THE INFLUENCE OF SURFACE RUN-OFF TO 3D SLOPE STABILITY ANALYSIS FOR RAINFALL INDUCED LANDSLIDE

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ABSTRACT: Expansion of urban and recreational developments in hilly areas has resulted in increasing number of residential, commercial properties and infrastructure that is threatened by landslides. A three dimensional (3D) slope stability analysis has emerged recently due to its capability of capturing complex terrain shape in more realistic manners, rather than two-dimensional (2D) approach. The Hovland method is one of the 3D slope stability analysis widely used due to its simple algorithm and practical engineering application. Previous studies have proposed modifying Hovland's method and integrating it with Geographic Information System (GIS) software to make it practical to be used in a real environment. However, scarce attention has been paid to improve 3D slope stability analysis and to take into account the influence of rainfall induced landslide. This is due to the dynamic behaviour and complex parameters involved. For regions with tropical climate like Malaysia, the study of rainfall induced landslide is crucial due to the many landslide incidents triggered by heavy rainfall. This paper seeks to address this problem by adding the rainfall factor as input to Hovland 3D slope stability analysis in the form of pore water pressure. Rainfall volume can be transformed into infiltration and surface runoff, such as the Infiltrated Excess Overland Flow (IEOF) and Saturated Excess Overland Flow (SEOF). This study only focuses on SEOF as a dynamic variable by using the Topographic Wetness Index (TWI) and Green-Ampt as input for SEOF equation and SEOF later used in pore water pressure computational replacing static water table level. The result of this research is an improved Hovland 3D slope stability analysis method by integrating SEOF factor in the calculation.
Keywords: rainfall, landslide, slope stability

INTRODUCTION

In recent years, there have been rapid growth of world's population living in urban areas. According to World Urbanization Prospect 2014 by the United Nations (2014), 3.9 billion people of the world population resides in urban areas in 2014 and the percentage is increasing over the time, especially in developing countries (Eltayeb Elhadary and Samat, 2012) including Asia (Department of Economic and Social Affairs, 2014). Malaysia is one of the developing countries has similarly achieved a high level of urbanisation (Mazlan, 2014). The United Nations estimated that nearly 86 per cent of Malaysians will live in cities by 2050 (United Nations, 2014). However, the major problem that comes with rapid growth is serious consequences to human lives and environmental degradation. The high development density in the urban area has created pressure to expand development to the hillside or hilly area to satisfy demands of urban inhabitants such as residential, commercial properties and infrastructure (Anderson et al., 2014; Di Martire et al., 2012). The major implications arising from the exploration on the hillside is weakening slope, and the high intensity and extreme of rainfall events can cause excessive environmental problems, such as landslides (Di Martire et al., 2012; Saadatkhah et al., 2014).

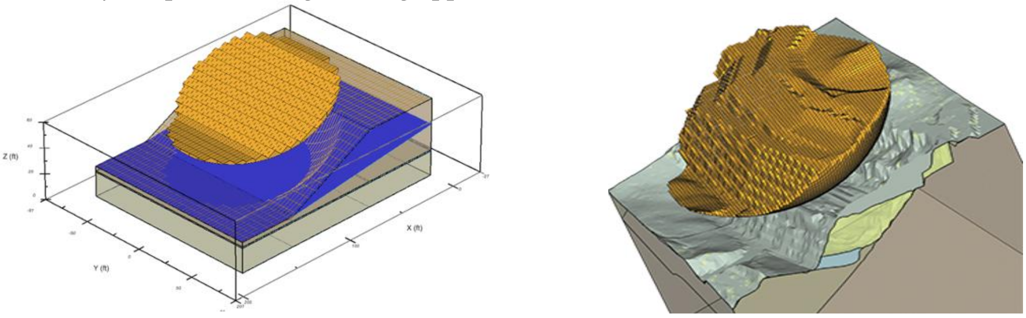
Landslides were ranked third among natural hazards that threaten human lives all over the world (EM - DAT, 2011) and in Malaysia. This hazard is the second most destructive disaster after flood and it directly affects the environment and infrastructure, and causes economic losses and a large number of casualties. Malaysia has a hot and humid tropical climate with high humidity and copious rainfall, particularly during the two monsoon seasons, first monsoon between November to January and second monsoon between April to May and dry season between June to September (Matori et al., 2012). Based on the Public Work Department of Malaysia data (2009), between 1973 and 2007, 440 landslide events occurred and caused a total of 31 fatalities in Malaysia. The total economic loss was about RM 3 billion. Heavy rainfall plays a key role as the hydrological triggering mechanism on manmade slopes in most of the landslide incidents (Othman et al., 2012). Recent developments in the field of the landslide have led to a renewed interest in enhancing slope stability analysis. Several studies have improved the practicality of slope stability analysis by taking advantage of the modern Geographical Information System (GIS) software, as implemented by Mergili et al. (2014), Shen et al. (2012), Thiebes et al. (2013), and Zheng and Yang (2011). However, the implementation of slope stability analysis currently fall short in the dynamic aspects where dynamic factors such as surface run-off are not considered in the safety factor computation (Luo et al., 2015). The aim of this study is to propose a spatio-temporal approach to analyse the influence of surface run-off to the slope stability and the integration of the surface run-off model and 3D slope stability (Hovland method) within the GIS environment.

METHODOLOGY

2D Slope Stability vs 3D Slope Stability

During heavy rainfall events, water infiltration into the soil will increase the pore water pressure, thus diminishing the ratio of porosity and permeability. The shear strength of the slope reduces when the pore water pressure reaches a critical point, causing slope instabilities and lead to landslides (Hamdhan and Schweiger, 2011). This mechanism plays a key role in slope stability. Initially, slope stability was performed using two-dimensional (2D) approach. Although the actual topography is three-dimensional (3D), the slope stability analysis usually have to be performed using 2D structural model due to its simplicity (Spencer, 1967). This method assumes the slopes to be symmetric and infinitely long in the third dimension. This oversimplification of methods resulted in inaccurate results which failed to represent the reality. Various optimisations of the structural model had been developed to overcome this deficiency, but improvements are still to be seen.

Evolution towards 3D slope stability has emerged in recent literature due to its capacity to handle complex terrain shape in a more realistic manner, as compared to 2D slope stability approach as shown in Figure 1. Past researches indicate that 3D analysis of slope stability generally provide more accurate result than 2D analysis (Hicks et al., 2014). Hovland (1977) appears to be the first to analyse a 3D slope stability using the column method which is the most popular method. Lam and Fredlund (1993) and Ahmed et al. (2012) state that the reasons for its popularity is due to its ability and high feasibility for practical engineering applications.



(a) 2D Slope Stability Visualisation (b) 3D Slope Stability Visualisation

Figure 1: Visualisation between 2D and 3D Slope Stability
Source: SoilVision.com, 2015

Hovland 3D Slope Stability

Hovland is a 3D slope stability method based on an extension of Fellenius 2D slope stability. Instead of using slices as in the 2D slope stability, Hovland uses columns. The normal and shear force components in Hovland are derived from column weight and simplify external and internal forces of the standard column model by ignoring all inter-column forces on the sides of the columns as well as pore-water pressure (Kalatehjari and Ali, 2013) as shown in Figure 2.

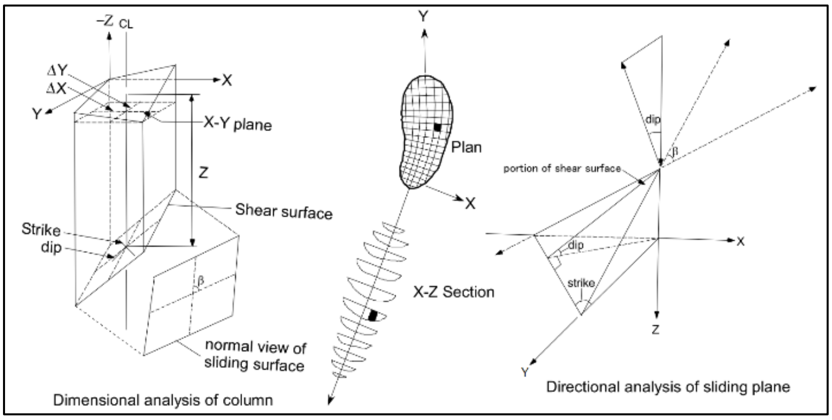


Figure 2: Hovland Column Model
Source: Tiwari and Douglas (2012)

Hovland method can be expressed by equation (1) (Tiwari and Douglas, 2012)

$$SF = \frac{\sum_X \sum_Y \left(\frac{c.\Delta X.\Delta Y.Sin\theta}{Cos\alpha_{xz}.Cos\alpha_{yz}}\right) + \sum_X \sum_Y (\gamma.Z.\Delta X.\Delta Y.Cos(dip).Tan\emptyset)}{\sum_X \sum_Y \gamma.Z.\Delta X.\Delta Y.Sin\alpha_{yz}} \quad (1)$$

where SF is the slope safety factor. Safety factor is the ratio of resisting force and driving force as shown in Figure 3. Resisting force is the force resisting downward movement by soil cohesion and internal friction. Conversely, the driving force is the force moving soil downward, mostly comes from gravitational force. Safety factor above 1 signifies that the slope is safe and safety factor below 1 signifies unstable slope and high probability for landslide to occur.

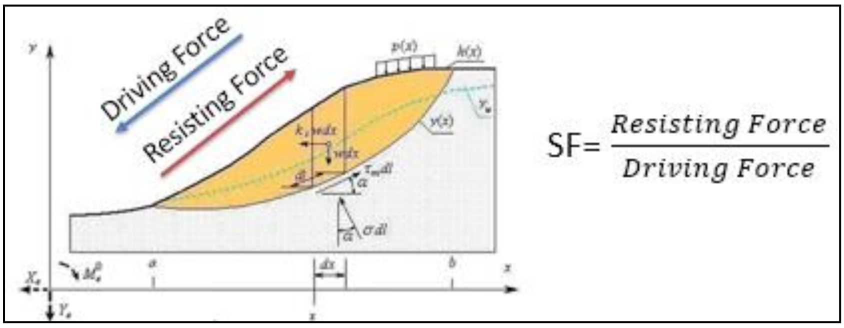


Figure 3: Safety Factor Ratio
Source: Adapted from Montenasoft.com

Pore Pressure Integration into Hovland

Pore pressure (Ps) is another source of driving force due to hydrostatic pressure, which can directly impact the safety factor. Pore pressure can be expressed as equation:

$$Ps = \gamma w.hw \quad (2)$$

where $\boldsymbol{\gamma w}$ is the water weight (9.81 kN/m) and $\boldsymbol{hw}$ is the water height. Figures 4, 5 and 6 show different scenarios for water table, saturated soil and surface water.

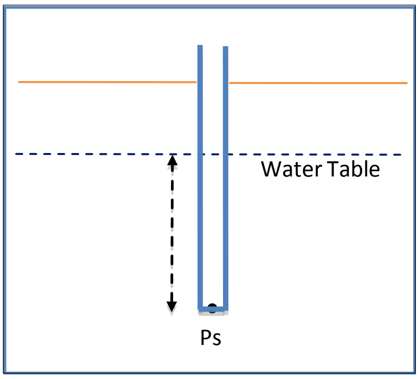


Figure 4: Pore pressure measurement with the water table

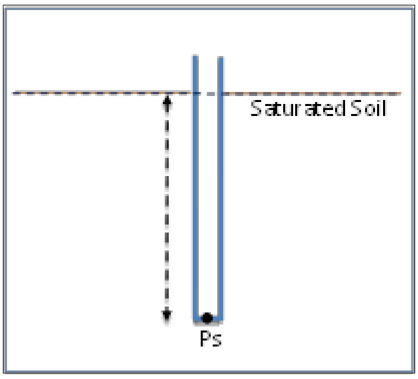


Figure 5: Pore pressure measurement with saturated soil

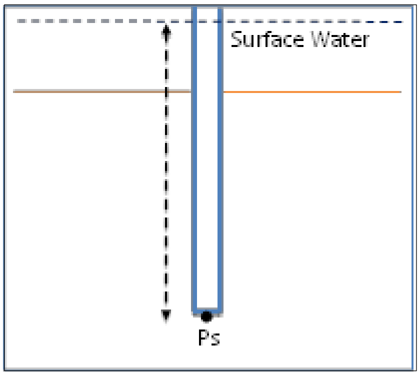


Figure 6: Pore pressure measurement with surface water

Hovland formula can be expanded to cover pore water pressure by adding an equation into the equation (1) , as shown in equation:

$$\boldsymbol{SF} = \frac{\sum_X \sum_Y \left(\frac{c.\Delta X.\Delta Y.Sin\theta}{Cos\alpha_{xz}.Cos\alpha_{yz}}\right) + \sum_X \sum_Y \left(\gamma.Z.\Delta X.\Delta Y.Cos(dip) - \gamma w.w\frac{\Delta X.\Delta Y.Sin\theta}{Cos\alpha_{xz}Cos\alpha_{yz}}\right)Tan\emptyset}{\sum_X \sum_Y \gamma.Z.\Delta X.\Delta Y.Sin\alpha_{yz}} \tag{3}$$

In ArcMap, Slope (β) is equivalent to dip value in Hovland formula (Tiwari and Douglas, 2012), so the equation can be expressed as:

$$SF = \frac{\sum_X \sum_Y \left(\frac{c.\Delta X.\Delta Y.Sin\theta}{Cos\alpha_{xz}.Cos\alpha_{yz}}\right) + \sum_X \sum_Y \left(\gamma.Z.\Delta X.\Delta Y.Cos(\beta) - \gamma w.hw\frac{\Delta X.\Delta Y.Sin\theta}{Cos\alpha_{xz}Cos\alpha_{yz}}\right)Tan\emptyset}{\sum_X \sum_Y \gamma.Z.\Delta X.\Delta Y.Sin\alpha_{yz}} \tag{4}$$

Pore Pressure Effect to Slope Stability and Surface Runoff Integration

Conventional method to add pore pressure into Hovland uses fixed water table level, which is obtained from pore hole survey as visualised in Figure 7. This is the approach taken by Jia et al., (2012) and Tiwari and Douglas (2012). However, this approach is only suitable to predict landslides in dry situation and less accurate to predict a landslide caused by rainfall. This is because in heavy rain, soil will be saturated and water ponding may occur, and this will cause the pore water pressure to change drastically, hence impacting the slope safety factor directly.

Rainfall has two effects on earth. Part of the water will infiltrate deep into the ground and the excess will flow through the surface. Jia et al., (2015) further expanded Hovland's model to improve accuracy in predicting the rainfall induced landslide by using infiltration model to include soil saturation into calculation as visualised in Figure 8. According to Luo et al. (2015), surface run-off is a hydrological process, which can directly affect 3D slope stability when the water is flowing or accumulated on top of the slope as visualise in Figure 9. Jia et al., (2015) approach however, did not take into account the run-off effect to the slope stability in Hovland method.

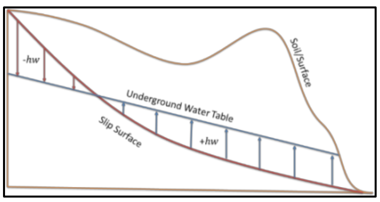


Figure 7: Pore pressure height from the slip surface to the water table

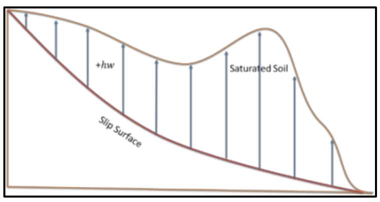


Figure 8: Pore pressure height from the slip surface to the saturated soil

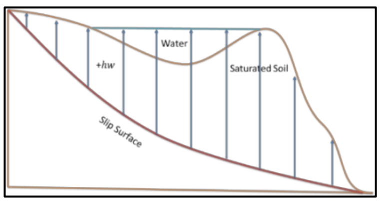


Figure 9: Pore pressure height from the slip surface to the saturated soil and water surface

There are two methods to calculate and predict surface run-off, which are Infiltration Excess Overland Flow (IEOF) and Saturation Excess Overland Flow (SEOF). IEOF occurs when the soil is not fully saturated and the rainfall rate is higher than the soil absorption rate. IEOF usually occurs in arid areas while SEOF occurs when the soil is fully saturated and remaining rainfall become surface run-off. This paper will focus on SEOF because the monsoon climate in Malaysia consists of long and heavy rainfall which result in saturated soil. SEOF's location and volume are determined by six factors which are rainfall, land use, slope angle, soil type, IEOF exclusion area and Topographic Wet Index (TWI) as shown in Figure 10.

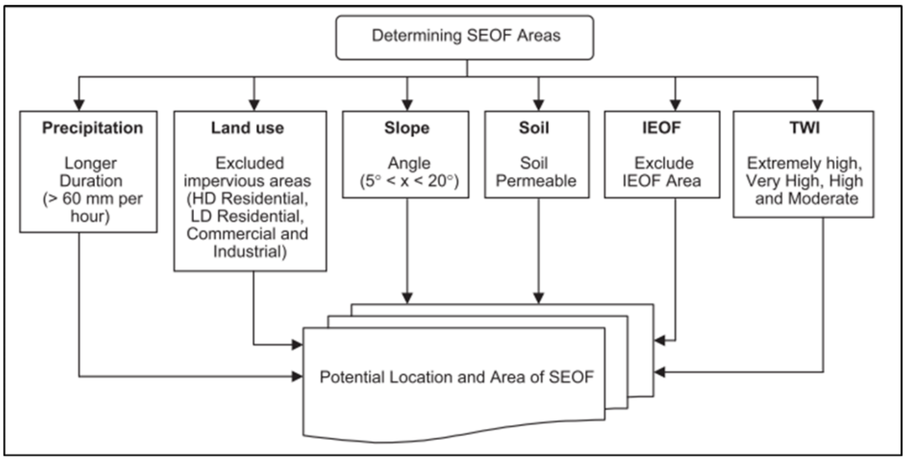


Figure 10: SEOF determination
Source: Izham et al., (2011)

RESULTS

The key to improve Hovland's 3D slope stability analysis in predicting rainfall induced landslide is by expanding pore water pressure computation in Hovland's method by taking into account SEOF factor. This approach has the advantages of simplicity, as no modification is required to the Hovland's formula itself and the adaptation is based solely on water table level input, which now needs to be fed from SEOF instead of using fixed data as shown in Figure 11.

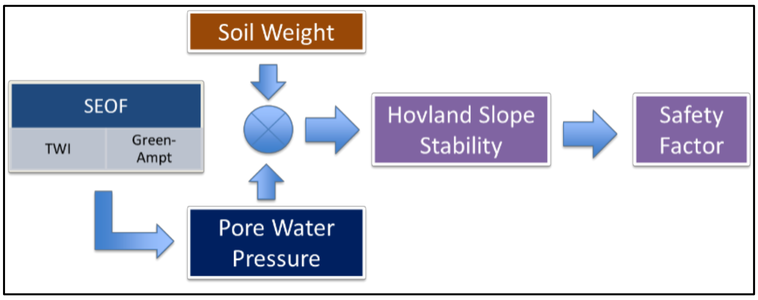


Figure 11: 3D Slope Stability Block Diagram

The first step to integrate SEOF into Hovland slope stability method is to determine the slip surface. Slip surface is defined as a slope cut out, which gives minimum safety factor for the respective slope. For Hovland, the slip surface shape is half ellipsoid. The parameters for slip surface ellipsoid are optimised using the Monte Carlo analysis. The minimum safety factor of this process is considered as a base safety factor. The next step is to integrate SEOF into the flow. SEOF will provide two additional piece of information into the equation, soil saturation and also water ponding. The existence of soil saturation and water ponding will directly impact the safety factor. Soil saturation and water ponding will determine how pore pressure is calculated, either as Figures 7, 8 or 9. If the soil is not yet saturated, the pore pressure is calculated from the water table from bore hole survey data as shown in Figure 7. Once the soil is saturated, but no water ponding is formed on top of slip surface, the pore pressure is calculated from saturated soil as shown in Figure 8. However, if there is water ponding, the pore pressure is calculated as shown in Figure 9. This process is repeated using rainfall data in order to give real time and dynamic safety factor analysis for the study area. The whole process can be summed up in Figure 12.

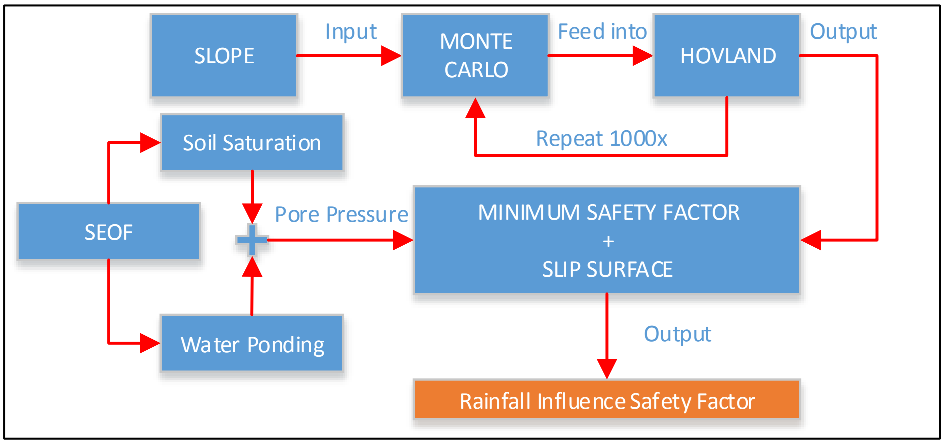


Figure 12: SEOF Integration Flow Chart

SUMMARY

Conventional Hovland slope safety factor analysis approach only takes into account the fixed water table from borehole survey, therefore it could not reflect the actual safety factor in the heavy rainfall situation. Continuous rainfall will cause soil to be saturated and will render the slope safety factor to deteriorate due to increase of the pore pressure. Depending on topography, water ponding may occur near the slope and will compromise the slope safety factor even further. The results of this research address these issues by improving Hovland 3D slope safety factor analysis method by taking SEOF factor into consideration and produce better rainfall induced landslide prediction. The practical application of this solution is clear. Policymakers and all stakeholders can utilise this solution to predict and simulate the worst case scenario in the monsoon season to determine the slope stability. With such insights, they can then take pre-emptive actions to tackle the slope stability problem before landslide occurs.

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