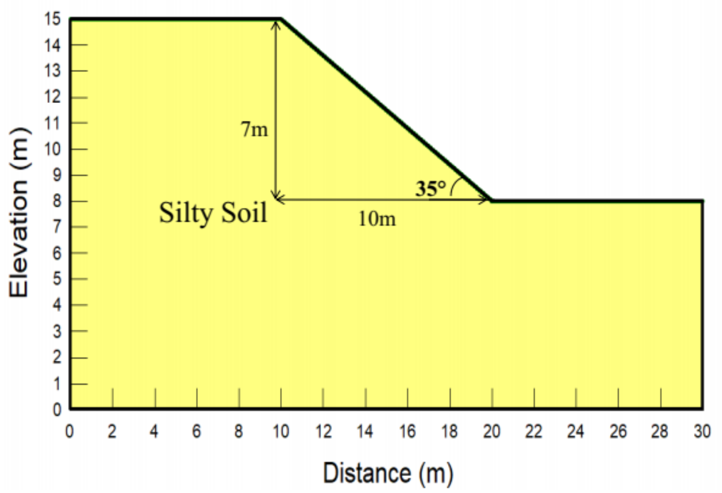
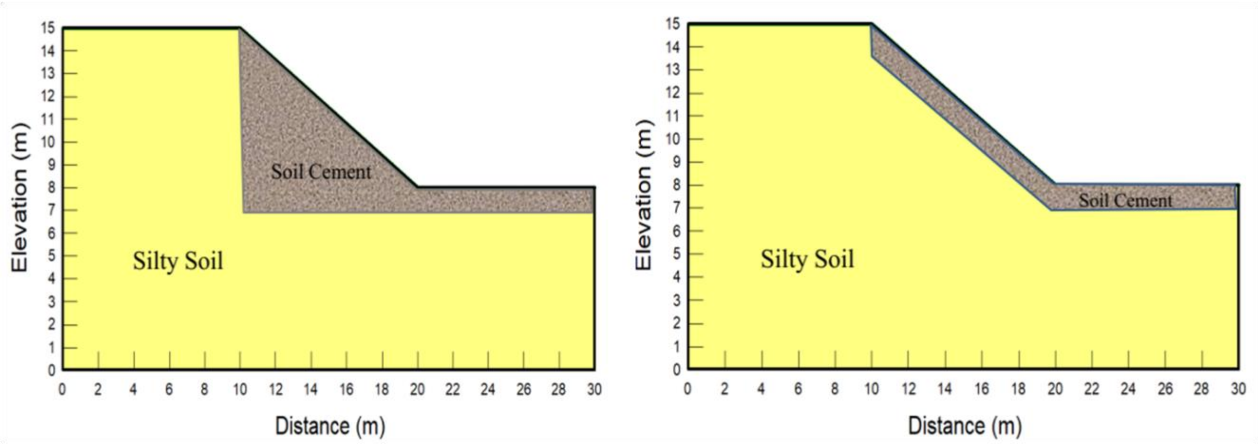


Figure 5. Typical section of a slope in silty soil



(a) **(b)**

Figure 6. Typical sections of upgraded slopes by (a) Vertical Layering and (b) layering along the slope

Table 1 summarises numerical simulations conducted in this parametric study.

Table 1. Numerical simulation plan

Slope angle (º)	Ground condition	Remark
	Existing ground	
30,35,45,60	Silty Soil	Investigation of existing slope stability
	Stabilization of slope by replacement of soil cement by vertical layering	
30,35,45,60	Silty soil replaced by soil cement	Stabilization of existing slope
	Stabilization of slope by replacement of soil cement by layering along slope	
30,35,45,60	Silty soil replaced by soil cement	Stabilization of existing slope

The stability of the slope in silty soil was investigated at four different slope angles which are 30º, 35º, 45º and 60º. After that, the slopes were upgraded by replacement of soil cement by using two different techniques of soil replacement (i.e. vertical layering and layering along the slope) and then investigated at four different angles.

3.1. Criterion for Slope Stability

The safety factor, with respect to the stability of a slope, is generally defined as the ratio between shear strength, τ_f of the soil along a possible slip surface and the corresponding mobilized shear stress, τ_{mob}.

$$FOS = \frac{\tau_f}{\tau_{mob}} \tag{2}$$

The FOS can also be described in terms of either forces or moments acting on the mass of soil. When FOS = 1, the slope is in a state of impending failure. Generally, FOS =1.5 with respect to strength is acceptable for the design of a stable slope [24].

3.2. Define the Problem

A LEM analysis was conducted using the Slope/W software package for the slope stability. The type of analysis is first decided and it is observed that failure will adopt a left to right direction. The Morgenstern Price's analysis procedure and half-sine function was selected. After that, the working area in Slope/W is adjusted to draw the geometry of the slope. The default values of the geometry and convergence settings in Slope/W are shown in Table 2.

Table 2. Default values of the convergence settings in SLOPE/W

Convergence settings	Default value
Minimum slip surface depth	0.1
Number of slices	30
Tolerable difference in FOS	0.001
Maximum number of iterations	100

3.3. Define Soil Parameters

The soil parameters of each of the layers of the soil slope were first defined and then allotted to the slope geometry. The Mohr-Coulomb failure criterion was selected for both types of soils. The input soil parameters required for the Mohr-Coulomb model are the unit weight of soil, the angle of internal friction and cohesion. Table 3 shows the Mohr-Coulomb soil parameters used in the SLOPE/W analysis.

Table 3. Mohr-Coulomb soil parameters [25]

Parameters	Silty Soil	Soil Cement *
Unit weight (kN/m^3)	20	20
Cohesion (c') (kPa)	5	300
Friction angle (ϕ')	30	33

* Cement Replacement in silty Soil = 7 % (By weight)

The pore water pressure (PWP) was specified by a piezometric line at one meter below the level of the ground surface. This was also assumed that the ground water table (GWT) level was remained constant throughout the year.

3.4. Numerical Modeling Procedure

The numerical modelling procedure is summarised as follows:

1. Set the working area: scale and grid;
2. Define the problem: Choose Morgenstern's Price Method;
3. Sketch axes;
4. Define Soil Properties: Mohr-Coulomb failure criterion;
5. Draw boundaries of the problem: draw the top line and the bottom line from the leftmost point;
6. Define Pore water pressure conditions: Draw Piezometric Line;
7. Draw the slip surface radius: draw the area of points for slip surface and specify 20 for the radius increment;
8. Draw the slip surface grid: draw the area and use 20 increments each side;
9. Solve the problem;
10. Post Processing.

4. Results and Discussions

In this study, limit equilibrium analyses were performed using SLOPE/W to evaluate the stability of slopes. The limit equilibrium analyses were performed on three different cases of slopes stabilization, for each case, the stability of slope was determined at four different slope angles (i.e. 30°, 35°, 45°, 60°). The FOS for each slope was obtained from LEM. In the limit equilibrium analysis, the FOS was obtained by Morgenstern and Price's method.

4.1. Results for Existing Soil Slope

Limit equilibrium analysis method was carried with 9261 number of slip surfaces. The analysis result of the critical failure surface is shown in Figure 7. The minimum value of the FOS is 1.13 and the circle centre coordinate x = 20.003 m and y = 22.055 m with a radius of 14.128 m. It implies that the slope in the existing soil condition is in a state of impending failure along the critical slip surface.

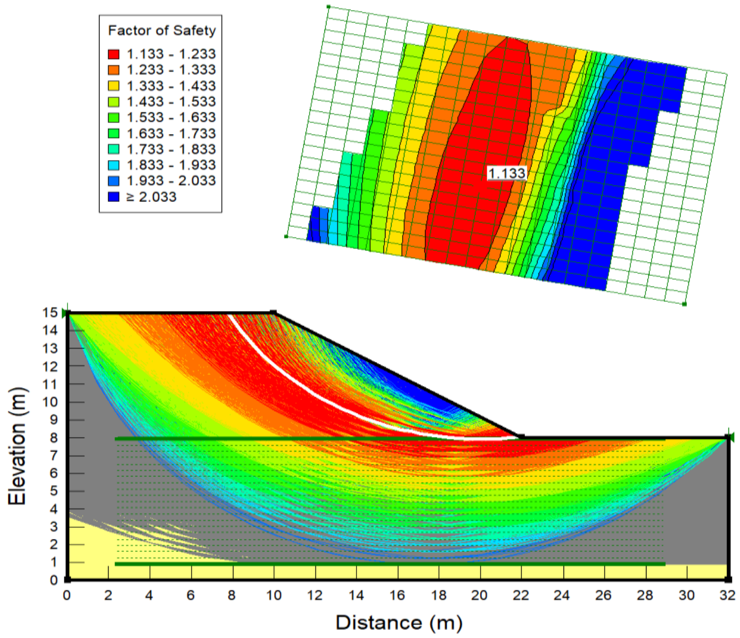


Figure 7. Plot of all failure surfaces for the slope of 30°

All surfaces of failure for 35° slope are shown in Figure 8. The minimum value of the FOS is 0.99 and the circle center coordinate x = 19.6 m and y = 21.35 m with a radius of 13.35 m. It implies that the slope in the existing soil condition is in a state of impending failure.

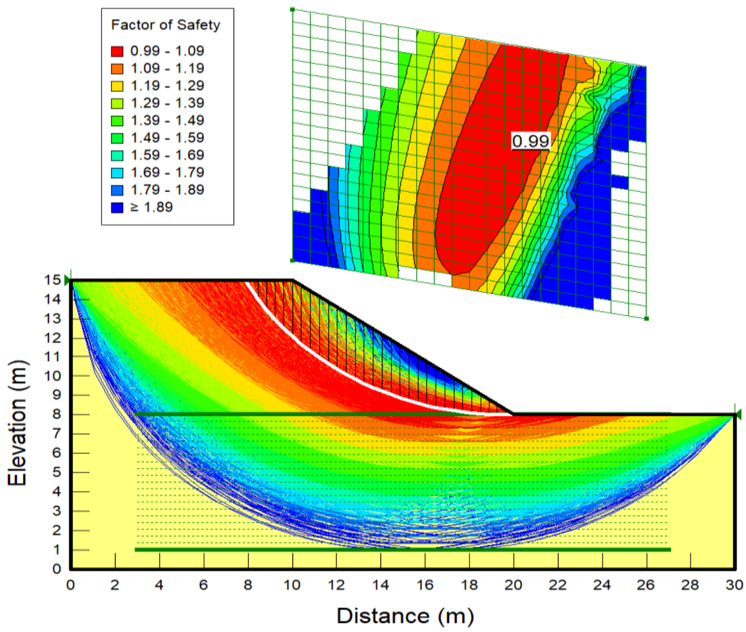


Figure 8. Plot of all failure surfaces for the slope of 35°

All surfaces of failure for 45º slope are shown in Figure 9. The minimum value of the FOS is 0.76 and the circle center coordinate x = 17.5 m and y = 17.75 m with a radius of 9.74 m. It implies that the slope in the existing soil condition is likely to be failed along the critical failure surface.

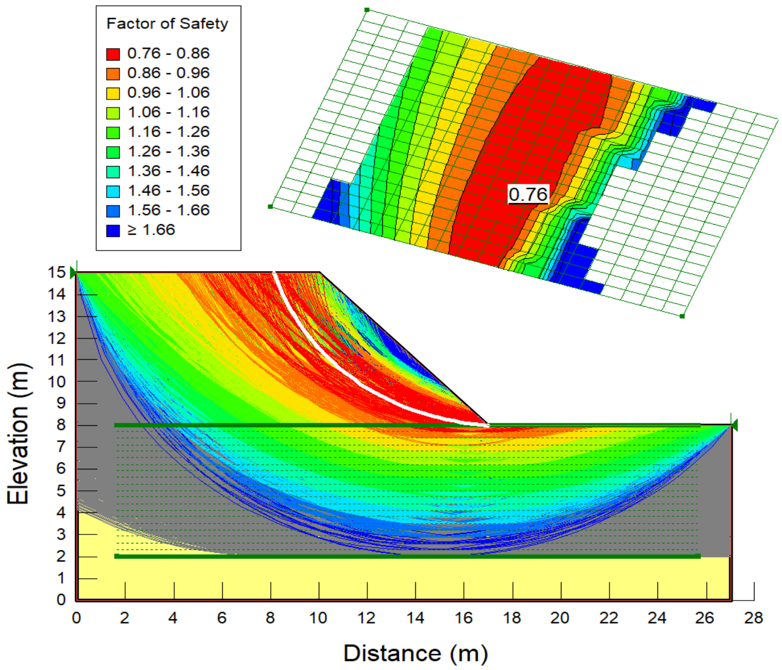


Figure 9. Plot of all failure surfaces for the slope of 45º

All surfaces of failure for 60º slope are shown in Figure 10. The minimum value of the FOS is 0.67 and the circle center coordinate x = 17.5 m and y = 17.56 m with a radius of 10.15 m. It implies that the slope in the existing soil condition is likely to be failed along the critical failure surface.

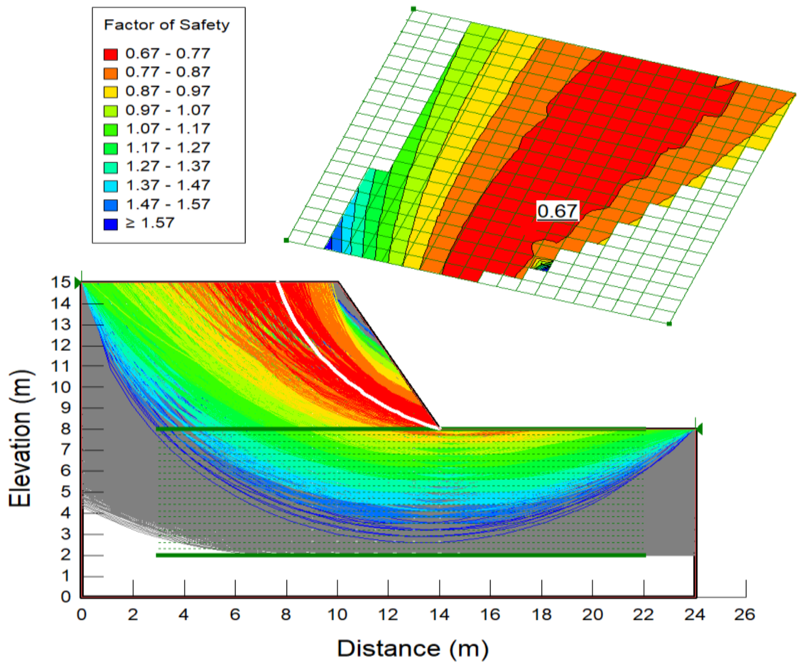


Figure 10. Plot of all failure surfaces for slope of 60º

Among all the existing slopes at different angles, the minimum FOS for the slope of 60º is the lowest. This shows that with the increase of slope angle the FOS value is decreasing.

4.2. Results for Upgraded Slope (Vertical Layering)

The analysis results for the upgraded slope by replacement of soil cement with vertical layering technique at different angles are shown below.

The existing soil is replaced by five vertical layers of soil cement. The depth of each layer replaced is 1.75 m. All possible slip surfaces for 30° upgraded slope are shown in Figure 10. It can be seen that the stability of slope has been improved significantly with minimum FOS= 2.96.

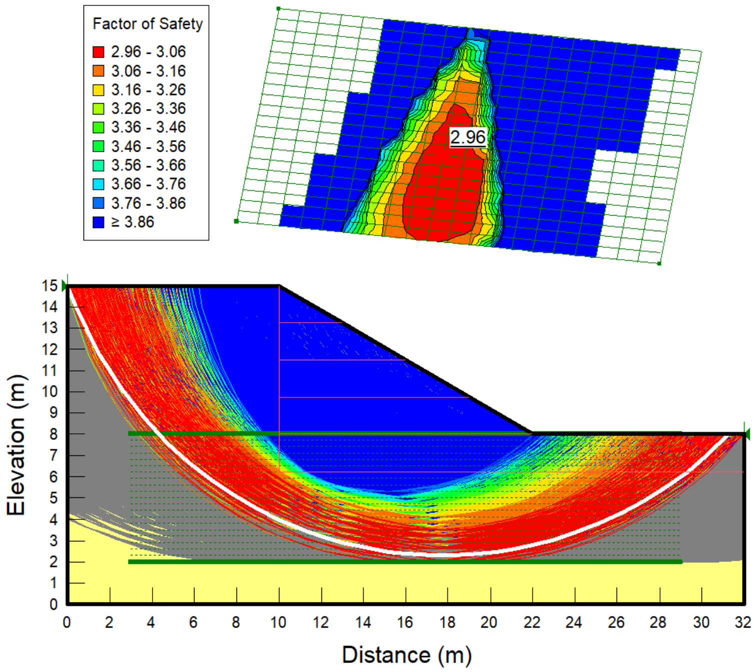


Figure 11. Plot of all failure surfaces for upgraded slope of 30°

All possible slip surfaces for 30° upgraded slope are shown in Figure 12. It can be seen that the stability of slope has been improved significantly with minimum FOS= 2.77

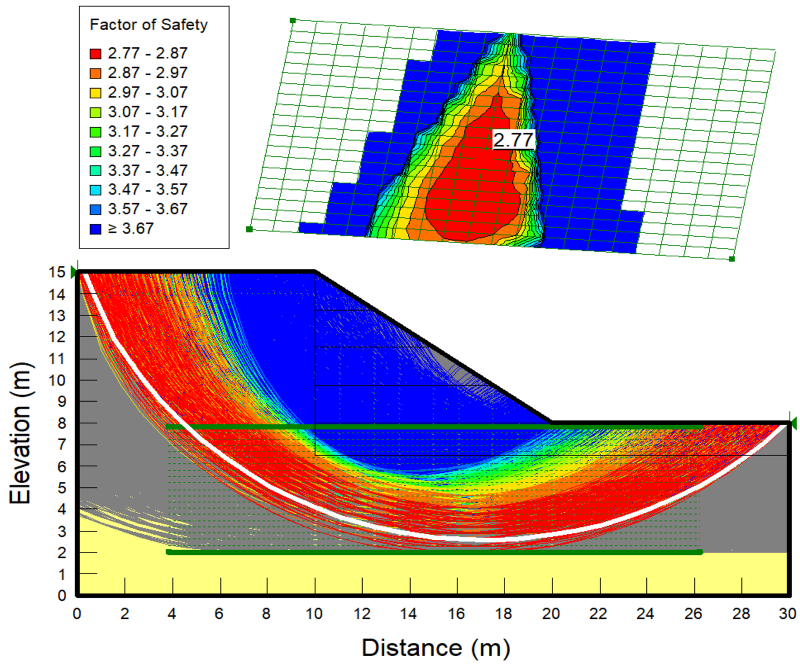


Figure 12. Plot of all failure surfaces for the upgraded slope of 35°

All possible slip surfaces for upgraded slope of 45° are shown in Figure 13. It can be seen that the stability of slope has been improved significantly with minimum FOS = 2.73.

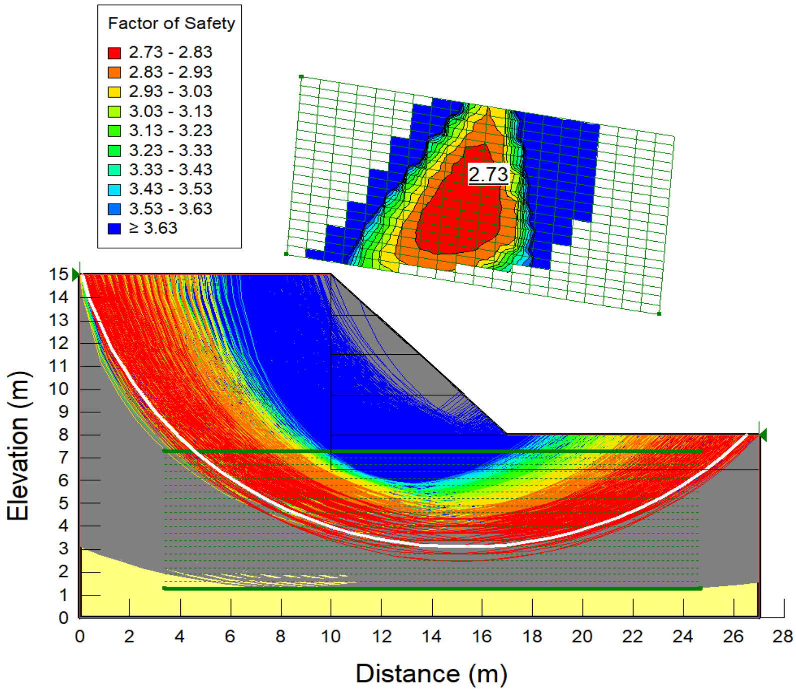


Figure 13. Plot of all failure surfaces for the upgraded slope of 45°

All possible slip surfaces for upgraded slope of 60° are shown in Figure 14. It can be seen that the stability of slope has been improved significantly with minimum FOS = 2.73.

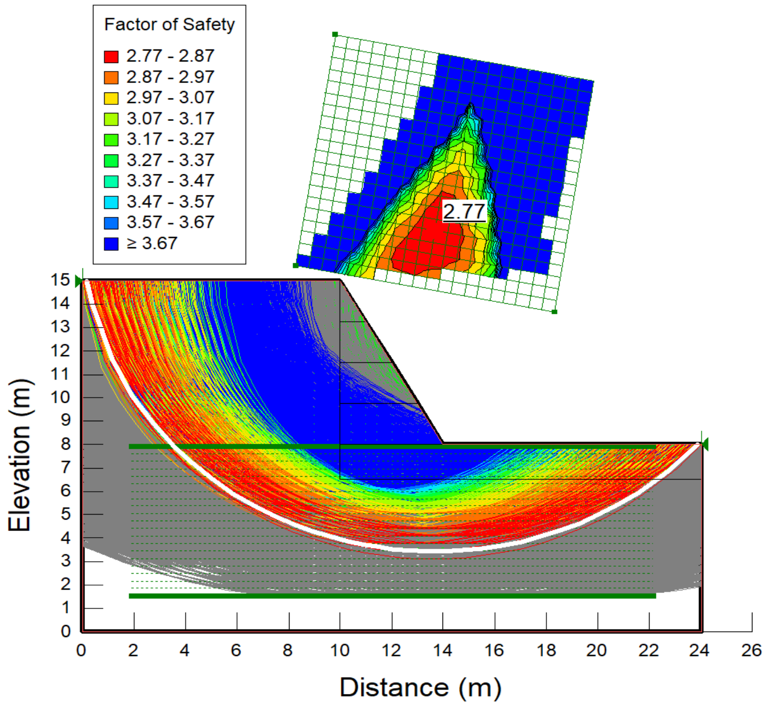


Figure 14. Plot of all failure surfaces for upgraded slope of 60°

From the above computed results of soil cement replacement by vertical layering it is clearly shown that the upgraded slope FOS is significantly improved.

4.3. Results for Upgraded Slope (Layering along the Slope)

The analysis results for the upgraded slope by replacement of soil cement with layering along the slope technique at different angles are shown below.

The existing soil is replaced by layering along the slope with soil cement. The depth of the layer replaced is 0.5 m.

Figure 15 shows the plot of all slip surfaces for upgraded slope of 30°. It can be seen that the stability of slope has been improved significantly with minimum FOS = 1.70

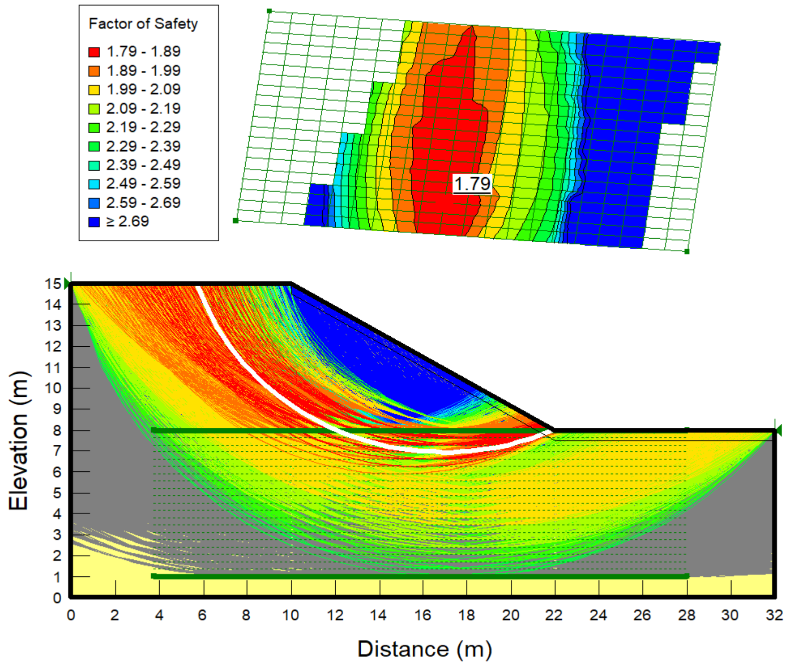


Figure 15. Plot of all failure surfaces for the upgraded slope of 30°

The depth of the layer replaced is 0.5 m. Figure 16 shows the plot of all slip surfaces for upgraded slope of 35°. It can be seen that the stability of slope has been improved significantly with minimum FOS = 1.66

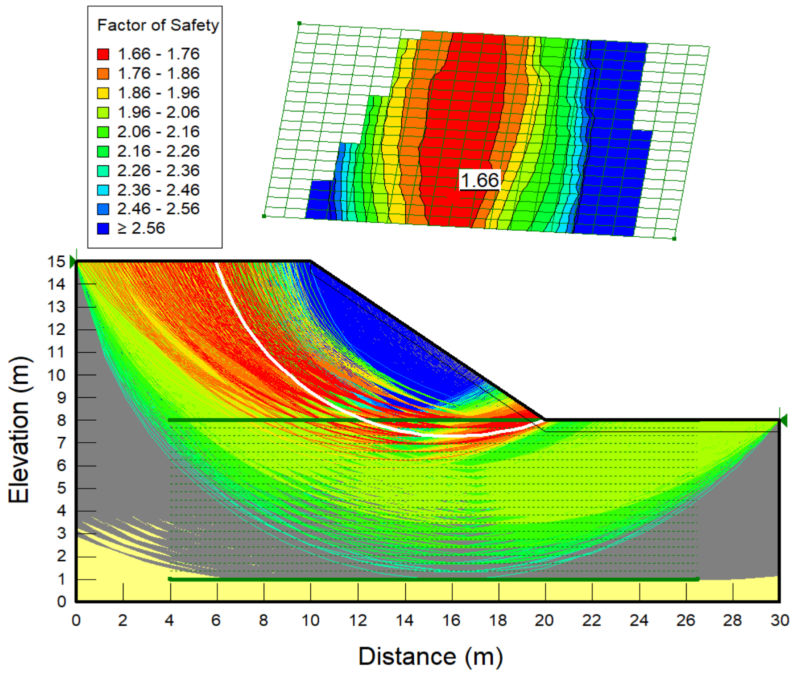


Figure 16. Plot of all failure surfaces for the upgraded slope of 35°

The depth of the layer replaced is 1 m. Figure 18 shows the plot of all slips surfaces for upgraded slope of 45°. It can be seen that the stability of slope has been improved significantly with minimum FOS = 1.85

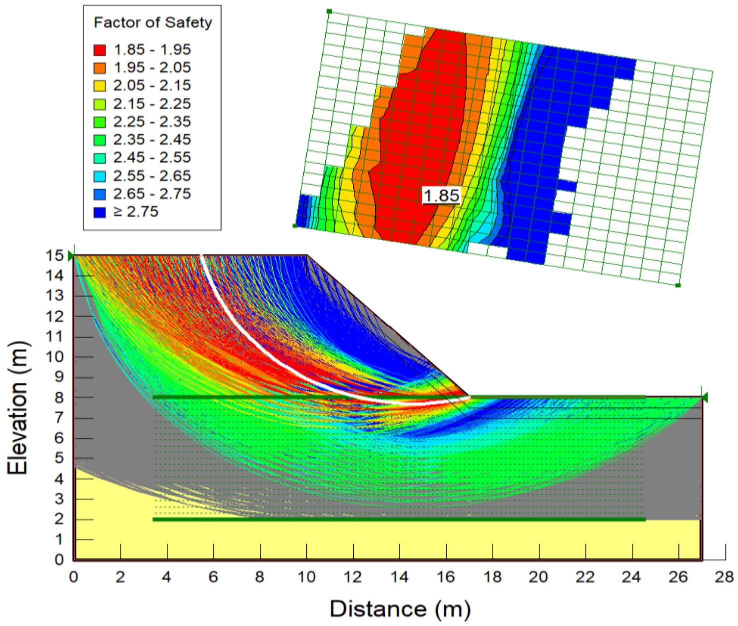


Figure 18. Plot of all failure surfaces for the upgraded slope of 45°

The depth of the layer replaced is 1 m. Figure 19 shows the plot of all slip surfaces for upgraded slope of 60°. It can be seen that the stability of slope has been improved significantly with minimum FOS = 1.47

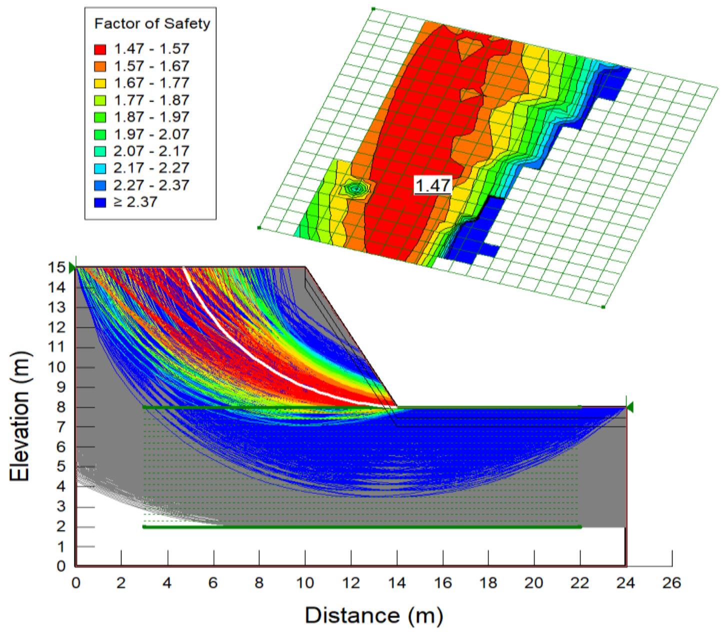


Figure 19. Plot of all failure surfaces for an upgraded slope of 60°

Table 4 shows the comparison of the critical factor of safety values of existing silty soil and upgraded slope by vertical layering and layering along the slope with soil cement. Below given table clearly shows that the upgraded slope FOS is significantly improved by using both replacement techniques.

Table 4. Summarizing the Critical FOS values

Slope angle (°)	Factor of safety		
	Existing soil slope	Vertical Layering	Layering along slope
30	1.13	2.96	1.79
35	0.99	2.77	1.66
45	0.76	2.73	1.85
60	0.67	2.77	1.47

5. Conclusions

Based on the slope stability analysis results by different stabilization techniques and slope geometry, the following conclusions have been drawn.

- The values of the minimum factor of safety of the existing slopes (at 30°, 35°, 45° & 60°) in silty soil were computed less than 1.5 required for minimum factor of safety. It implies that the existing slopes are not stable and likely to be failed.
- The existing slopes were stabilized by replacing soil-cement (7% by weight) by two different methods (i.e. vertical layering and layering along the slope).
- The factor of safety improved significantly after replacing soil cement by both methods of soil stabilization.
- The vertical layering of soil replacement method improves the factor of safety significantly but in comparison with layering along the slope method this method requires more excavation and soil-cement replacement.
- Among the two methods of soil stabilization, it was revealed that the layering along the slope method of soil replacement was most economical and easy to be executed at the site.
- Among the four different slope angles (i.e. 30°, 35°, 45° & 60°) the slopes of 45° and 60° are more suitable and economical as these slopes required less soil-cement replacement.

6. Acknowledgements

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7. Conflicts of Interest

The authors declare no conflict of interest.

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