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Effect of Shear Modulus on Slope Stability Analysis

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Abstract. Slopes fail due to various factors, which can damage structures and cause threat to life. Slope failures such as in landslides are sudden, discontinuous and complex in nature. There is much necessity to overcome such disasters by adopting appropriate prediction methods for slope failures. The objective of the present study is to analyze the slope failure mechanism using a mathematical approach, which simulate the field conditions. Mathematical formulation has been developed for checking the stability of slope, based on soil properties such as shear modulus of soil and geometrical properties of the slope at failure. The shear modulus of soil is effected by rainfall induced in the natural slopes which results in variation of stiffness property of soil on the failure plane. The present approach shows the threshold values of critical factor of safety leading to failure which may be greater than 1, where conventional methods application are lacking. The parametric study has been carried out for determining the effect of shear modulus and stiffness on critical factor of safety of the slope and also for different properties of the soil along the failure plane of the slope. Critical factor of safety decreases with increase in shear modulus of the soil.

Keywords: shear modulus, slope stability, landslide, failure plane.

1 Introduction

In recent studies many analysis were carried out to understand the behaviour of soil at different strain levels. The initial shear modulus, G_o is a very important parameter not only for seismic ground response analysis but also for a variety of geotechnical applications. The modulus of a soil is one of the most difficult soil parameters to estimate because it depends on so many factors. In slope analysis, the material property along with structural property plays vital role in its stability. Thus one has to understand the behavior of material property at verge of failure along the slopes. Shear modulus and stiffness are the soil properties at failure are to be considered in the slope stability analysis. Slope failures such as Landslides have resulted in economic loss and casualties in many regions globally due to its complex instability mechanism. The complexity associated with the slope failure mechanism, especially in the evolutionary process of landslides is still not fully understood (Runqiu et al., 2015). There are more than 300 landslides occurred due to earthquakes and intense rainfall in North Eastern states of India, (Malleswari et al., 2013). The instability mechanism of slope depends on many factors and also the sliding soil mass characteristics are often very different on the failure plane. Numerous equilibrium methods were used in slope stability analysis which can give valid results in many of the slope failure cases. But, these methods cannot explain the slopes of very low angles as in the case of landslides. The effect of local precipitation and human activity on intensity of landslides can be better studied using a numerical analysis such as cusp catastrophe theory (Yun Tao et al., 2013). An accurate slope stability analysis and its failure mechanism need to consider the evolving strains and path dependency by means of a constitutive model (Laouafa et al., 2002). Stress-strain relations of a soil under all loading conditions can be well represented by a constitutive model. For computing shear deformations of any type of constitutive soil behavior, mathematical solutions can be more emphasized for better results (Hans Peter Jostad et al., 2012). Various factors such as shear modulus, stiffness, wedge soil mass etc. combined together will ultimately lead to a catastrophic landslide or slope failure with no warning symptoms (Sarma et al., 2017)

In landslides, the slope failure mechanism is initiated when the soil properties along the shearing plane keep on changing due to various external factors. In the present study, a physical model is proposed and analyzed using mathematical theory, which deals better with geomorphic changes, such as landslides. The constitutive behavior of soil is characterized along the planar shear plane and comprised of two different soil properties with different strength parameters. The stiffness of the soil on shear plane depends on shear modulus, length of the soil medium and displacement ratio. The factor of safety of the slope is determined and differentiates the landslide slow moving landslide threshold values. By varying different variables, the parametric analysis is done to determine the factor of safety.

2 Methodology

A physical model of planar failure slope is considered, which is an non-homogeneous intercalation composed of two media with different strengths, where one media is elastic medium and the other is elasto-plastic medium. Assuming that the sliding slope surface is inclined at β with horizontal and the soil mass above a sliding surface is a rigid mass (Fig. 1).

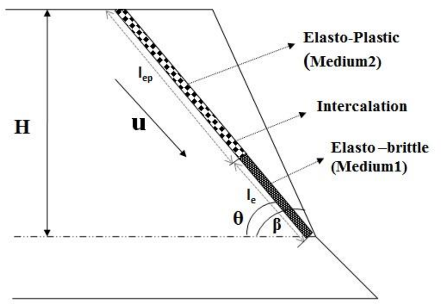

Fig.1. Mechanical model of a landslide with planar sliding slope (Bala et al.,2016)

According to Qin et al., (2001), the critical factor of safety for a constitutive curve of two different soil media (i.e., elastic-brittle and strain softening) is based on stiffness ratio of the material lying on the failure plane. Similarly the present study is carried out with elasto-plastic soils instead of strain softening materials and using the mathematical approach namely cusp catastrophe theory with same governing principles. Thus, the critical factor of safety proposed with these conditions (Bala et al., 2016) is given by,

$$FS_c = [(1-\sqrt{(2\ (1-k)^{(1/2)}/2)})(e^{\sqrt{(2(1-k))}}+k)]/(\alpha*[1+k+\sqrt{2/3}\ (1-k)^{(3/2)}\ ]\ ) \quad (1)$$

$$k=[(Ge*le*\ e^{(u/u_o)})]/(G_{ep}*l_{ep}\ ) \quad (2)$$

Where, k is the stiffness ratio of the material along the failure plane, it is defined as the ratio of stiffness of the elasto-brittle to the stiffness of the elasto-plastic soil. Stiffness ratio, k depends upon the mechanical properties and geotechnical properties of the soil. u is the displacement along the failure plane, u_o is the displacement of average shear stress α is the displacement factor based on the displacement of the soil mass on the failure slope. G_e is the shear modulus of the elasto-brittle soil medium. G_{ep} is the initial shear modulus of the elasto-plastic soil medium. l_e and l_{ep} are the lengths of the soil medium 1 & 2 respectively.

3 Results and Discussions

The variation of critical factor of safety of a planar failure slope for different parameters such as lengths of soil media ratio (l_e/l_{ep}), displacement ratio (u/u_o), and shear modulus ratio (G_e /G_{ep}) is studied.

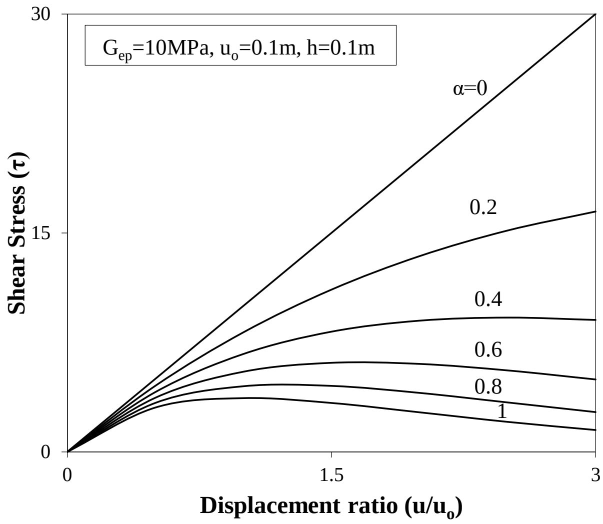

Fig. 2. Variation of shear stress (τ) with displacement ratio (u/u_o)

In Fig. 2, the variation of shear stress (τ) with the displacement (u/u_o) is plotted for different displacement factors (α) and for G_{ep}=10Mpa, u_o=0.1m, h=0.1m. The shear stress is decreasing with increase in displacement ratio (u/u_o). Shear stress is linearly increasing with increase in displacement ratio (u/u_o) for displacement factor, α=0, which implies that it is similar to elastic-brittle soil (medium 1). Shear stress tend to become non-linear and decreases with increasing displacement ratio (u/u_o) and decreases with increase in displacement factor (α).

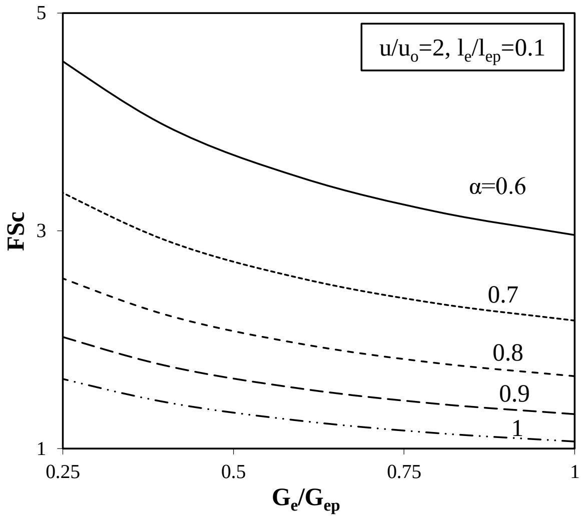

Fig. 3. Variation of critical factor of safety (FS_c) with shear modulus ratio (G_e/G_{ep}) for varying α values

Figure 3 shows the variation of critical factor of safety (FS_c) with shear modulus ratio (G_e/G_{ep}) for different displacement factors (α) and for u/u_o=2, l_e/l_{ep}=0.1. The critical factor of safety (FS_c) is decreasing non-linearly with increase in shear modulus ratio (G_e/G_{ep}) and decreases with increase in displacement factor (α). The decrease in shear modulus ratio may occur mainly due to the seepage of water. Porosity of the soil along the failure plane is one of the parameter on which the shear modulus ratio (G_e/G_{ep}) depends. In the case of rainfall triggering landslides, the increase in rate of infiltration of rainfall result in decrease of shear modulus ratio values. Therefore the decrease in G_e/G_{ep} ratio decreases the FS_c leading to instability of the slope.

In Fig. 4, the variation of critical factor of safety (FS_c) with displacement factor (α) for different displacement ratios (u/u_o) and for G_e/G_{ep}=1, l_e/l_{ep}=0.1 is shown. The critical factor of safety (FS_c) is decreases gradually with increase in the displacement factor (α). With increasing displacement ratio (u/u_o) from 0.5 to 2 the FS_c is showing minimal decrease. At α=0.7 for u/u_o=0.5 the FS_c is 2.68 and for u/u_o=1, the FS_c is 1.6. But for the increase in α from 0.6 to 1.0, it is observed that the FS_c decreased from 1 to 2 approximately. The displacement factor (α) is dependent on the displacement of the soil along the failure plane and the peak strength of the soil. As shear stress increases the displacement of soil mass decreases for constant shear modulus ratio G_e/G_{ep} resulting in decrease in α value. Thus the stability of the slope increases with decrease in α.

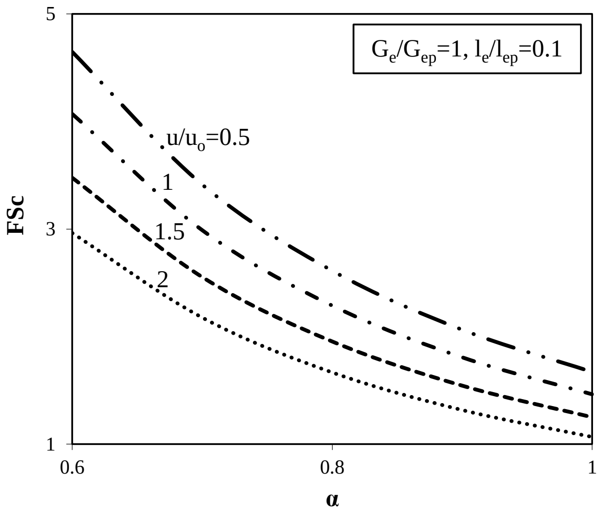

Fig.4. Variation of critical factor of safety (FSc) with displacement factor (α) for varying displacement ratios (u/u_o)

Fig. 5 shows the variation of critical factor of safety (FS_c) with displacement ratio (u/u_o) for varying displacement factor (α) and for G_e/G_{ep}=1, l_e/l_{ep}=0.1. It depicts that the FS_c is decreasing with increase in displacement ratio (u/u_o) and it is also decreasing with increase in displacement factor (α). With increase in u/u_o from 0 to 2, the FS_c decreased from 2.9 to 1.9 for α=0.8. Increase in u/u_o ratio is due to strain softening nature of soil which is commonly seen in over consolidated clays or in dense soils. These soils initially possess greater peak shear strength values at very small incremental strain. Later shear stress decrease with increase in displacement. It is observed that the rate of increase in FS_c is increasing with decrease in α value. As α decreases or equal to 0 the soil along the failure plane behaves like elastic-brittle soil. This makes the slope more stable, thus increasing the critical factor of safety.

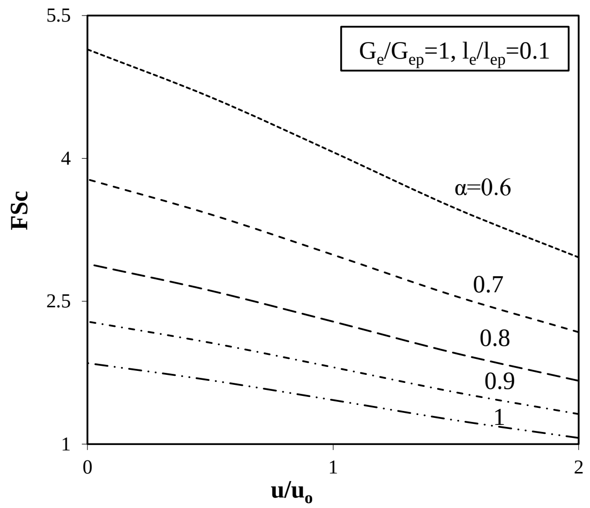

Fig.5. Variation of critical factor of safety (FS_c) with displacement ratio (u/u_o) for vary ing α values

4 Conclusions

1. The mechanical model considered is appropriate for natural slopes with sudden change in material behavior at failure like rainfall induced landslides.
2. The critical factor of safety (FS_c) of the slope decreases with increase in the Shear modulus ratio (G_e/G_{ep}).
3. At shear modulus ratio, G_e/G_{ep}= 0.2, the FS_c = 2.1 which is threshold value leading to failure of the slope. In slope stability analysis, the application of conventional methods are lacking in sudden failures of slopes at FS >1.
4. The increase in displacement ratio (u/u_o) from 0 to 2 decreases the critical factor of safety from 2.8 to 1.68 for α=0.8.

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