SLOPE STABILIZATION USING EPS GEOFOAM

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ABSTRACT

Expanded polystyrene (EPS) has been used as a super light-weight soil substitute in treating unstable roadway embankments over soft ground for more than 25 years. Among different types of traditional methods currently in use to stabilize slopes, installation of geofoam is easy and fast. However, as the cost of geofoam is high relative to soil, the amount and location of geofoam to achieve a desired level of stability improvement can be important. This paper presents a method of slope stability analysis in which the use of EPS geofoam is optimized. A supplementary program was developed using a moment reduction method. The program provides the volume and location of EPS geofoam for different factors of safety. Geofoam installation in parallelogram configurations gave best results.

KEY WORDS: geofoam, limit equilibrium, moment reduction, safety factor, slope, stability

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INTRODUCTION

Slope stability problems are of broad interest in civil engineering applications and particularly in the construction and operation of surface transportation facilities. Slopes fail because the soil strength and slope geometry can not sustain disturbing forces resulting from soil weight and surcharge loads, high groundwater conditions or seismic loading. Failure of slopes may disrupt economic activity and can cause hazard to life and property. Investigation, repair and maintenance of unstable slopes require considerable allocation of resources. Economic growth and population increases necessitate development or upgrading of transportation networks with attendant need to modify existing slopes or construct new ones. In many cases, improving the stability of a slope without altering the existing geometry would be most desired. Strategic substitution of soil by a very light weight but competent material, EPS geofoam, is a relatively new and effective method of slope stabilization. This paper presents a method for analysis and optimization to improve the stability of slopes to desired levels of factor of safety considering both the volume and location of geofoam blocks.

SLOPE STABILITY

Soil slopes represent ground surface of steep gradient. Depending on the soil strength, ground water conditions and extent of surcharge, natural or man made slopes adjust to acquire equilibrium. The process of adjustment or failure may be gradual or sudden. In the case of new construction, foundation conditions, geometry and soil material composition must be considered to design a safe slope. Under cutting by erosion or excavation, surcharging or steepening, seismic action, high groundwater conditions; lead to reduction of safety factors and possible failure. Slopes can be flattened or benched, ground water levels can be lowered or a toe berm can be constructed to improve stability. These alternatives are shown in Figure 1 and constitute methods that rely on either reducing the driving mass or increasing the resisting mass. Implications of these alternatives are summarized in Table 1. All except groundwater lowering involve changes in slope geometry. Additional methods that rely on introduction of reinforcing elements or additives to increase shear strength or resistances are a separate subset of remedial measures.

Overall, the factor of safety of slopes or the degree of effectiveness of remedial measures are commonly assessed by limit equilibrium methods. The slope mass is partitioned into slices, as shown in Figure 2. Forces on a free body diagram (Figure 3) of each slice are considered. Equilibrium of forces in two directions and summation of moments together with strength criteria for the soils are supplemented with simplifying assumptions to compute safety factors. Different simplifying assumptions have led to different stability analyses methods (Fredlund and Krahn, 1976). A number of commercial programs are available for stability analysis. The programs feature alternative methods that rely on different assumptions. In general, safety factors computed by the different methods are in reasonably good agreement (Duncan, 1996). Finite element or finite difference methods wherein progressive failure and strain patterns can be examined have also been used to assess slope stability. Limit equilibrium methods are much more widely used. The further discussion of slope stabilization presented in this paper relies on limit equilibrium analysis results.

IMPROVING STABILITY

A slope or embankment is first analyzed by a limit equilibrium method. When the safety factor is found to be low, alternative methods of improvement are selected and associated safety factors are determined. For example, different options of conventional stability improvement are shown in Figure 1. Flattening of a slope is an economical method for stability improvement. Increases in factor of safety with decreasing inclination of a particular slope are shown in Figure 4. For safety factor improvement from 1.0 to 1.2, the corresponding change in slope angle would be from 19.2° to 12.7°. This may require a significant realignment for a case involving a railroad or highway side slope. Constructing a toe berm adds beneficial weight to increase sliding resistance. Figure 5 shows improvements in factor of safety with increasing berm height. A berm with dimensions of 15.2m x 2.1m would improve the factor safety from 1.0 to 1.2, for the example case. Adding a berm at the toe may not be acceptable or feasible. The hydraulic conductivity of the soil profile may be too low to make permanent ground water lowering measures workable. Benching and possible grade separation may also be unacceptable. As tried and tested traditional methods fail to meet project constraints, stability improvement by substitution of geofoam for soil can be a viable solution.

STABILIZATION USING GEOFOAM

Geofoam has a unit weight of up to 100 times less than compacted soil. Replacing soil by geofoam blocks can be effective in improving the safety factor of deep-seated critical surfaces and potentially unstable slopes. Detailed accounts of slope stabilization using geofoam have been reported by Sheeley (2000), Elragi (2000), Jutkofsky et al (2000) and Srirajan (2001) has conducted a parametric study of slope geometry, soil properties and geofoam amount and location. Figure 1B shows alternative slope profiles in which geofoam has been substituted for compacted soil. Profiles 1B(b), 1B(c) and 1B(c) represent cases for which the geofoam configuration options are restricted. For case 1B(a), the full height of the slope, except the soil cover along the slope face and overlying pavement structure, can be constructed out of geofoam. However, the installed price of geofoam can be about five times the cost of compacted soil of equal volume. There may therefore be justifiable need to limit the amount of geofoam and carefully select the most effective replacement location.

As shown in Figure 2, to analyze a slope problem by limit equilibrium methods, a trial failure having a center O and a radius R is sub-divided into a number of vertical slices. A free body diagram for a trial slice is shown in Figure 3. A vector W through the centroid represents the weight of the slice. The shear resistance T at the base is due to the soil shear strength consisting of a cohesion and friction component obtained from the normal stress multiplied by the tangent of the soil friction angle. The weights of the slices that have a positive angle of base inclination, α, contribute to driving forces. Slice weights in the vicinity of the toe that have a negative inclination, α, contribute to resisting forces. Each force component is multiplied by the corresponding moment arm to obtain driving and resisting moments. A global factor of safety for the slope is calculated by dividing the sum of driving moments by the sum of resisting moments. Introducing light-weight geofoam into the soil mass results in weight reduction. Correspondingly, the shear resistance due to friction would also be reduced. However, the net effect of weight reduction is to increase the factor of safety. The consequence of weight reduction due to geofoam substitution can be reviewed in reference to the expression of factor of safety for the well known ordinary method of slices (Craig, 1994).

$$F = (\Sigma(c*l + (\tan \phi)* (W*\cos \alpha - u*l)))/ \Sigma W*\sin \alpha \qquad (1)$$

Where c is cohesion, l is arc length segment, ϕ is friction angle, W is the total weight of the slice, α is the inclination of the base to the horizontal and u is the pore water pressure. The installation of geofoam and provision of effective perimeter drainage decrease or eliminate u and for simplicity the u*l contribution can be neglected. For a given critical surface and soil parameters, the only variable in the expression that can be manipulated to achieve factor of safety improvements is reduction of the weight of slices

Geofoam can be included in a slope section and stability analysis can be performed taking into account the material properties that apply. Repeat analysis to identify an optimum amount and location of geofoam for a targeted improvement in safety factor can become tedious. A more simple design method that would reduce the amount of analysis required to attain a viable solution is described below.

MOMENT REDUCTION

For a given slope, the critical surface with the lowest factor of safety is first identified by conventional limit equilibrium analysis. The summary output for the analysis provides the net moment contribution of each slice. Figure 6 represents a plot of moment difference with horizontal distance or slice position for a particular slope. A negative moment difference for a slice means that the driving moment is greater than the resisting moment for that slice and thus the slice is unstable. The central idea is to concentrate the geofoam treatment to slices that contribute the most to instability. These would be the slices that have the largest magnitude of negative moment. Introducing light-weight geofoam blocks into slices with highest negative moment difference reduces the driving forces and result in the greatest improvement to stability of the slope. To determine the height of the geofoam blocks to be placed, a threshold moment, such as shown in Figure 7, is selected. The threshold moment represents a limit moment difference to be achieved after geofoam blocks are installed. Only slices that have a moment difference lower than the selected threshold would receive geofoam. The height of geofoam blocks required to achieve the moment reduction can be determined from the change between the threshold moment and the moment difference for each slice. The following equation can be used to determine the height of geofoam blocks.

$$h = \left(\frac{H}{M_d} \right) * \overline{M} \qquad (2)$$

Where h is the geofoam height; H is the slice height; M_d is the driving moment and $\overline{M}$ is the difference between the negative moment difference and the threshold moment. The negative moment difference represents the difference between the driving moment, M_d, and the resisting moment M_r. A maximum negative moment difference of 8.85E+02 kNm is associated with slice number 7. For a threshold moment of 5.44E+02 kNm, geofoam would be placed only in slices 4 through 12. With the modified moment differences that apply for slice numbers 4 and 12, a new sum of driving moments can be calculated. The improved factor of safety would then be determined as the ratio of the sum of resisting and driving moments.

The resulting geofoam configuration within the slope mass for a factor of safety of 1.2 is shown in Figure 8. The trapezoidal configuration is modified to a parallelogram by shifting geofoam blocks vertically downward in slices 6 through 8 as shown in Figure 9. The vertical position of a geofoam block within a slice does not change the factor of safety for the slice. For ease of construction, geofoam blocks would be placed as high within the slope as possible allowing for sub-base and pavement as well as cover on the side slope. The threshold moment is adjusted to obtain the desired factor of safety. Once a target factor of safety and geofoam configuration is obtained by this method, a formal check is made in a conventional stability analysis program.

SUMMARY OF THE MOMENT REDUCTION METHOD

1. Perform a limit equilibrium stability analysis using one of a number of programs. Example – REAME, GEOSLOPE, etc.
2. From the summary printout, calculate the moment difference for each slice. The moment difference is the difference between the resisting moment and the driving moment.
3. Plot moment difference against slice number (or horizontal distance). A negative moment difference implies that the driving effect for that slice is greater than the resisting and thus the slice is unstable.
4. Select an initial threshold moment. The threshold moment represents the maximum moment difference in the slices after geofoam blocks are placed. Some amount of protective cover would be placed over the geofoam, thus the threshold moment would be less than zero.
5. Isolate slices that have a moment difference less than the threshold moment.
6. Determine the improved factor of safety and change the threshold moment, if necessary. Alternatively, perform analyses for different threshold moments and plot factor of safety against geofoam volume.
7. Include the geofoam blocks in the slope as a parallelogram, accounting for the required depth of cover.
8. Confirm the safety factor improvement due to geofoam substitution by conventional analysis.

SUPPLEMENTARY PROGRAM

A supplementary spread sheet program has been developed to automate the process of optimizing the geofoam substitution exercise described above (Srirajan, 2001). The program requires the width, height, resisting moment and driving moment of each slice. This can be imported from a limit equilibrium analysis summary for the slope problem such as, REAME, GEOSLOPE etc. The user must also enter the required depth of cover, geofoam block dimensions and the maximum depth of excavation. The program automatically performs the above steps and provides the required number of geofoam blocks in each slice for different factors of safety. A plot of safety factor against geofoam volume, as shown in Figure 10, is generated. Output from the spread sheet program is used as input for a check analysis in a conventional slope stability analysis program. The new critical surface for the slope section with geofoam tends to be larger and lower into the slope than the initial critical surface for the soil slope without geofoam. The spread sheet program considerably reduces the tedium of performing a series of trial and error analysis.

SUMMARY AND CONCLUSIONS

The analysis and design of slope stabilization using geofoam can be performed with conventional slope stability programs. A supplementary spreadsheet program for optimizing the amount and location of geofoam has been developed. The supplementary program is based on minimizing destabilizing moments. In comparison to other alternatives of slope stabilization, a geofoam solution usually has a higher initial cost. The approach presented in this paper provides a means of analyzing the effectiveness of a geofoam placement for slope stabilization.

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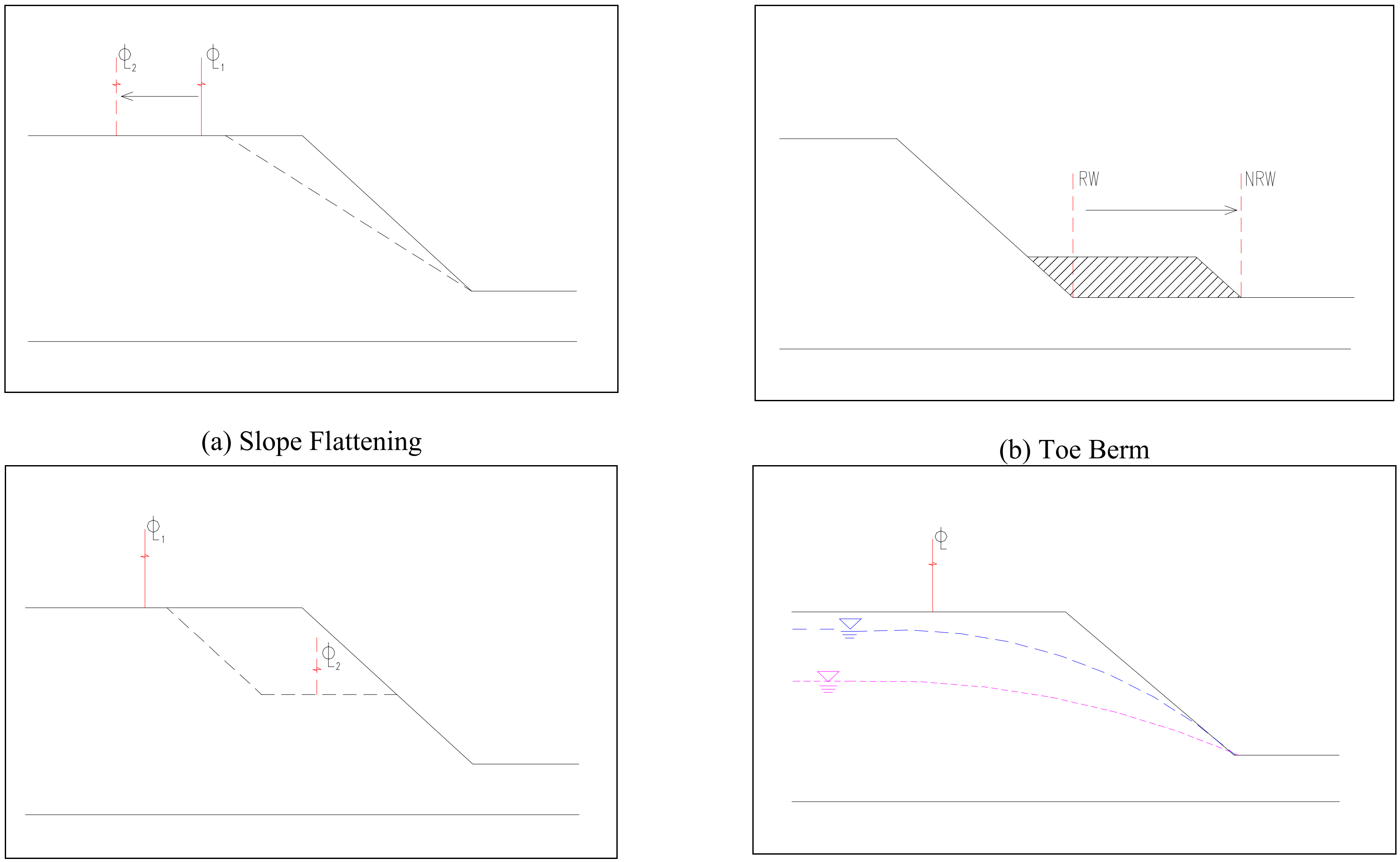


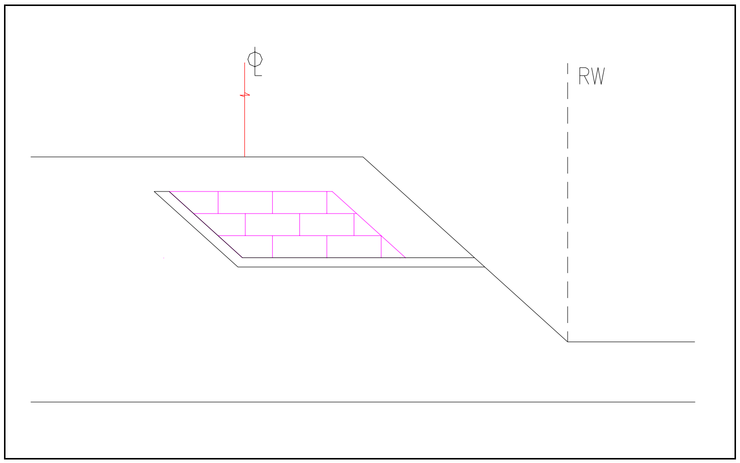
(a) Slope Flattening

(b) Toe Berm

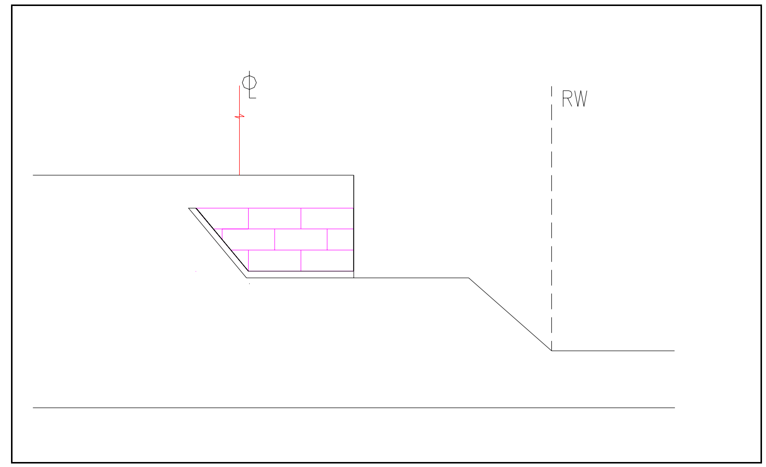
(c) Benching

(d) Ground Water Lowering

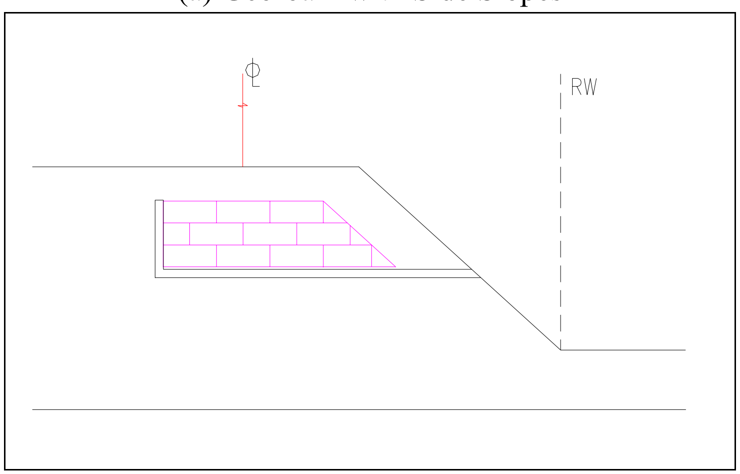
Figure 1A. Alternatives for slope stabilization



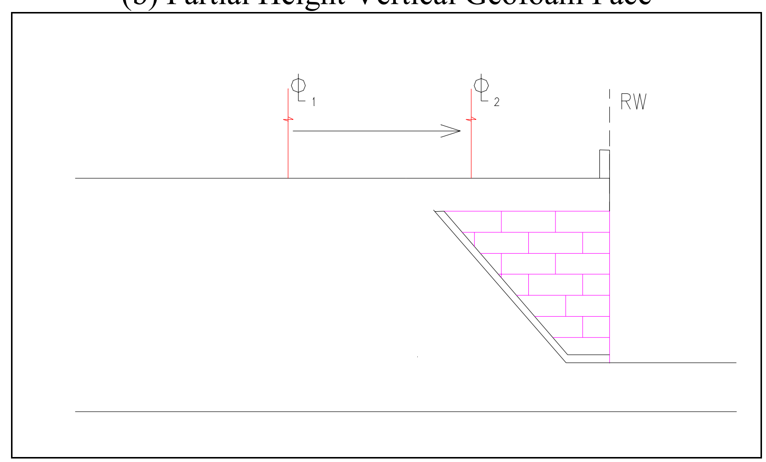
(a) Geofoam with Side Slopes



(b) Partial Height Vertical Geofoam Face



(c) Geofoam with Vertical Back Slope



(d) Full Height Vertical Wall Geofoam Face

Figure 1B. Slope stabilization with geofoam

Figure #	Without Geofoam	Remarks
1	Slope Flattening	Recessed centerline, loss of slope face and frontage on terrace.
2	Benching	Split level, loss of elevation and frontage at upper terrace, gain lower terrace
3	Toe Berm	Retain or gain frontage at lower terrace and elevation, may require right of way widening
4	Groundwater Lowering	Retain centerline, terrace frontage, slope face and elevation, may not be effective with low hydraulic conductivity soils
	With Geofoam	
5	Geofoam with Side Slopes	Retain centerline, terrace frontage, slope face and elevation
6	Geofoam with Vertical Back	Retain centerline, terrace frontage, slope face and elevation, may have to resist significant lateral earth pressure
7	Partial Height Vertical Face	Retain terrace frontage and elevation but partially lose slope, facing required
8	Full Height Vertical Face	Increase terrace, maintain elevation, widen and utilize full right of way lose slope face, facing required

Table 1 Alternatives for slope stabilization

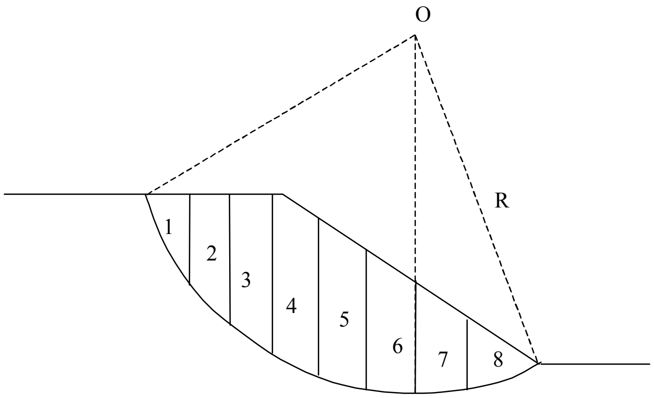


Figure 2. The method of slices

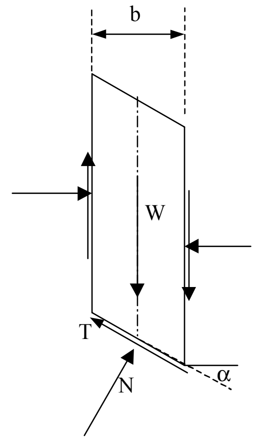


Figure 3. Free body diagram

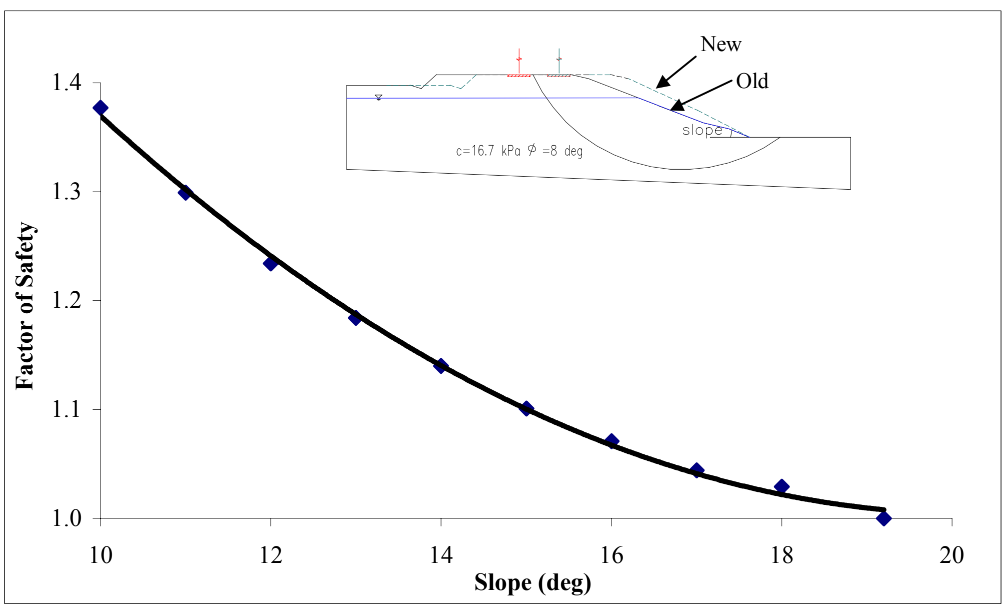


Figure 4. Factor of safety improvement by slope reduction

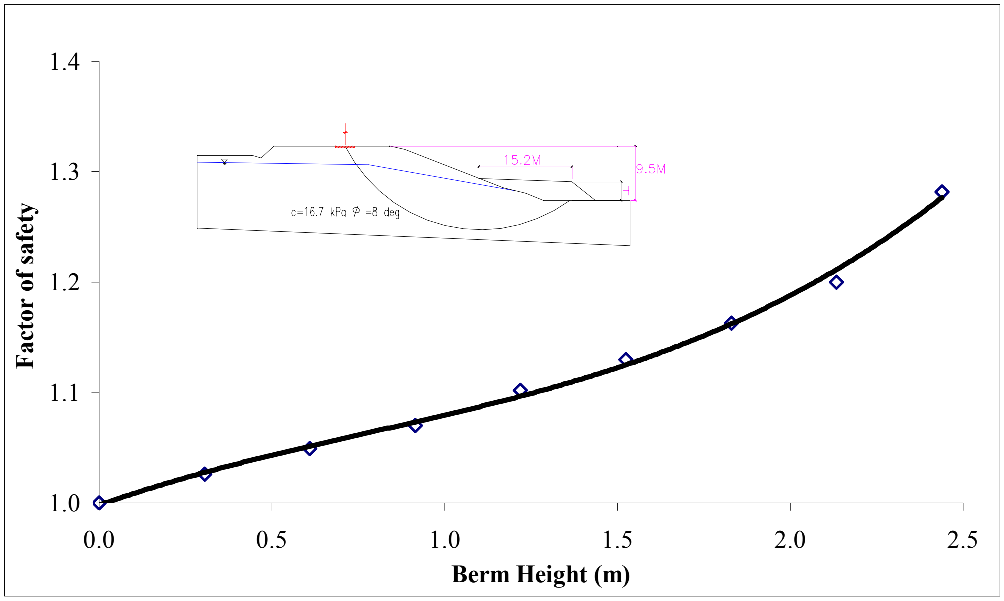


Figure 5. Factor of safety improvement by toe berm

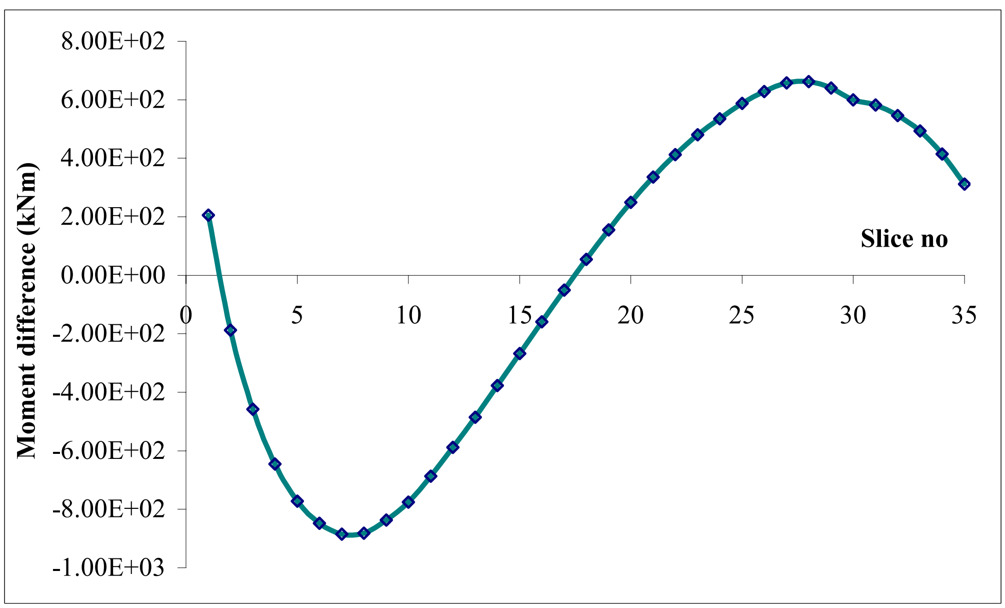


Figure 6. Moment difference diagram for a critical soil slope

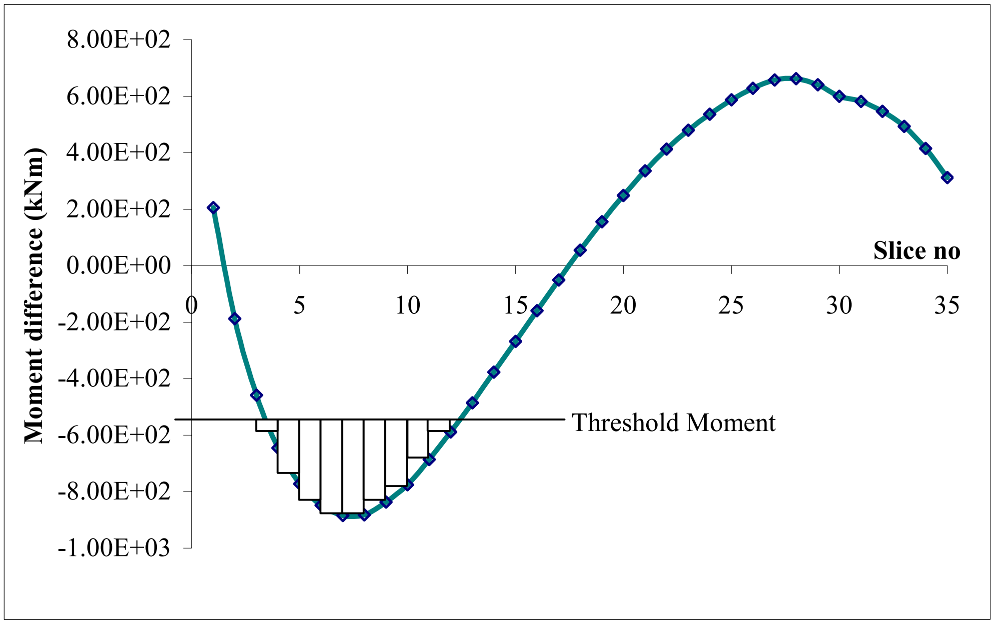


Figure 7. Moment reduction by geofoam inclusion

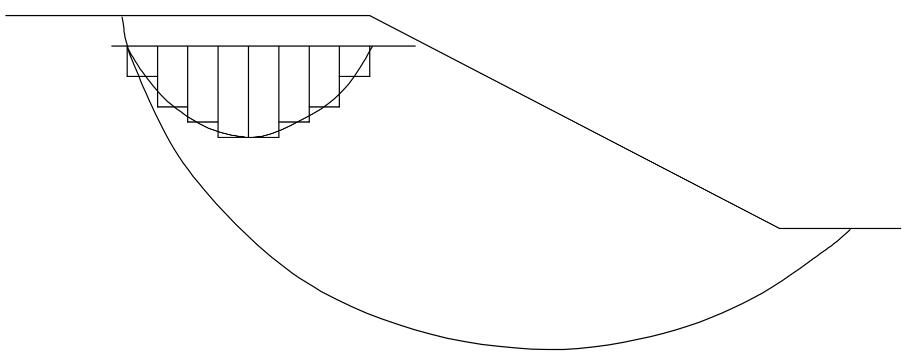


Figure 8. Possible geofoam configuration within the slope mass for a factor of safety of 1.2.

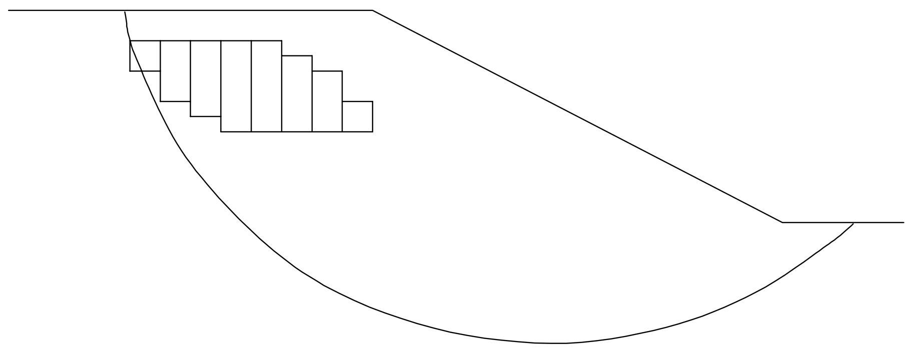


Figure 9 . Equivalent parallelogram arrangement of geofoam blocks for factor of safety improvement from 1.0 to 1.2.

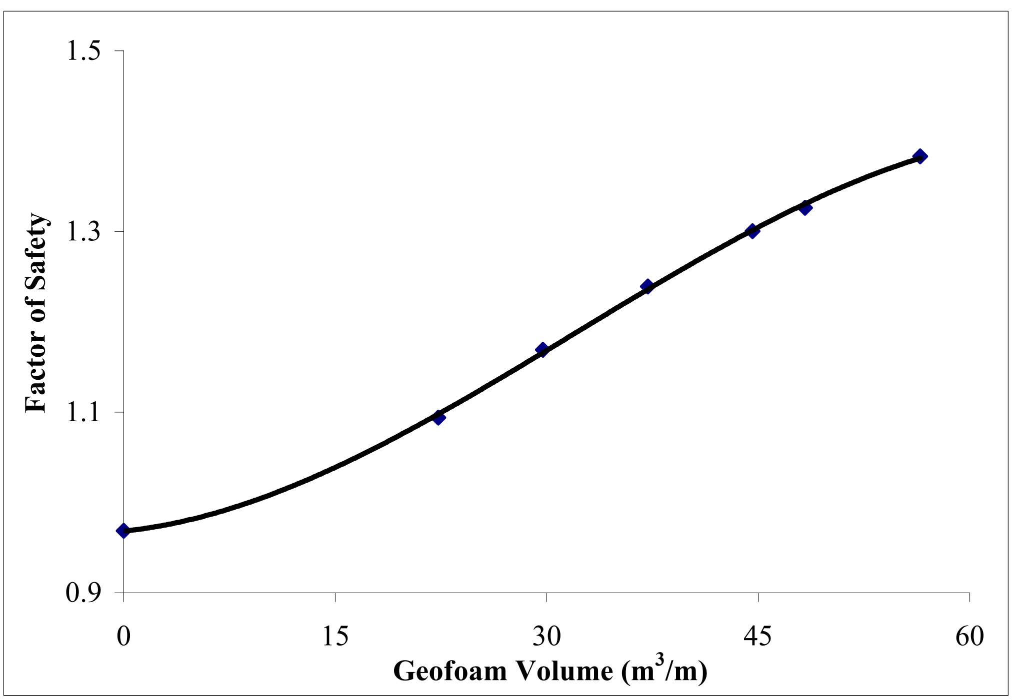


Figure 10. Factor of safety improvement for a given slope with geofoam volume provided by the supplementary program