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Analysis of Rain Fall Induced Landslides Using Catastrophe Theory

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ABSTRACT

Most of the landslides are catastrophic in nature. Rainfall is a major triggering factor of landslides that claim the lives of many and leads to economic loss in a particular region. It will be more appropriate to consider the soil displacement aspect rather than shear strength alone in the analysis of slope stability. In this paper, for the analysis of landslide evolution process, a nonlinear cusp catastrophe theory is used. The condition similar to cusp catastrophe model is been developed by assuming the planar failure slope model, which is composed of different soils with different strengths. The stability of the slope depends on various parameters such as the displacement of soil wedge, the length of soil along failure plane and stiffness ratio of the soil media. The effect of each parameter on stability of the slope is analyzed and found that using this approach the occurrence of landslides can be predicted most effectively.

INTRODUCTION

Landslide due to rainfall during monsoon season is a very common phenomenon. Different conventional methods are in use to analyze the slope stability but the rainfall triggered landslide failure mechanism is remaining as a open issue. The cusp catastrophe theory (Rene Thom, 1972), is applied for a certain catastrophic landslide, which has features like sudden changes, hysteresis and bimodal behavior. The factors that influence stability of a slope and rainfall induced landslides relationships change over time (Polemio M & Petrucci O, 2000). A nonlinear dynamical model, like cusp catastrophe is suggested for such catastrophic failures, which are discontinuous. According to Qin et al. (2001b), it was observed that the behavior of external environmental factors (rainfall, climate, earthquakes etc.) and soil along the slope are complexly nonlinear. Slope stability due to rainfall should be analyzed as a dynamic problem involving environmental factors instead of a static problem as conventional methods (H.Rahardjo et. al 2002). In rock mass stability analysis, the application of catastrophe theory is vastly carried out (Jiang-Teng et al., 2005, Zhang Jixun et al., 2014). Cusp catastrophe model reflects the real situation of a landslide (Yang et al., 2008) when compared to the conventional models. The depth of sliding surface and the time of shallow landslide can be determined approximately by rainfall infiltration models (A S Muntohar et al. 2010).The effect of local precipitation and human activity on intensity of landslides is studied using this theory (Yun Tao et al., 2013) by providing a new approach to predict landslide. Based on the Qin et al. (2001b) governing equations, which describes the evolution of landslides, are used for different types of soils in the present study.

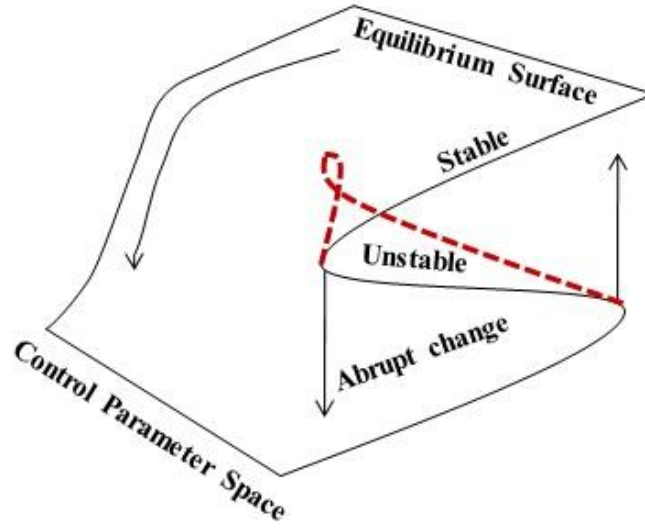


Figure 1. Cusp catastrophe mathematical model

CUSP CATASTROPHE MODEL

According to Qin et al. (2001b, 2006), using cusp catastrophe the condition leading to a landslide can be derived by obtaining overall potential energy for a mechanical model with planar failure plane. Assuming that the planar failure plane is comprised of two different soil media with varying shear strengths such as elasto-brittle and elasto-plastic soils. The overall potential energy can be written as follows

$$P = l_s \int_0^u G_s \frac{u}{h} e^{-\left(\alpha \frac{u}{u_0}\right)} du + \frac{1}{2} \frac{G_e l_e}{h} u^2 - m g u \sin \beta$$

where G_{ep} is the initial shear modulus; G_e is the shear modulus; u is displacement; u_0 is the displacement value at peak stress (Fig. 3); α is the displacement factor; l_{ep} and l_e are lengths of the sliding surface for the elasto-plastic medium and elasto-brittle medium respectively; h is the thickness of the intercalation, β is the failure slope angle and $m g$ is the weight of the rock mass.

$$x^3 + ax + b = 0$$

The above equation is the standard cusp catastrophe model of the equilibrium surface, with a and b as its control parameters and x is state variable.

$$x = \frac{(u-u_1)}{u_1}, a = \frac{3(k-1)}{2}, b = \frac{3(1+k-k\xi)}{2}, \xi = \frac{m g h \sin \beta}{G_e l_e u_1}$$

Stiffness ratio is defined as the ratio of stiffness of elastic medium to the stiffness of strain softening medium.

$$\text{Stiffness ratio, } k = \frac{G_e l_e}{G_{ep} l_{ep} e^{-\left(\alpha \frac{u}{u_0}\right)}}$$

Control parameters a and b can be related to human activity and rain precipitation respectively. The catastrophe occurs only when $a \leq 0$ and $b < 0$ i.e., for stiffness ratio ($k \leq 1$). Which implies that if $a > 0$ then the slope is in a very stable state and catastrophic failure doesn't take place. Stiffness ratio is based on geometry and material property of the system. The condition leading to the catastrophic failure is dependent on the internal characteristics of the slope system. Stiffness ratio, which is also based on the displacement aspect along the failure-sliding plane, describes the stability of the slope.

RESULTS AND DISCUSSIONS

The effect of various parameters such as lengths ratio (l_e/l_{ep}) and displacement factor (α) on k is analyzed. Hence, parametric study has been carried out to know the effect of various parameters on stability of the slope.

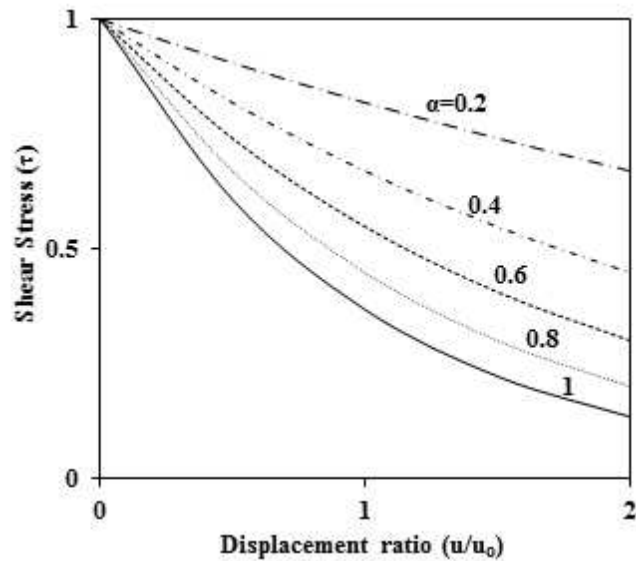


Figure 2. Shear stress (τ) versus Displacement ratio (u/u_0)

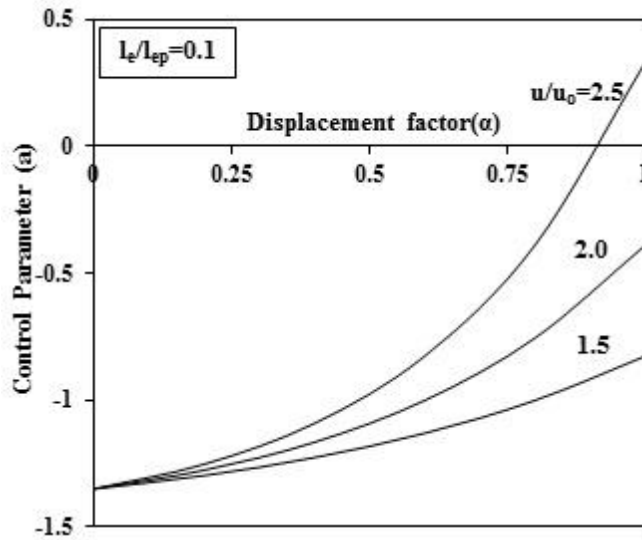


Figure 3. Variation of control parameter (a) with different α values

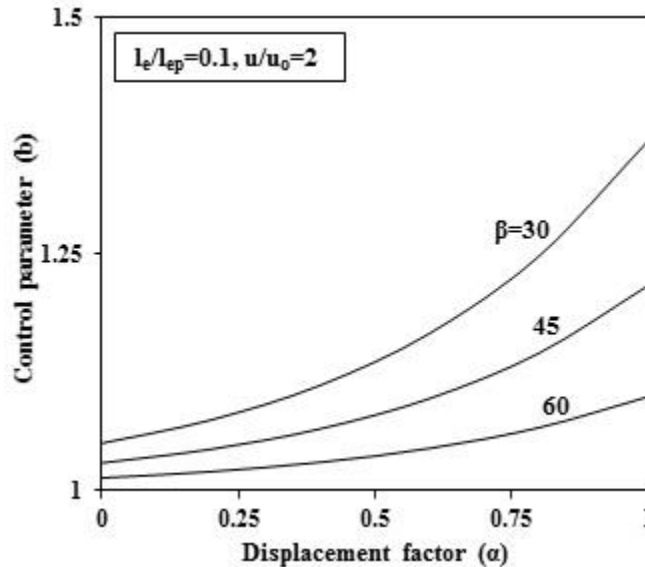


Figure 4. Variation of control parameter (b) with different α values

Fig. 2 shows the variation of shear stress with displacement ratio (u/u_0) with varying displacement factor (α). It is understood that the shear stress decreases nonlinearly with increase in displacement ratio. The shear stress also decreases with increasing α . The displacement factor (α) varies based on the porosity and the moisture content of the soils along the failure-sliding plane. In Fig.3, variation of control parameter (a) with displacement factor (α) for varying displacement ratio (u/u_0) is as shown. Control parameter 'a' increases nonlinearly as the displacement factor (α) increase. The increase in 'a' with increase in u/u_0 indicates that the slope is more prone to sliding or failure. The displacement ratio (u/u_0) depends upon the type of soil and nature of its density. If the soil is in loose state, the u/u_0 will be relatively more when compared to dense state.

Fig. 4, shows the variation of the control parameter 'b' with displacement factor (α) for varying failure slope angle (β). Control parameter 'b' is increasing with the increase in

displacement factor and decreases with in failure slope angle (β). The rainfall-induced landslides are mainly due to the rate of precipitation, which effects the failure slope angle and stiffness ratio. The increase in β value decreases the control parameter 'b' and thus decreases the stability of the slope.

In Fig. 5, shows the variation of stiffness ratio with displacement factor for varying lengths ratio. Stiffness ratio (k) decreases with increase in displacement factor and increase with lengths ratio (l_e/l_{ep}) resulting in stable slopes. The lengths ratio may vary due to the intensity of rainfall, degree of saturation and permeability of soil along the failure-sliding plane.

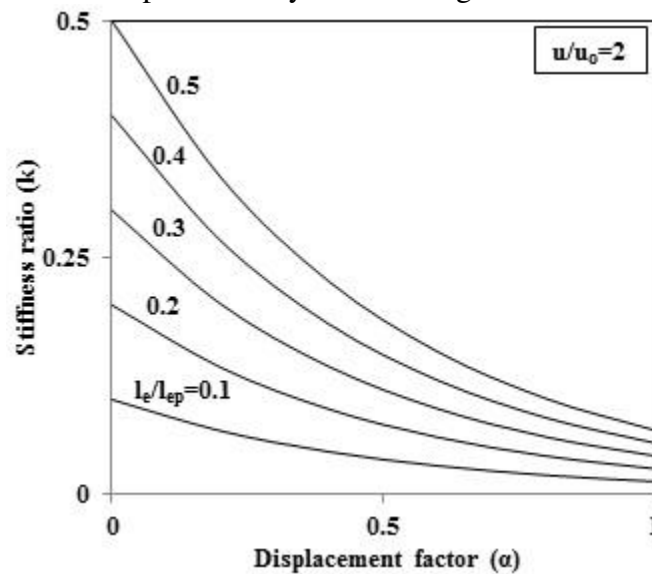


Figure 5. Stiffness ratio with respect to displacement factor for varying lengths ratio

CONCLUSION

- It is observed that, the displacement criterion is more relevant to field conditions to determine the instability mechanism of the planar sliding slope.
- The shear stress varies linearly with u/u_0 upto, $\alpha=0.2$ and with increase in α it increases nonlinearly.
- The increase in control parameter 'a' increases the displacement ratio, u/u_0 from 1.5 to 2.5 which results in unstable slopes.
- The control parameter 'b' effects the displacement factor (α) nonlinearly with decreasing failure slope angle (β).
- The stiffness ratio increases with increase in l_e/l_{ep} ratio (0.1 to 0.5) and displacement factor (α - 0.1 to 1)). As stiffness ratio is increasing, the stability of slope structure also increases gradually.

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