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Critical Analysis of Slope Stability Analysis Methods

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***Abstract* - Earth slopes may be found in nature or may be man-made. These are invariably required in the construction of highways, railways, earth dams and river-training works. The stability of these earth slopes is, therefore, of concern to the geotechnical engineer, since failure entails loss of life and property. In the geotechnical field, stability analysis aim to support the safe and functional design of soil slopes. Preliminary analysis can be carried out in order to determine the critical parameters of work stability. Parametric analyses allow one to assess the physical and geometrical problem parameters influence on the slope stability. The present study is carried out in order to ensure that the slope analyzed is safe and also to minimize the probability of slope failure. It focuses on the use of Geo-studio software to model, analyze and perform parametric study of factors influencing the stability of geotechnical slopes subjected to static forces. The comprehensive formulation of SLOPE/W has made easy the analysis of slope stability problems using a variety of methods to calculate the factor of safety. Comparative studies of various factors influencing the performance of earthen slopes such as cohesion(C), angle of internal friction(Φ), height of slope (h) and unit weight of soil(γ) are carried out and also the sensitivity of each of these factors are identified.**

Key Words: Slope/W; Geo Studio;

I. INTRODUCTION

A slope is an unsupported, inclined surface of soil mass. Slopes can be natural or manmade. These may be above ground level as embankments or below ground level as cuttings. Earth slopes are formed for railway embankments, earth dams, canal banks, levees, and at many other locations. Instability related issues in engineered as well as natural slopes are common challenges to both researchers and professionals. Instability may result due to rainfall, increase in groundwater table and change in stress conditions. Similarly, natural slopes that have been stable for many years may suddenly fail due to changes in geometry, external forces and loss of shear strength. In addition, the long term stability is also associated with the weathering and chemical influences that may decrease the shear strength. In such circumstances, the Sliding may occur along any of a number of possible surfaces and shear strength generally varies throughout time. It is therefore normal in practice to use appropriate safety factors when analyzing slope stability.

Slope stability is based on the interplay between two types of forces i.e. driving forces and resisting forces. Driving forces promote down slope movement of material, whereas resisting forces deter the movement. So, when driving forces overcome resisting forces, the slope is unstable and results in failure of slopes. The basic concept of these two types of forces is quite simple. The interplay between driving forces and resisting forces are experienced down a steep slope. The main driving force in most land movements is gravity. The main resistive force is the material's shear strength. The ratio of resisting forces to driving forces is the factor of safety (FoS):

$$FoS = \frac{\text{Resisting Forces}}{\text{Driving Forces}}$$

Usually a safety factor of around 2 to 3 is used in design to accommodate slight variances in materials and construction practices. Many different methods have been developed for computing factors of safety using Geo-Studio. All the methods are based on limit equilibrium formulations.

- General limit equilibrium (GLE) method was developed by Fredlund at the University of Saskatchewan in the 1970s (Fredlund and Krahn 1977; Fredlund et al. 1981). This method encompasses the key elements of all the other methods available in SLOPE/W. The GLE method provides a framework for discussing, describing and understanding all the other methods. The GLE formulation is based on two factor of safety equations and allows for a range of interslice shear-normal force assumptions. One equation gives the factor of safety with respect to moment equilibrium (F_m), while the other equation gives the factor of safety with respect to horizontal force equilibrium (F_f). The GLE factor of safety equation with respect to moment equilibrium is:

$$Fm = \frac{\sum(c'\beta + (N - u\beta)R\ tan\varphi')}{\sum Wx - \sum Nf \pm \sum Dd}$$

The factor of safety equation with respect to horizontal force equilibrium is:

$$Fm = \frac{\sum(c'\beta cos\alpha + (N - u\beta)tan\varphi' cos\alpha)}{\sum Nsin\alpha - \sum Dcos\ \omega}$$

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The terms in the equations are:
c' = effective cohesion
φ' = effective angle of friction
U = pore-water pressure
N = slice base normal force
W = slice weight
D = concentrated point load
β, R, x, f, d, ω = geometric parameters
α = inclination of slice base

• Ordinary or Fellenius method: The simplest form of the Ordinary factor of safety equation in the absence of any pore-water pressures for a circular slip surface is:

$$Fm = \frac{\sum(c\beta + N tan\phi)}{\sum W sin\alpha}$$

• Bishops Simplified Method: A simple form of the Bishop's Simplified factor of safety equation in the absence of any pore-water pressure is:

$$FS = \frac{1}{\sum W sin\,\alpha} \sum \frac{c\beta + W tan\phi - \frac{c\beta}{FS} + sin\alpha tan\phi}{m\alpha}$$

FS is on both sides of the equation as noted above. The equation is not unlike the Ordinary factor of safety equation except for the m_α term, which is defined as:

$$m\alpha = \cos\alpha + \frac{\sin\alpha \tan\alpha}{FS}$$

To solve for the Bishop's Simplified factor of safety, it is necessary to start with a guess for FS. In SLOPE/W, the initial guess is taken as the Ordinary factor of safety. The initial guess for FS is used to compute $m\alpha$ and then a new FS is computed. Next the new FS is used to compute m_α and then another new FS is computed. The procedure is repeated until the last computed FS is within a specified tolerance of the previous FS.

• The Janbu's Simplified method is similar to the Bishop's Simplified method except that the Janbu's Simplified method satisfies only overall horizontal force equilibrium, but not overall moment equilibrium.

• Morgenstern-Price method: Morgenstern and Price (1965) developed a method similar to the Spencer method, but they allowed for various user-specified interslice force functions. It,

• Considers both shear and normal interslice forces,
• Satisfies both moment and force equilibrium, and
• Allows for a variety of user-selected interslice force function.

II. ANALYSIS

A typical soil slope of height (h) with an inclination (i), cohesion(c), angle of internal friction (φ), unit weight (ϒ) and resultant of surcharge load (w) is considered in the analysis as in Fig. 1 using Morgenstern-Price method by Geo-Studio.

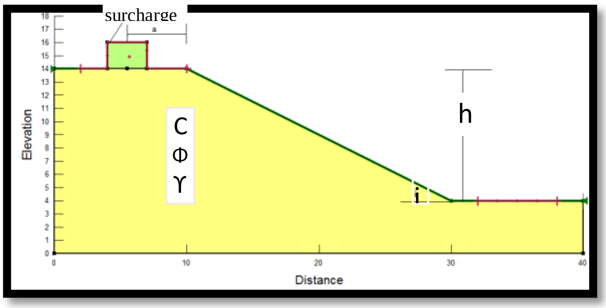

Fig. 1: A typical homogenous soil slope

• Height of slope is varied from 5 to 25 m keeping all others parameters constant. Fig.2 indicates the effect of height of slope on the factor of safety against stability of slope. It can be seen that the factor of safety decreases with increase in the height of slope. For the given configuration, critical factor of safety is achieved at a height of around 14m .The variation is non linear.

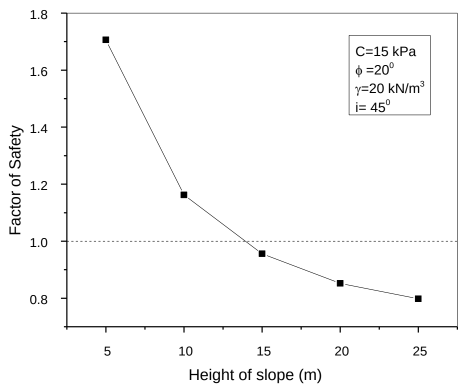

Fig. 2: Variation of factor of safety with height of slope

Angle of internal friction of slope is varied from 0 to 40° keeping all other parameters constant. Fig.3 indicates the effect of internal friction on the factor of safety against stability of slope. In the figure, angle of internal friction is plotted along the horizontal axis and factor of safety is plotted along the vertical axis. It can be seen that the factor of safety increases with increase in the angle of internal friction. For the given configuration, critical factor of safety is achieved when the angle of internal friction is 8°.The variation is observed to be close to linear.

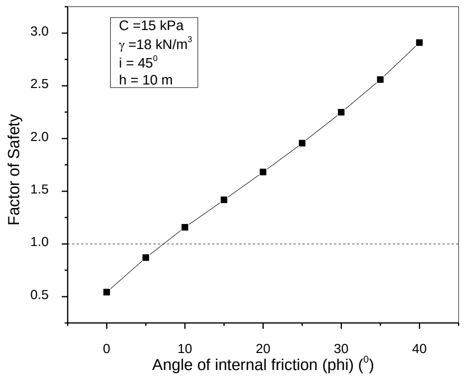

Fig. 3: Variation of factor of safety with angle of internal friction of slope

Fig. 4 and 5 present the variation of factor of safety of soil slope with angle of internal friction and height of slope. The factor of safety increases with increase in the angle of internal friction and reduces with increase in the height of the soil slope.

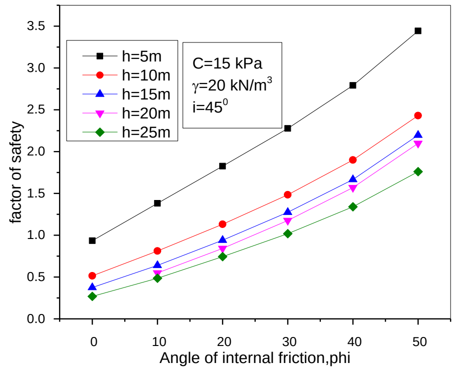

Fig. 4: Variation in factor of safety with angle of internal friction (phi) and height of the slope (h)

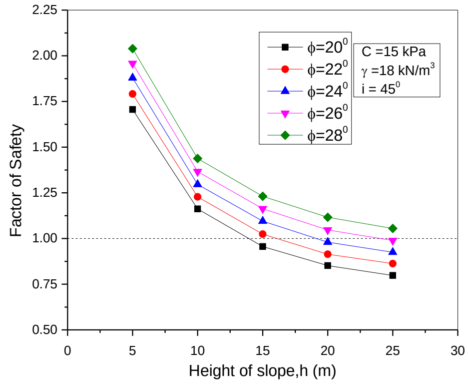

Fig.5: Variation in Factor of Safety with height of the slope and angle of internal friction

Unit weight of slope is varied from 12 to 24 kN/m^3 keeping all other parameters constant.Fig.6 and Fig.7 indicate the effect of unit weight of slope on the factor of safety and angle of internal friction against stability of slope. It can be seen that the factor of safety decreases with increase in the unit weight of slope. For the given configuration, critical factor of safety is achieved when the unit weight of slope is 24 kN/ m^3.The variation is observed to be non linear.

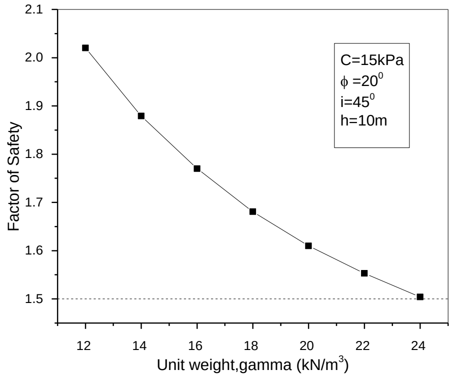

Fig.6: Variation in Factor of Safety with unit weight of soil of the slope

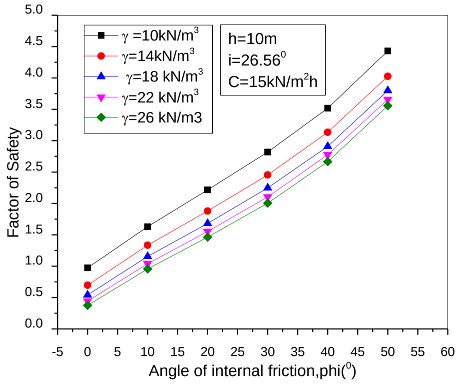

Fig.7: Variation in factor of safety wrt angle of internal friction and unit weight of soil slope

Fig.8 and Fig.9 indicate the effect of cohesion of slope on the factor of safety against stability of slope. It can be seen that the factor of safety increases with increase in the cohesion of slope. For the given configuration, critical factor of safety is achieved when the cohesion of slope is less than 5 kN/m^2.The variation is observed to be nearly linear.

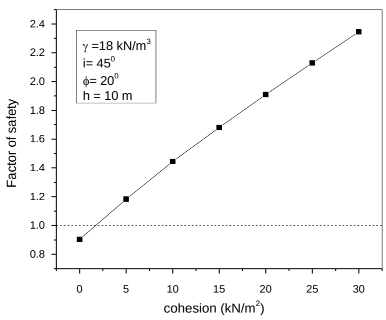

Fig.8: Variation in Factor of Safety with cohesion of soil of the slope

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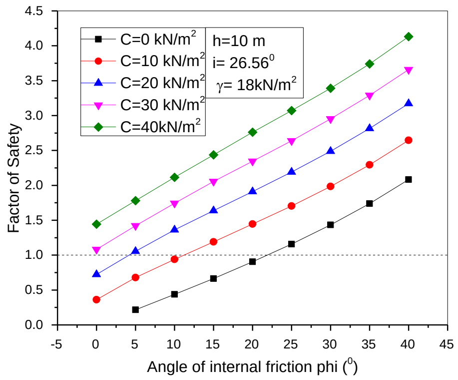

Fig.9: Variation in factor of safety wrt angle of internal friction and cohesion of soil slope

Fig.10 and Fig.11 indicate the effect of slope angle on the factor of safety against stability of slope. It can be seen that the factor of safety decreases with increase in the slope angle. For the given configuration, critical factor of safety is achieved when the slope angle is 65°.The variation is observed to be non linear.

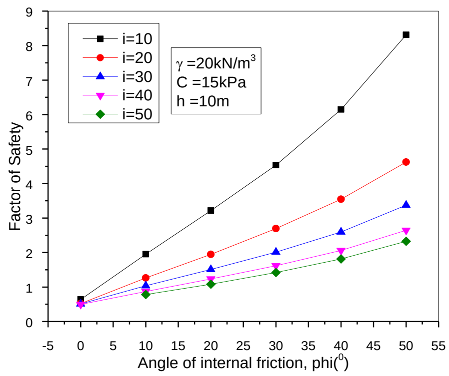

Fig.10: Variation in Factor of Safety with slope angle (i) and angle of internal friction (φ)

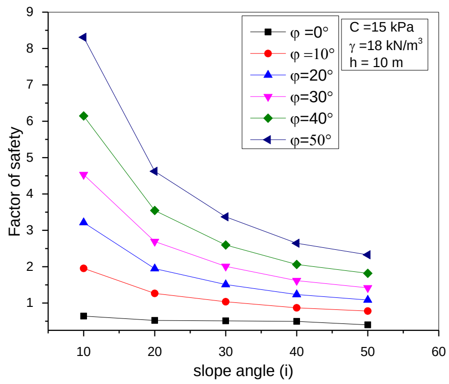

Fig.11: Variation in Factor of Safety with slope angle (i) and angle of internal friction (ϕ)

Magnitude of surcharge is varied from 480kN/m to 1440kN/m keeping all other parameters constant. Fig.12 indicates the effect of magnitude of surcharge on the factor of safety against stability of slope. It can be seen that the factor of safety decreases with increase in magnitude of surcharge. The variation is observed to be non linear.

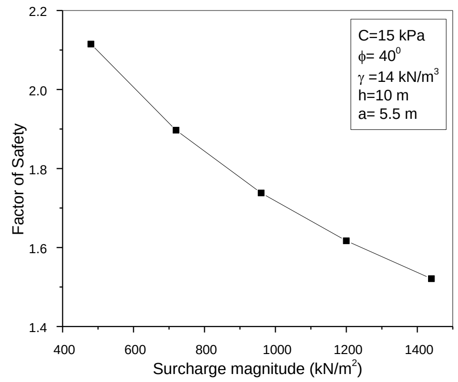

Fig.12: Variation in Factor of Safety with magnitude of surcharge on the soil slope

Position of resultant of surcharge from the edge of the slope is denoted by x. Position of resultant of surcharge is varied from 1.5 m to 7.5 m keeping all other parameters constant. Fig.13 indicates the effect of position of surcharge on the factor of safety against stability of slope. It can be seen that the factor of safety increases with increase in distance of resultant of surcharge.

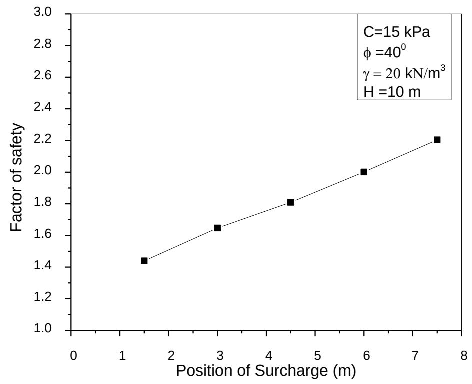

Fig.13: Variation in Factor of Safety with position of Surcharge

The effect of the various parameters influencing the performance of geotechnical slope is studied. It was found that increase in cohesion and friction angle increase the stability of slope whereas the increase in surcharge, angle of slope, height of the slope decreases the stability of slope. Further increase in density of slope material showed that the stability decreases contrary to actual condition.

The various parameters in a two layered soil slope influencing the performance of slope with varying height of the soil, slope angle, angle of internal friction, unit weight of the soil, cohesion of the soil particles and surcharge load are studied. A typical non homogenous soil slope with two layers as shown in Fig.14 with c1, ϕ1 and γ1 and c2, ϕ2 and γ2 being cohesive strength, angle of internal friction and unit weight of the soil in the first and the second layers respectively. The boundaries on either side are considered to be on roller and below subsoil boundaries are considered fixed. The distances beyond the slope are considered to be at h, 2h, 4h, 8h, 16h and the analysis is carried out. Factor of safety against slope failure is plotted in vertical axis for different cases as detailed above. In the present situation it has been observed that boundary effect is minimal when distance is considered to be above 4h. Hence in the present analysis distance is equal to 10m for all situations.

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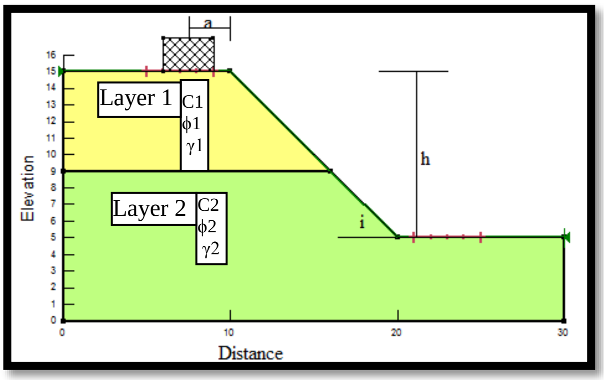

Fig.14. Two layered soil with the its parameters

Slope angle is varied from 10^0 to 60^0 keeping all other parameters constant. In Fig.15 it can be seen that the factor of safety decreases with increase in slope angle. For the given configuration, critical factor of safety is obtained when slope angle is 60^0. The variation is observed to be non linear.

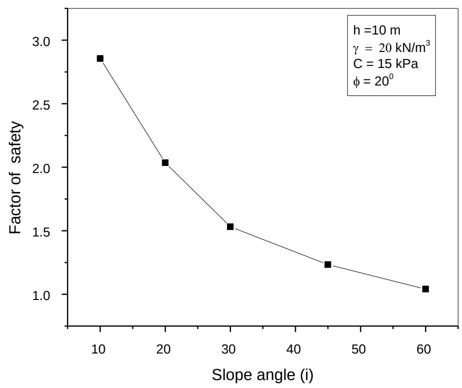

Fig.15: Variation of factor of safety with slope angle in a 2 layered soil

Cohesion ratio is the ratio of cohesive force in one layer of soil to that of another layer. Cohesion ratio is varied from 0.25 to 4 along with varying height of second layer from half of height to two thirds of height of slope keeping all other parameters constant. Fig.16 indicates the effect of cohesion ratio & height of second layer on the factor of safety against stability of slope. In the figure, angle of internal friction is plotted along the horizontal axis for different slope angle and factor of safety along the vertical axis. It can be seen that the factor of safety increases with increase in angle of internal friction and decreases with increase in slope angle of the soil.

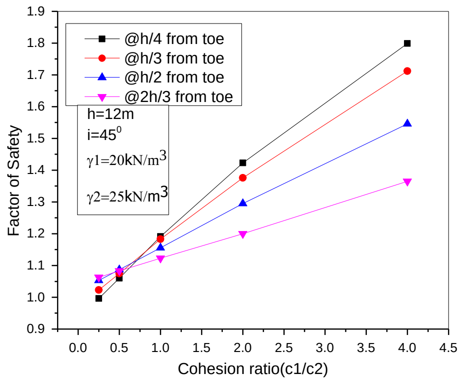

Fig.16: Variation of factor of safety with cohesion ratio & height of soil layer from toe of the slope

Magnitude of surcharge is varied from 80 to 240 kN keeping all other parameters constant. Fig.17 indicate the effect of magnitude of surcharge on the factor of safety against stability of slope. It can be seen that the factor of safety decreases with increase in magnitude of surcharge on the soil.

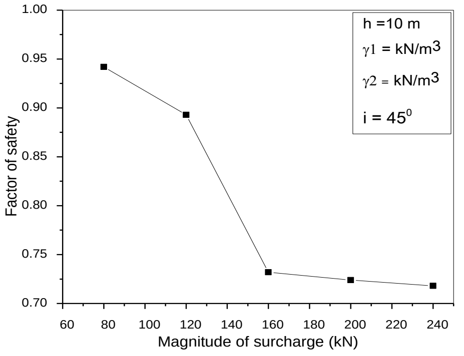

Fig.17: Variation of factor of safety with magnitude of surcharge on a two layered soil slope

position of surcharge is varied from 1.5 m to 7.5 m keeping all other parameters constant. Fig. 18 indicates that the factor of safety increases with increase in position of surcharge.

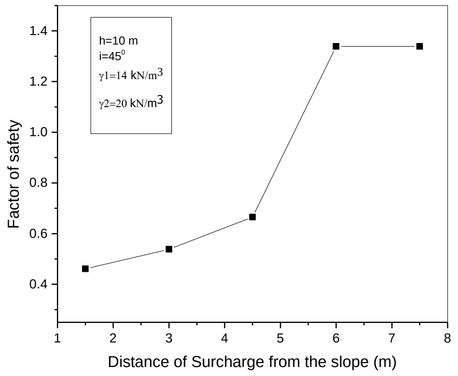

Fig.18: Variation in factor of safety with distance of surcharge from the two layered soil slope

Effect of ratio of unit weight on the overall stability of slope in terms of factor of safety is studied here. For this purpose, ratio of unit weight is varied from 0.3 to 0.5 keeping all other parameters constant. Fig.19 indicate the effect of ratio of unit weight on the factor of safety against stability of slope. In the figure, ratio of unit weight is plotted along the horizontal axis and factor of safety along the vertical axis. It can be seen that the factor of safety increases with increase in ratio of unit weight. The variation is observed to be almost linear.

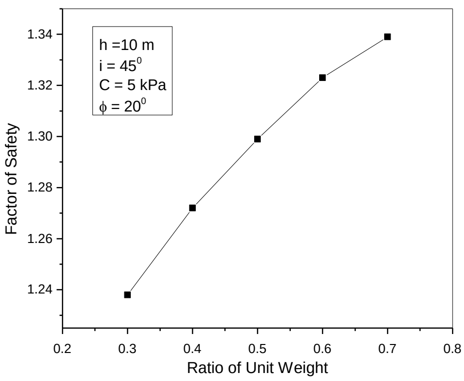

Fig.19: Variation in factor of safety with the ratio of unit weight of the material of the two layered soil slope

Fig.20 indicate the effect of cohesion ratio on the factor of safety against stability of slope. In the figure, cohesion ratio is plotted along the horizontal axis and factor of safety along the vertical axis. It can be seen that the factor of safety increases with increase in cohesion ratio. The variation is observed to be non linear.

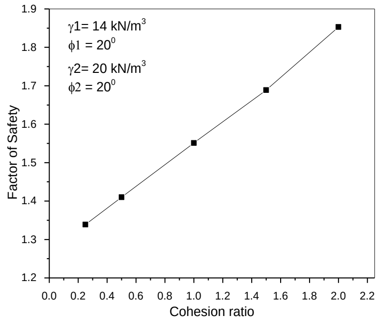

Fig.20: Variation in factor of safety with cohesion ratio of the slope

It is observed that the strength ratio of the two layers and the position of the second layer influence the performance of the slope. Parametric study for various factors like cohesion ratio, friction ratio and unit weight suggest that the slope is more stable when the bottom layer is stiffer than the top layer.

III. RESULTS AND DISCUSSIONS

The following are the major findings from the present work:

- ❖ Geo studio is an essential software in the slope stability analysis and acts as an integrated tool to study the effect of various soil parameters on the stability of slopes.
- ❖ For a single layered soil slope, the various parameters affect the factor of safety as follows:

• The increase in height of the soil slope, unit weight of the soil, slope angle and magnitude of surcharge reduces the factor of safety of the soil slope.

• The increase in cohesion, angle of internal friction and position of surcharge from the edge of the slope increase the factor of safety.

- ❖ For a two layered soil slope, the various parameters and their influence on factor of safety are as follows:
- The increase in height of the soil slope, unit weight of the soil, slope angle and magnitude of surcharge reduces the factor of safety of the soil slope.
- The increase in cohesion, angle of internal friction and position of surcharge from the edge of the slope increase the factor of safety.

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