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Rainfall induced slope failure detection using infiltration type slope stability method applying non-linear failure envelope

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Abstract. Rainfall induced shallow slope failures in hilly terrain in the tropics is a complex soil mechanical behavior when it is difficult to be back analysed using the conventional slope stability method. The basis of the problem is in the applications of the linear soil shear strength failure envelope with cohesion intercept that over-estimate shear strength on the low stress levels i.e. for effective stresses less than 100 kPa or for failure depth less than 5 m. At this low stress levels the genuine shear strength behaviour is in fact non-linear with zero cohesion. Besides, the failure is not related to the groundwater table (GWT) when it is located at greater depth and has no influence on the failure. Theoretically the shallow slip failure surface is very difficult to be replicated with factor of safety (FOS) less than unity and that pose difficulties in understanding the failure. A slope stability method that deployed mechanics of unsaturated soils and calculate stability base on the advancement of the wetting front has been applied to characterize the shallow slips. The stability method uses the soil true non-linear soil shear strength behavior with respect to effective stress and suction. The method has been validated against a shallow slips triggered by rainwater infiltration that occurred along a road side in Cameron Highland, Malaysia.

1. Introduction

Pre-detection of potential landslide is very important to avoid the risk of lives and properties. However this is the problem faced by the geotechnical engineers. It is the rainfall induced slope failure that is difficult to be quantified theoretically. The developments of the slope stability methods started since the nineteen seventies when geotechnical researchers in Hong Kong find difficulties to back analyse the shallow land slips using the conventional slope stability methods. When the plane envelope soil shear strength model of Fredlund *et al.* [10] was introduce then engineers began to understand the role of rain in triggering landslide. When the soil is in the state of unsaturation there exists suction that pulls the soil particles together and produce extra shear strength known as apparent shear strength. The infiltration of rain water into the slope resulted in the reduction of suction in the ground which in turn reduces the apparent shear strength and may end up with failure. Therefore the application of unsaturated soil mechanics is inevitable in order to understand rainfall induced slope failures.

Then Rahardjo and Fredlund [30] introduced a slope stability method that incorporates the contribution of suction on the stability. This is the first time the role of rainfall infiltration has been incorporated in the slope stability mechanics to quantify slope instability. This is the real understanding on how rainfall actually influences stability of slopes. It is the advancement of the wetted band into the slope that triggers the slope failure in the hillsides and not the rise of the GWT as commonly understood. Nevertheless, the mechanics apply the plane envelope soil shear strength model of Fredlund *et al.* [10] which over-estimate the shear strength for shallow slips as shown in Figure 1. Then the developments of this soil mechanics continued with the introduction of the curved surface envelope soil shear strength model of Md Noor and Anderson [21]) and its application in the state-of-the art infiltration type slope stability method introduced by Md Noor [20] and Md Noor *et al*, [22]. This method considers the advancement of the wetting front into the slope forming a band of wetted zone underlying the slope surface parallel to the contour of the slope face. As infiltration continues, this band becomes thicker and the wetted front progress deeper into the slope. This wetted band is considered to have zero suction. The slope would fail when the critical thickness of this wetted band is reached. By this method, slope instability influence by rainfall infiltration can be accurately detected. The reliability of this method will be validated in Section 4.0.

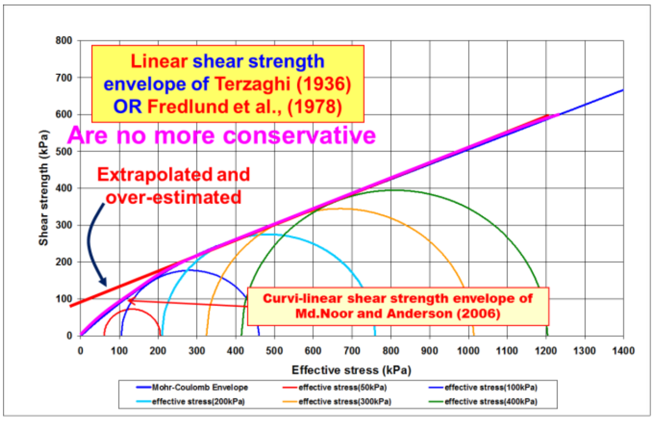

Figure 1. Over-estimation of shear strength at low stress levels when using linear soil shear strength model with cohesion intercept.

2. Problems in the conventional slope stability methods to quantify rainfall induced slope failure

The incidence of slope failure in the tropics has already puzzled geotechnical engineers. This is because they faced problem to quantify the failures theoretically. This dilemma need to be resolved and the right mechanics of failure need to be developed and validated. There was a study conducted by Othman [24] to check the stability of 118 slopes along Karak Highway, Malaysia and his finding showed that 90% of the slope has FOS less than unity but the slopes are still standing. This is giving a strong indication that there is something wrong with the current slope stability methods and there is a direct requirement for those methods to be revamped. In the contrary, engineers have difficulties to achieve FOS less than unity for failed slopes. Slopes that have failed would produce FOS less than unity when being back analysed. In addition, back analysis should also replicate the actual failure surface whether it is shallow or deep seated slip. Especially the shallow slip surface is very difficult to be modeled.

Brand [4] quoted his experience dealing with slopes in Hong Kong that in highland area the groundwater is too far down to have influence on the failure at the top. This means that the shallow rainfall induced shallow failure is not associated with the rise of the GWT and instead it is very much related to the infiltration of the surface water [14]. Despite that, the technique of modelling rainfall induced slope failure by elevating the groundwater table (GWT) has become a common practice among geotechnical engineers despite not replicating the actual occurrence in the field. This practice is still insisted because that is the only available method to quantify. When the GWT rises then the effect of buoyancy will reduce the effective stress between the soil grains and thereby reduce the shearing resistance or the shear strength of the soil. This shearing resistance is actually resisting the sliding failure and if it is being reduced then the resisting variable become less and when it has become

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smaller and being overcome by the disturbing variable derived from the weight of the soil or slope external loading then failure will be triggered. This dilemma was earlier quoted by Lumb [14] as follows;

"*The association of failures with heavy rain is clear, but this qualitative association must be quantified on a physical basis, if at all possible, before reliable design methods can be established. Some advances can be made in this direction if infiltration is postulated as the dominating factor*."

In the nineteen seventies there is still no engineering mechanics for stability of slopes that relates to rainfall except the practice of elevating the GWT. Therefore the effect of rainfall on slope failure is still not understood. Then Brand [3] has quoted a controversial statement in the 11th International Conference on Soil Mechanics and Foundation Engineering, San Francisco regarding predicting the performance of residual soil slopes in Hong Kong as follows;

"*It is concluded that our soil mechanics predictive tools are far from adequate for analysing residual soil slopes, largely because of the difficulties of predicting pore pressures and of modeling geological detail which often controls the mode of slope failure*."

In Hong Kong, residual soil slopes are located in elevated hilly terrain where the GWT is far below the ground surface and the failure is inevitably due to surface water infiltration. In other words, Brand [3] is nullifying the applicability of all the slope stability equations that were developed before 1985 for predicting rainfall induced slope failures. This includes the slope stability equation of Fellenius [8,9], Simplified Bishop Method [2], Morgenstern and Price [23], Spencer's method [27,28] and Sharma method [25]. These are the common methods used in the slope stability software and the effect of rainfall is modeled by elevating the GWT. These methods would produce various values of FOS and the validity of those FOS is questionable. All those slope stability equations applied soil shear strength equation of Terzaghi [2] and this equation is a linear type of equation with cohesion intercept and it does not replicate the true soil shear strength behaviour. Then the FOS produced by those slope stability equations will be dubious. Therefore it is very important to use the legitimate non-linear soil shear strength equation that can replicate the true non-linear shear strength behavior. There are many non-linear soil shear strength equations that have been published like De Mellow [7], Hoek and Brown [12], Maksimovic [16], Md Noor and Anderson [21] and Lade [1]. This is already giving the indication that many have realized that the true soil shear strength behavior with respect to. effective stress is in fact non-linear. Its application in analyzing slope stability is inevitable especially for shallow rainfall induced failure. Then, it is very important to choose the one that can make excellent replication of the shear strength envelope as obtained from laboratory tests.

The over-estimation of the FOS when the shear strength equation of Terzaghi [29] with cohesion intercept is applied in slope stability analysis is further emphasized by Lade [13] with his quotation as follows;

"*It is not safe to employ the classical infinite slope failure analysis procedure in which the Coulomb failure criterion is used, because a very large portion of the factor of safety is assigned to the effective cohesion which is not present in the soil*."

Besides, Md Noor and Hadi [17] also quoted that;

"The practice of extrapolating linear shear strength envelope at low stress levels to intercept the τ axis is dangerous since it can produce a misleading high slope stability factor."

Therefore it is very important to deploy the right non-linear soil shear strength equation with zero cohesion intercept in slope stability analysis for shallow rainfall induced slope failure in order to avoid getting a misleading over-estimated FOS. The paradox of zero cohesion intercept for all soil under drained condition has been thoroughly discussed by Md Noor [19]. This is a fundamental concept which is not realized by many. Even if Weald clay [11], London clay and Avonmouth clay [1] have zero cohesion intercept then why would other soils which has only a portion of clay would need to be assigned a small value of cohesion intercept.

The current slope stability software available in the market applied either the linear model of Terzaghi [29] or the incline plane type of Fredlund *et al.* [10] soil shear strength model with cohesion intercept. The true soil shear strength behavior is in fact non-linear with zero cohesion intercept for drained type of analysis or also known as effective stress analysis unless the soil is cemented like cement in rock mass. This true aspect of shear strength behavior makes a lot of difference at low stress levels and is very important for analysis of shallow landslide. Applying the linear or the plane type of soil shear strength model would over-estimate the shear strength at the lower stress range as shown in Figure 2 and its application in analysis would produce a higher FOS [26,13,19]. Therefore the application of the linear soil shear strength model with cohesion intercept is no more conservative as initially thought by geotechnical engineers. In other words, slope is thought to be safe with a fake high FOS and this is why Lade [13] referred this as being "not safe". When this method is applied in slope failure investigation the geotechnical engineer would has the difficulties to achieve the theoretical failure condition with FOS less than unity. Thus the failure is hard to explain. Therefore, it is very important to apply the true non-linear soil shear strength behavior where the shear strength is neither over-estimated nor under-estimated and the resulted FOS in the analysis would be a realistic value [19].

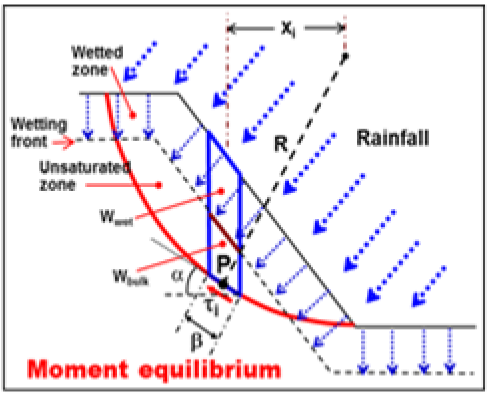

Figure 2. Typical slice considered in the infiltration type slope stability method.

3. The state-of–the art infiltration type slope stability method

Slope failure due to rainfall is triggered by the advancement of the wetting front into the slope which is termed as infiltration [5,6]. The infiltration type slope stability method replicates exactly the mechanics of slope failure due to rainfall. This is in contrary to the conventional method which assumes the failure due to rainfall is triggered by the rise of the GWT as resulted from the continuous rainfall.

Most importantly, this state-of-the art method make use of the latest advancement of soil shear strength model which is the shear strength model of Md Noor and Anderson [21] which replicates very well the non-linear shear strength behavior with respect to effective stress and suction for tropical residual soil as shown in Figure 3. Essentially the soil shear strength behaviour is non-linear with respect to effective stress and suction whereas the earlier model assume linear in both respect. The uniqueness of these equations is that they matched the non-linear soil shear strength behavior base on the geometrical dimensions that representing the shear strength parameters. Unlike the rest of the proposed non-linear equations that make use of the fitting parameters in the exponential type of equations. Even though the equations of Md Noor and Anderson [21] look slightly complex but most importantly it is able to make excellent agreement with the laboratory data for both shear strength variation with respect to net stress/ effective stress and suction. This makes it superior than the existing equations. The algorithm for the slope stability FOS calculation in the infiltration type slope stability method using the strength variation with respect to net stress/ effective stress and suction as shown in figure 4.

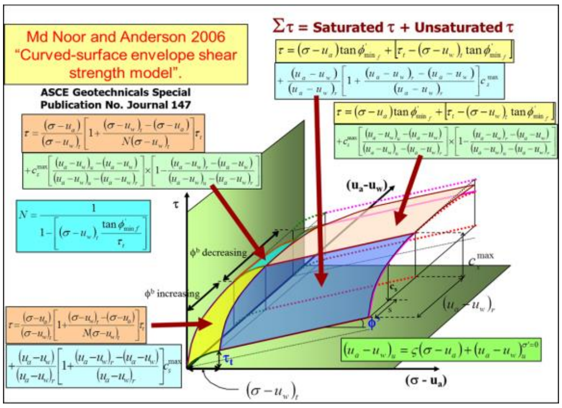

Figure 3. Curved surface envelope of Md Noor and Anderson [21] able to replicate the true soil shear strength behaviour and being applied in the state-of-the art slope stability software.

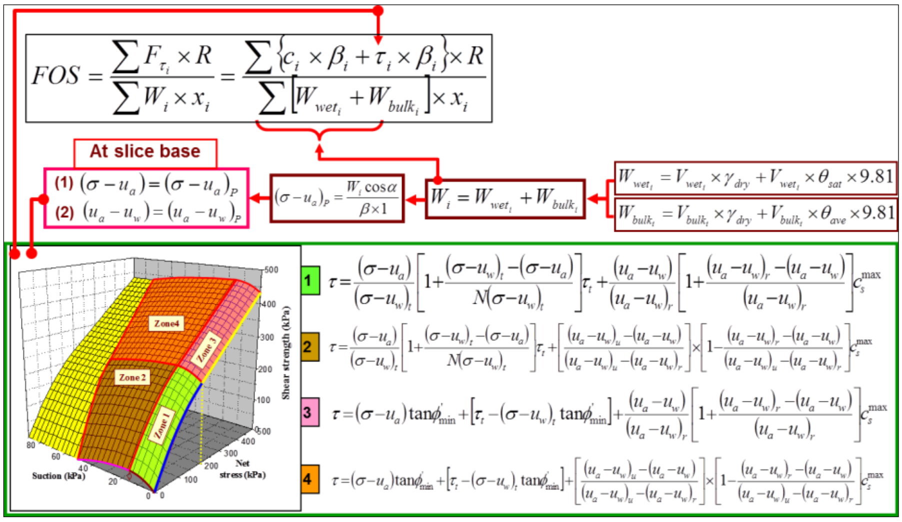

Figure 4. The algorithm for the slope stability FOS calculation in the infiltration type slope stability method.

4. Validation of the infiltration type slope stability method against shallow rainfall induced failure in Malaysia soil

Any new introduction of slope stability method needs to be validated against a failure case. It should be able to replicate the actual failure surface whether it is shallow or deep type of failure with FOS less than unity. This is the basic requirement in order to verify its applicability. If this cannot be proved then the method is not valid to be applied. It is to be noted that geotechnical engineers faced difficulties to back calculate rainfall induced slope failures with FOS less than unity.

A road side up slope, land slip has occurred in Cameron Highland. The incidence happened during a rainy season. The failure is a shallow slip of 2 m deep as shown in a survey cross sectional drawing in Figure 5. There is no groundwater table (GWT) encountered in the boreholes. Therefore the failure is not associated with the elevation of GWT. CIU triaxial tests have been conducted on three undisturbed soil specimens to determine shear strength failure envelope of in-situ soil. A test at low stress level has been specifically conducted at effective stress less than 50 kPa in order to substantiate that the non-linear failure envelope converges to zero cohesion intercept. The Mohr circles obtained are plotted in Figure 6 and the interpreted linear and non-linear failure envelopes are also shown. Figure 7 shows the Mohr circles and the envelopes as defined in the software SLOPE-RAIN applied to

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conduct stability analysis. The inset shows the Mohr circles data as obtained from the CIU triaxial tests. The result of the analysis is shown in Figure 8. Essentially the software produced a FOS of 0.99 at 2 m depth of infiltration with wetted suction in the wetted band of 5 kPa. This means that the failure was triggered even before the wetted band is fully saturated. The failure slip circle is confined within the wetted band and this is in accordance to the findings by Md. Noor and Hadi [18] and Md.Noor *et al.* [15]. This proves exactly how the failure has occurred at the site.

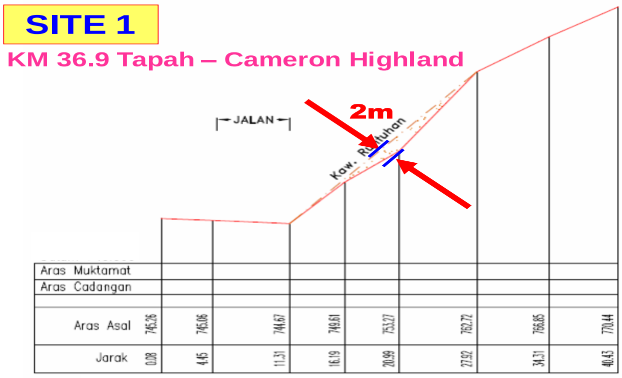

Figure 5. Shallow slope failure at Tapah, Cameron Highland: Site 1.

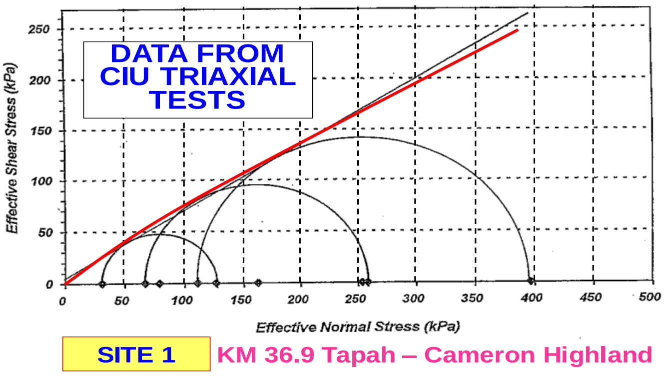

Figure 6 .Mohr circles as obtained from conducting CIU triaxial tests on undisturbed soil samples and the deduced linear and non-linear failure envelopes.

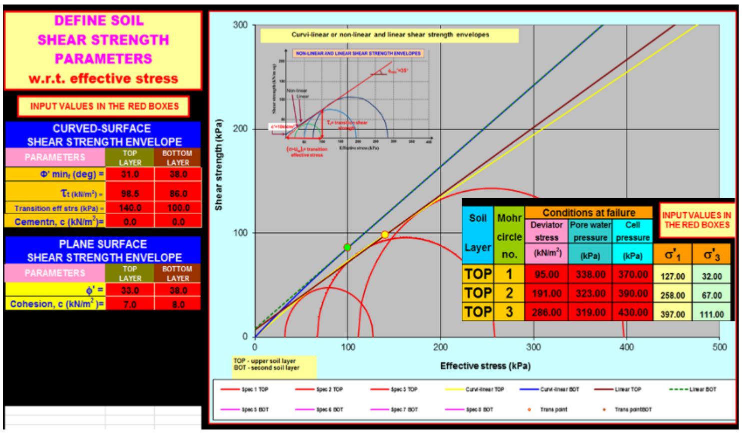

Figure 7. Definition of the shear strength envelopes according to linear and non-linear failure envelopes in the software.

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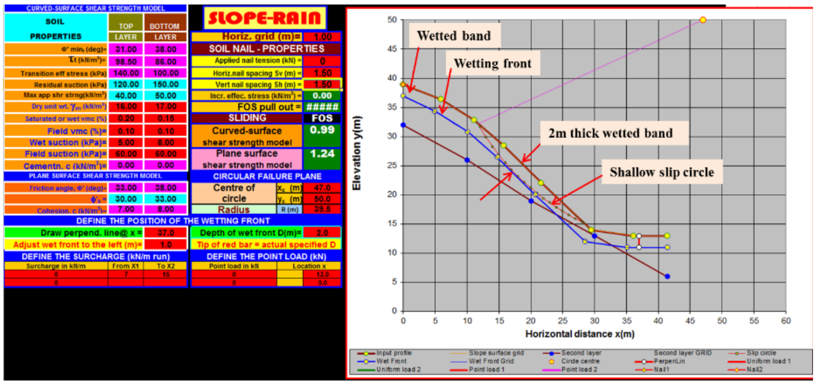

Figure 8. Essentially the infiltration type slope stability method produced a FOS of 0.99 at 2 m depth of infiltration to prove exactly as failure has occurred.

5. Conclusions

The conclusions that can be drawn from this technical paper are that the infiltration type slope stability method:-

1. Can back calculate failure by replicating the actual slip plane with FOS less than unity and thus it is very reliable to be applied in slope failure investigation triggered by infiltration of surface water.
2. Can be applied be applied to check the genuine state of stability of a slope in effect of rainfall.
3. Can be applied to reliably check for potential slope instability due to rainfall.
4. Can be used by the government departments, geotechnical consultants and the state Municipal Council to check the real state of stability of their slopes and with this potential mishap can be pre-determined and the potential risk can be identified earlier and precautions can be taken to avoid loss of lives and damaging buildings.
5. Can be effectively applied in slope risk mapping projects to produce a reliable risk map against rainfall induced failures.

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