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INFLUENCE OF SURFACE CRACKS ON THE STABILITY OF CRACKED SOIL SLOPE

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Abstract. The slope stability is a major concern to geotechnical engineers. Traditional methods of slope stability analysis have potentially ignored the influence of surface cracks. It is also known that seasonal rainfall and seepage through crack are closely related with slope failure. First, surface cracks provide special flow channels which increase the soil permeability and decrease the soil strength. Second, water-filled cracks apply an additional active force on the slope. Finally, cracks can create a part of the critical failure surface that has no shear strength. The objective of this paper is to investigate the influence of existing cracks on the stability of a cracked soil slope in different state. The effects of crack depth, slope angle and water-filled cracks on the stability of the cracked slope are explored. The analysis was conducted using the computer modelling programs Optum G2 to analysis of slope factor of safety. The results show that with increasing of slope angle the factor of safety decreases and this problem is significant in the slope with water filled cracks. Also, Factor of safety for all of slope angles in Dry and water filled cracks states with increasing the crack depth, decrease significantly.

Keywords: surface cracks, in Dry and water filled cracks, Optum G2, slope factor of safety

ВЛИЯНИЕ ПОВЕРХНОСТНЫХ ТРЕЩИН НА УСТОЙЧИВОСТЬ ГРУНТОВОГО СКЛОНА

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Аннотация. Устойчивость склонов является серьезной проблемой для инженеров-геотехников. Традиционные методы анализа устойчивости склонов, как правило, игнорируют влияние поверхностных трещин. Также известно, что сезонные осадки и просачивание их через трещины может приводить к обрушению склона. Во-первых, поверхностные трещины создают специальные каналы для потоков воды, увеличивают проницаемость грунта и снижают его прочность. Во-вторых, трещины, заполненные водой, оказывают на склон дополнительное активное давление. Наконец, трещины могут создать часть критической поверхности разрушения, которая не способна сопротивляться сдвигу. Целью данной работы являлось исследование влияния существующих трещин на устойчивость грунтового откоса в различном состоянии. Исследовано влияние глубины трещины, угла наклона и наличия трещин, заполненных водой, на устойчивость склона. Анализ проводился с использованием программы компьютерного моделирования Optum G2 для оценки коэффициента запаса устойчивости. Результаты показывают, что с увеличением угла откоса коэффициент запаса устойчивости снижается, и эта проблема актуальна для склонов с трещинами, заполненными водой. Также коэффициент запаса устойчивости для всех углов откоса для сухих и водонасыщенных трещин с увеличением глубины трещины значительно снижается.

Ключевые слова: поверхностные трещины, сухие и заполненные водой трещины, Optum G2, коэффициент запаса устойчивости склона

INTRODUCTION

The fact of landslides and instability of slopes is a major concern in many parts of the world. The failure mechanism of slopes and geological history of a slopes can be very complicated and important for a slope stability analysis. Seasonal rainfall is an essential cause for many slope failures and catastrophic landslides. The primary reason for landslide was loss of matric suction of soil due to rainwater infiltration. It is familiar that rain water infiltration into subsurface soil slopes or through soil cracks will start to saturate the soil layers and eventually reduce the matric suction of soil. The notable reduction of matric suction causes the reduction of soil shear parameters. Factors such as soil texture, intensity and rainfall duration and degree of saturation, soil moisture content, surface cover and slope angle also influence rainfall infiltration [1-2].

The classical and primary way to analyze of slope stability is accessed using two methods; either continuum mechanics, or the limit equilibrium approach. Generally cracks are formed at the tension zones and a series of micro cracks is formed at the upper surface and will cause obvious cracks at tension zones at dry periods after a prolonged wet and dry cycle. The cracks usually supply easy pathways for rainfall infiltration into soil mass and subsurface layers [3]. The water head due to the soil cracks causes the additional force for rain water infiltration. The water content in deeper layers is higher in cracked slopes than uncracked slopes due to rain infiltration. Generally higher matric suction will obtain at dry seasons at unsaturated soil zones and it improves the shear strength of the soil [4]. A new approach is used by Stephen and Colin to specify the direct prediction of the tension cracks on a river bank. This tension cracks are assumed to be formed by two essential group of forces. The first group is formed by shrinkage on soil and is caused by desiccation fact. The second is related with gravitational force where the weight of the soil separates a great block on a soil slope. The tension cracks are founded at upper layer failure surface when the tensile strength (σ_s) in the upper soil layer be more than the tensile stress (σ_τ) of the soil [5]. Cai et al. investigated the vertical cut slope stability with using a number of soil parameters such as the geometry of crack at upper slope surface, curves relating the parameter of strain energy density factor and the non-dimensional variable from slope geometry $N = H / C$ ratio of slope height to distance of crack from edge of slopes. In this research, the curves were developed through numerous parametric studies. They concluded that the failure surface is not circular on a simple straight line. However, failure surfaces are regularly in good and suitable agreement with the results of classical slope stability analysis [6].

Fan et al. studied the effects of rainfall infiltration on fractured slopes. The authors showed that rainwater infiltrates into existing fractures in slopes, and that pore water pressure in soil rises correspondingly [7]. Wang et al. illustrated that cracks in soil slopes decrease stability of slope through three effects: (1) water filled cracks exert an additional and active driving force on the slopes (2) Cracks supply particular flow channels which increase permeability of soil and decrease soil strength and (3) cracks can form part of the critical and serious slip surface that has no special shear strength [8].

GUI and Han showed two Malaysian landslides that occurred after heavy rainfall in 1999. They investigated that the stability of this slopes was significantly affected by the rainfall. They concluded rainfall infiltration into existing fractures reduced the matric suction and shear strength of the slope. This was further worsened when rainfall infiltration increased the mobilized shear stress and self-weight of the slopes [9]. Post analyses of landslides phenomenon in the past by Nurly et al. at Air Laya, Indonesia concluded that existing tension cracks caused slope failure. Rainfall infiltration caused in formation of weak planes which activate to failure of slope [10].

More recently, Zeng et al [11] and Mukhlisin and Khiyon [12] investigated the effect of the characteristics, such as the angle, depth, location and density of surface cracks, on the pore water pressure and stability of slopes under rainfall infiltration by numerical modeling. They concluded that as the crack depth increases, both the pore water pressure in the crack and the infiltration depth increase at the end of rainfall phenomenon, and the safety factor of the slope remarkably decreases. In terms of crack angle, the former research showed that as the crack angle increases, the infiltration depth decreases. The latter described that when the crack angle is parallel to the sliding surface, the safety factor of the slope is clearly decreased, which is consistent with the result of Zhang et al. [13]. Also, Zeng et al. reported that when the crack density increases, the isolated saturated zones with positive pore water pressures attach with each other in the slope gradually. Mukhlisin and Khiyon concluded that the crack distance is to the top of the slope is closer, the safety factor of the slope is lower.

From the above studies, one can note that the distribution characteristics of surface cracks in depth have main and essential influences on the seepage operation and stability of slopes. However, little attention was paid on the influence of cracks on stability of slopes. For this reason, this paper aims to investigate the distribution characteristics, including the crack depth, effect of dry or water filled cracks and slope angle (β) on stability of slopes by numerical calculations. The program "Optum G2" is employed in the analysis of the slope stability in different state.

THEORY AND METHOD

A commercial finite element limit analysis (FELA) software, OptumG2 [14], was employed to analyze of cracks effect on the stability of slope in different state. This rigorous numerical technique has been successfully employed to solve various problems in geotechnical engineering as demonstrated by Ukritchon and Keawsawasvong, Nielsen [15-16].

Darcy's law can be used in the flow of water through both unsaturated and saturated soils. The difference is that the soil permeability (hydraulic conductivity) is no longer a constant value under conditions of unsaturated flow. The hydraulic conductivity varies with changes in water content of soil. According to conservation of flux the partial differential water flow equation in two dimensions can be defined [17].

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial H}{\partial y}\right) + Q = \frac{\partial \theta}{\partial t} \qquad (1)$$

Where, "H" is the total head, k_x and k_y are the hydraulic conductivity in "x" and "y" direction, "Q" is the applied boundary flux, θ is the volumetric water content and "t" is time.

This equation expresses that the difference between the flow entering and leaving an elemental volume of soil at a point in special time is equal to the change in the storage of the soil. More basically, it reveals that the sum of the rates of change of flow in the x and y direction plus the external flux is equal to the rate of change of the water content with respect to time [18].

The safety factor is mostly used to assess whether a slope is stable or not. Many methods are developed to assess the factor of safety. Most of this methods are based on limit equilibrium methods. A potential sliding mass is first divided into many vertical slices in the limit equilibrium state. Then the force and moment of each of this slices are calculated individually. Finally the safety factor of the slope is analyzed by adding up the results of all of the slices. The differences between different methods are the static equations used and inter-slice forces included.

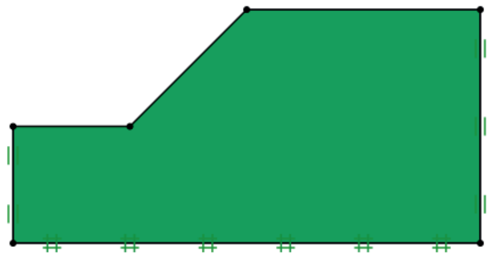
Spencer's method accepts a constant relationship for the inter slice shear to normal force ratio. The critical failure surface of with the lowest safety factor needs to be determined. Finding the critical failure surface involves a trial procedure. There are many ways to describe the positions and shape of trial failure surfaces. Between these methods an auto search method can give circular or combined slip surfaces. A crack can form a part of the combined failure surface using this method [19]. While Limit Analysis method deals with the problem of determining the ultimate magnitude of reference loads, Strength Reduction analysis (phi-c reduction method) deals the complementary problem of determining the strength necessary to prevent collapse and failure given a set of actual loads. The Strength Reduction analysis in Optum G2 software goes on by computing a strength reduction factor by which the material parameters need to be reduced in order to reach a condition of incipient collapse. A safety factor greater than 1 thus expresses a stable system while a safety factor less than 1 implies that additional strength is required to prevent collapse and failure.

NUMERICAL SIMULATION

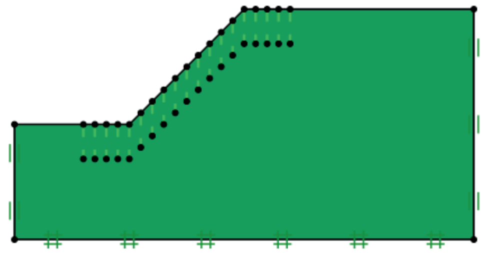
The two-dimensional numerical model of clayey soil slope in different state (without crack, Dry crack and water-filled crack) is investigated. In order to examine the influence of the spatial distribution characteristics of cracks on safety factor of slopes, a numerical parametric study is conducted to better understand the performance of this slopes. The slope had a height of 10m, wet density of soil is 20kN/m^3, initial cohesion is 60kN/m^2 and other investigated parameters are listed in Table 1. Figure 1 presents the model geometry for a slope of without crack, Dry crack and water-filled crack, respectively. In this study, the crack thickness is assumed to be 10cm based on the results of field surveys and shear strength of the cracks is assumed to be zero.

Table 1. Scheme of numerical calculations used in numerical modeling

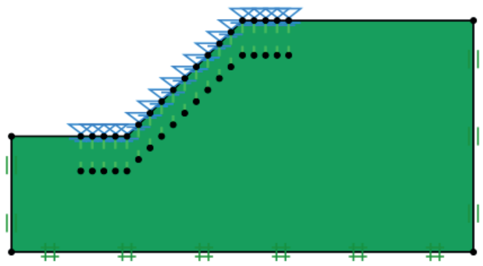
Parameter	Value	Parameter state
Height of slope (m)	10	constant
Wet density ($\mathbf{kN/m^3}$)	20	constant
cohesion	60	constant
crack depth, D_{crack} (m)	0, 1, 2, 3, 4	variable
Slope angle, β (degree)	30, 45, 60, 75	variable
Crack condition in slope	Without crack, Dry crack, water filled crack	variable



(a) Without crack



(b) Dry crack



(c) Water filled crack

Figure 1. Geometry model of slope in different state of analyses

NUMERICAL RESULTS AND DISCUSSION

To investigate the effect of crack depth on the safety factor of slope with different slope angle, Dry and water filled cracks with 1, 2, 3 and 4m depths located at Longitudinal direction of the slope of the slope is considered. Figures 2 to 5 show the variation of factor of safety with crack depth for the case with slope angle of 30, 45, 60 and 75 degree, respectively. It clearly observe that factor of safety for all of slope angles in Dry and water filled cracks states with increasing the crack depth, decrease significantly. The reason of decreasing of safety factor is that the deep crack does form a part of slip surface. In Figures 6 and 7 are showed the displacement contours for 2m crack depth, 45 degree slope angle in Dry and water filled cracks states respectively.

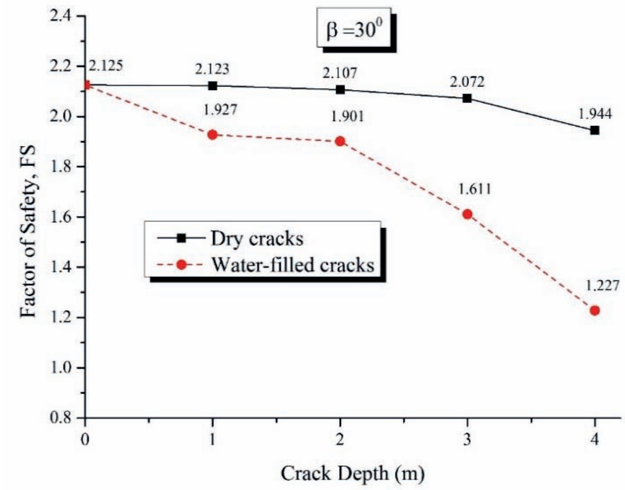


Figure 2. Variation of factor of safety with crack depth for β=30

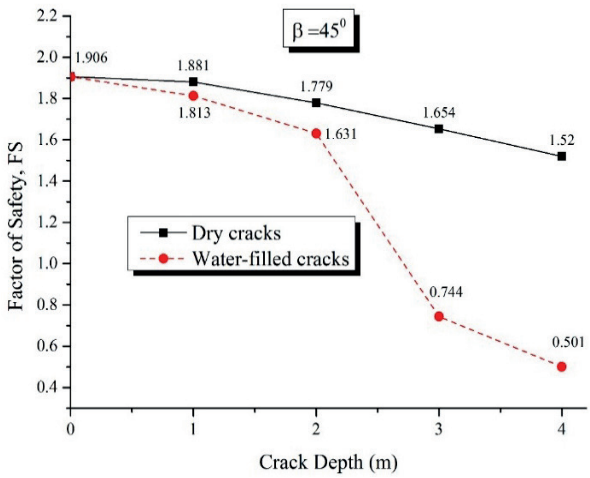


Figure 3. Variation of factor of safety with crack depth for β=45

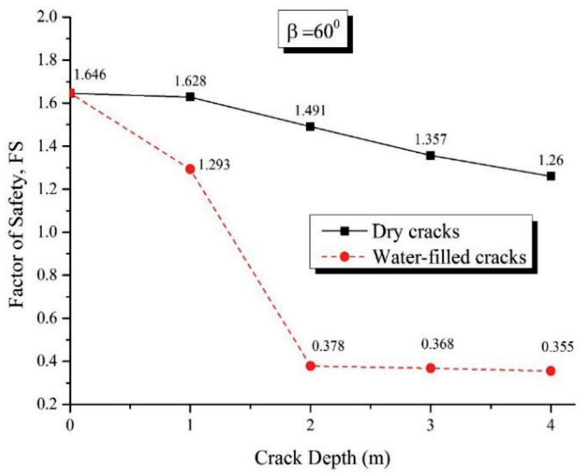


Figure 4. Variation of factor of safety with crack depth for β=60

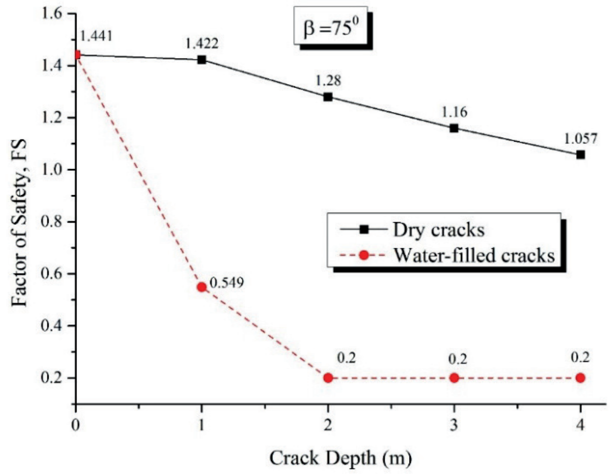


Figure 5. Variation of factor of safety with crack depth for β=75

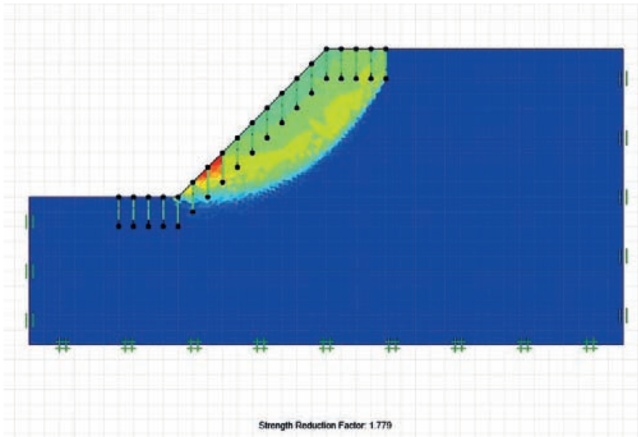


Figure 6. Displacement contour for dry crack state (D_{crack}=2m, β= 45˚)

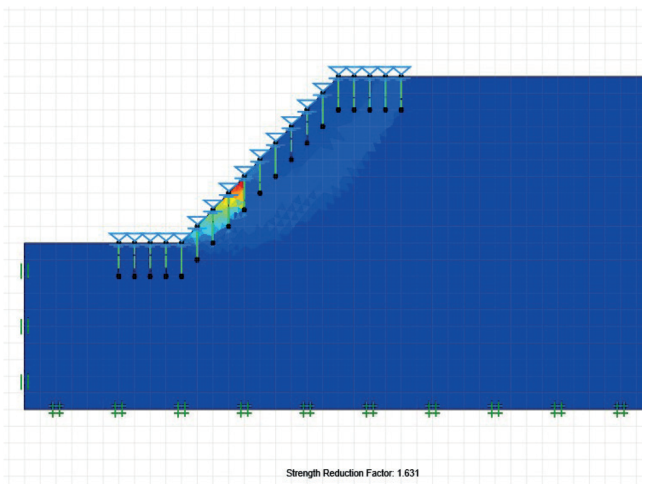


Figure 7. Displacement contour for water filled crack state (D_{crack}=2m, β= 45˚)

To study the effect of slope angle on the slope stability in different crack depth, three conditions are considered: 1) slope without crack, 2) slope with dry cracks, 3) slope with water filled cracks. Figures 8 to 12 show the variation of factor of safety with slope angle for the case with without any crack, crack with depth of 1, 2, 3 and 4 m, respectively. The results of finite element limit analysis using Optum G2 program demonstrated that with increasing of slope angle the factor of safety decreases and this problem is significant in the slope with water filled cracks. As the shear strength of the crack is zero, it is reasonable that the safety factor decreases when the slip surface passes through the crack especially in water filled cracks state. The decrease of slope stability in water filled cracks state is mainly because of the increase in water content, which leads to a decreased shear strength of the slope soil.

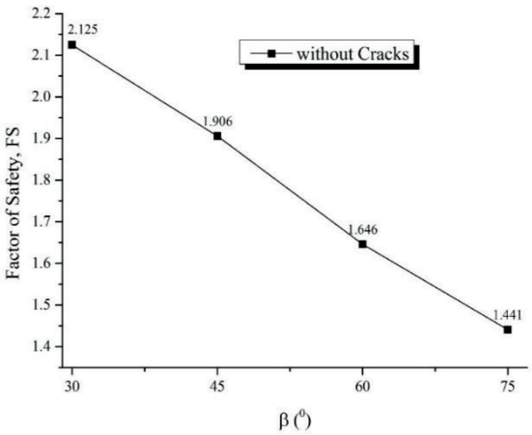


Figure 8. Variation of factor of safety with slope angle in without crack slope

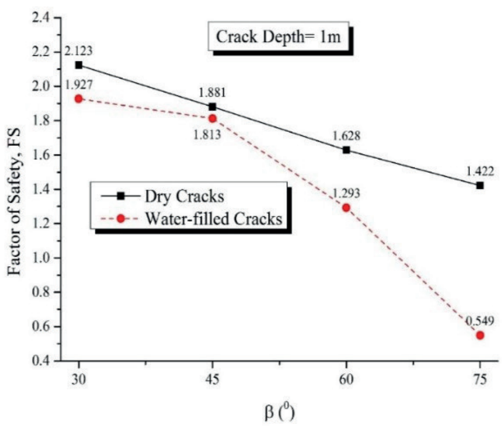


Figure 9. Variation of factor of safety with slope angle in D_{crack}=1m

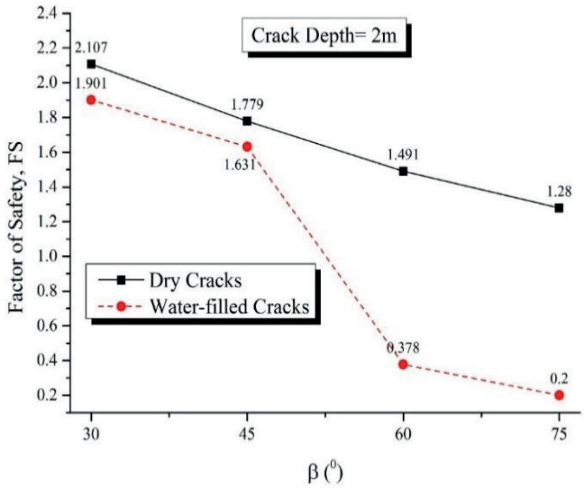


Figure 10. Variation of factor of safety with slope angle in D_{crack}=2m

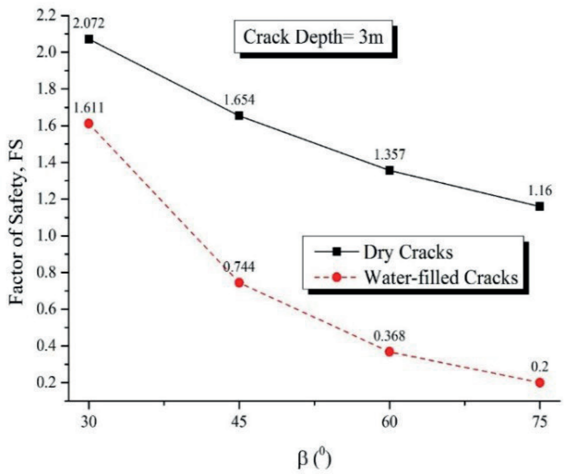


Figure 11. Variation of factor of safety with slope angle in D_{crack}=3m

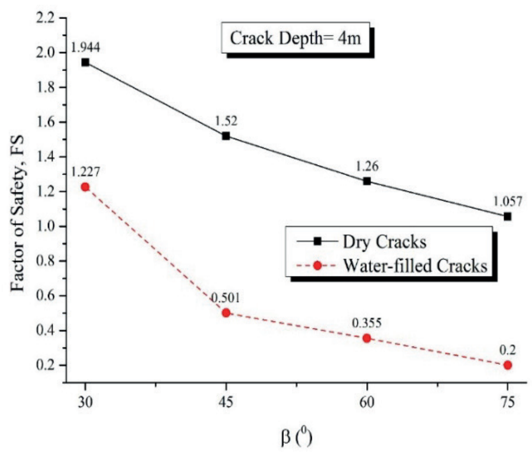


Figure 12. Variation of factor of safety with slope angle in D_{crack}=4m

CONCLUSION

In this study, numerical modeling results of Influence of cracks on the stability of a cracked soil slope were presented using a commercial finite element limit analysis (FELA) software. The effect of crack depth, slope angle on the factor of safety in two state for cracks (dry crack and water filled crack) were examined. Based on the numerical analysis using FELA software conducted in this study, the following results were obtained:

- Factor of safety for all of slope angles in Dry and water filled cracks states with increasing the crack depth, decrease significantly
- The reason of decreasing of safety factor is that the deep crack does form a part of slip surface.
- With increasing of slope angle the factor of safety decreases and this problem is significant in the slope with water filled cracks.
- As the shear strength of the crack is zero, it is reasonable that the safety factor decreases when the slip surface passes through the crack especially in water filled cracks state.

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