Application of Electrical Resistivity Imaging and Slope Modelling in the Investigation of Landslide Sliding Geometry in Phuket

A. Puttiwongrak[1] and N. N. Htwe[2]
[1,2]Interdisciplinary Graduate School of Earth System Science and Andaman Natural Disaster Management (ESSAND) Prince of Songkla University Phuket Campus, Phuket, Thailand
[1]Andaman Environment and Natural Disaster Research Center, Prince of Songkla University Phuket Campus, Phuket, Thailand
[1]E-mail: puttiwongrak.a@gmail.com

ABSTRACT: Over the last decade, landslides triggered by rainfall in Phuket have been a major problem affecting development and tourism. An investigation of areas susceptible to landslides is necessary in order to institute policies to reduce the impact of landslide and to ensure the safety of tourists. In this study, two-dimensional electrical resistivity imaging (2D-ERI) was applied and slope stability modelling was conducted to investigate the sliding surface and the thickness of the sliding mass in a study area which is prone to landslide during intense and prolonged rainfall. The result of the 2D-ERI was used to validate the result of a simulation of the slope stability to determine the landslide sliding surface and the thickness of the sliding mass based on rising piezometric head due to rainfall. Further, the model geometry of the slope stability was reconstructed using the 2D-ERI data, and the simulation was repeated. The result for the factor of safety (FS) when the piezometric head was rising was found to have been overestimated in the original simulation Therefore, the reconstruction of the model geometry is essential to avoid the over-estimation of the FS in slope stability modelling in conditions of rising piezometric head.

KEYWORDS: Landslide, Sliding surface, Electrical resistivity imaging (ERI), Slope modelling, Factor of safety (FS)

1. INTRODUCTION

Landslides is a typical hydro-geotechnical problem in mountainous areas in tropical and sub-tropical regions in which rainfall is an extrinsic factor**.** Rain infiltration reduces the strength of the ground and affected the slope stability due to rising pore water pressure near the subsurface and triggers slope failures. The thickness of the sliding soil and the sliding surface of the landslide appear to be the most important factors in the instability of landslides (De Vita et al., 2006). Consequently, mountainous areas are prone to landslides and in order to identify the thickness and sliding surface of a landslide the wetted zone at a shallow depth near the slope surface needs to be investigated.

Phuket is a mountainous island situated in the Andaman Sea. It has a tropical climate and rainfall occurs during eight months in a year. As a popular tourist destination, Phuket has to deal with increasing tourist arrivals and this has led to rapid and mostly unplanned land development. This largely unplanned and rapid process of urbanization due to tourism involves construction activities in mountainous areas leading to many slope instability problems (ADPC, 2008). Landslides in Phuket triggered by heavy and prolonged periods of rainfall represent a significant natural hazard and a threat to buildings and people living around the hillside areas. It has been estimated that landslides in Phuket are responsible for economic losses of more than 3 million US Dollars annually (Mairaing and Thaiyuenwong, 2010).

Although most previous studies have focused on rainfall as the key factor triggering landslides in Phuket **(**Chotikasathien and Soralump, 2007; Mairaing and Thaiyuenwong, 2010; Soralump, 2010), none have investigated the contribution of the slip surface which is closely associated with landslides during intense precipitation**.** Moreover, no study has considered the detailed geometry of landslides and the process of slope instability in Phuket, nor has the spatial and temporal development of subsurface water transfer capacity during heavy and prolonged rainfall been identified. Unfortunately, surveying the subsurface geometry along the steep slopes of the fractured granite mountains in Phuket is difficult using conventional techniques (De Vita et al., 2006), i.e., by the drilling and borehole methods. Such conventional methods are common but require intensive labour, often costly field work and entail the problem of carrying heavy equipment into the study area.

Electrical resistivity imaging (ERI) is a useful tool for investigating landslides because it is a standard method for producing data with high accuracy from a large number of sample points, which is impossible by the use of conventional techniques (Batayneh and Al-Diabat, 2002). ERI is a non-destructive, portable, and less time-consuming technique capable of covering large area at a relatively low cost (Bobrowsky et al., 2004; Mairaing and Thaiyuenwong, 2010). In this study, ERI was used to define the geometry and some physical properties of landslide masses in the study area. The soil thickness of potential landslide masses was investigated to assess the sliding surface of the landslide geometry. Two-dimensional ERI (2D-ERI) was conducted to identify those parts of the study area which are more susceptible to sliding on fractured granite. The sliding surface and the landslide geometry are key parameters controlling the dynamics of mobilized shear strength, which causes landslides, and these parameters were used to validate the 2D-ERI slope modelling.

According to Acharya et al. (2016) slope failure mechanisms and subsurface hydrology need to be studied in in-depth research (and the use of slope modelling techniques and methods of simulating slope stability have been developed which have taken advantage of improvements in computer performance (Baba et al., 2012). Although statistical models are frequently used to study landslides triggered by rainfall, they are possible only if a large amount of data are available regarding the relationship between the landslide area and the rainfall conditions (Acharya et al., 2016). Therefore, slope modelling was carried out in this study due to the limited amount of data available to analyze the slope stability. A coupled simulation of the hydrological and slope stability features was used to model the instability of the slope when, as a result of heavy rainfall, pore water pressure rises in near subsurface, the factor of safety (FS) decreases markedly to lower than 1.00 and the sliding mass starts to slowly slide. This study aimed to investigate the subsurface geometry and the mechanism of the landslide using 2D-ERI and slope modelling in an area of Phuket susceptible to landslides. The application of ERI and slope modelling provides a new means of rapid investigation with only a limited amount of data but is still able to produce accurate simulation results. The results of 2D-ERI allowed a model of the geometry of the landslide body to be produced outlining the sliding surface and susceptible areas characterized by high water capacity. Furthermore, the slope modelling was combined with an analysis of the relationship between hydrological and slope stability and simulations were conducted to estimate the effects of the occurrence of a landslide in the study area.

2. SITE DESCRIPTION

Phuket is one of the most economically important provinces in Thailand and it has many hotels built both on flat and sloping areas. Phuket's climate is tropical with an annual average temperature of 28.5 °C and annual average rainfall of 1008 mm. Most of the rainfall occurs during April-November**.** The study area selected as a pilot site was in Chalong district, on the eastern flank of a mountain range with an east-west slipping direction as shown in Figure 1**.** Geographically, it is located at 7° 51' 47.32**"**N and 98° 19' 42.39**"**E, and the elevation of the mountain peaks is 529 meters above sea level. Among the geomorphic features of the study area is a high slope gradient of approximately 28°**.** The geological formation consists of granite from the Cretaceous period and modern beach sediments from the Quaternary period**.** The granitic formation is in a moderately to highly weathered condition and slope failure sometimes occurs in the weathered granite in the study area, which is highly prone to landslides**.** The residual granite is up to 5 m thick and is often exposed by erosion as shown in Figure 2, thus becoming prone to major landslides**.** Therefore, the principal geologic units of a landslide in the area can be classified into a superficial deposit, fractured granite **(**sliding soil**)**, and bedrock **(**granite**).**

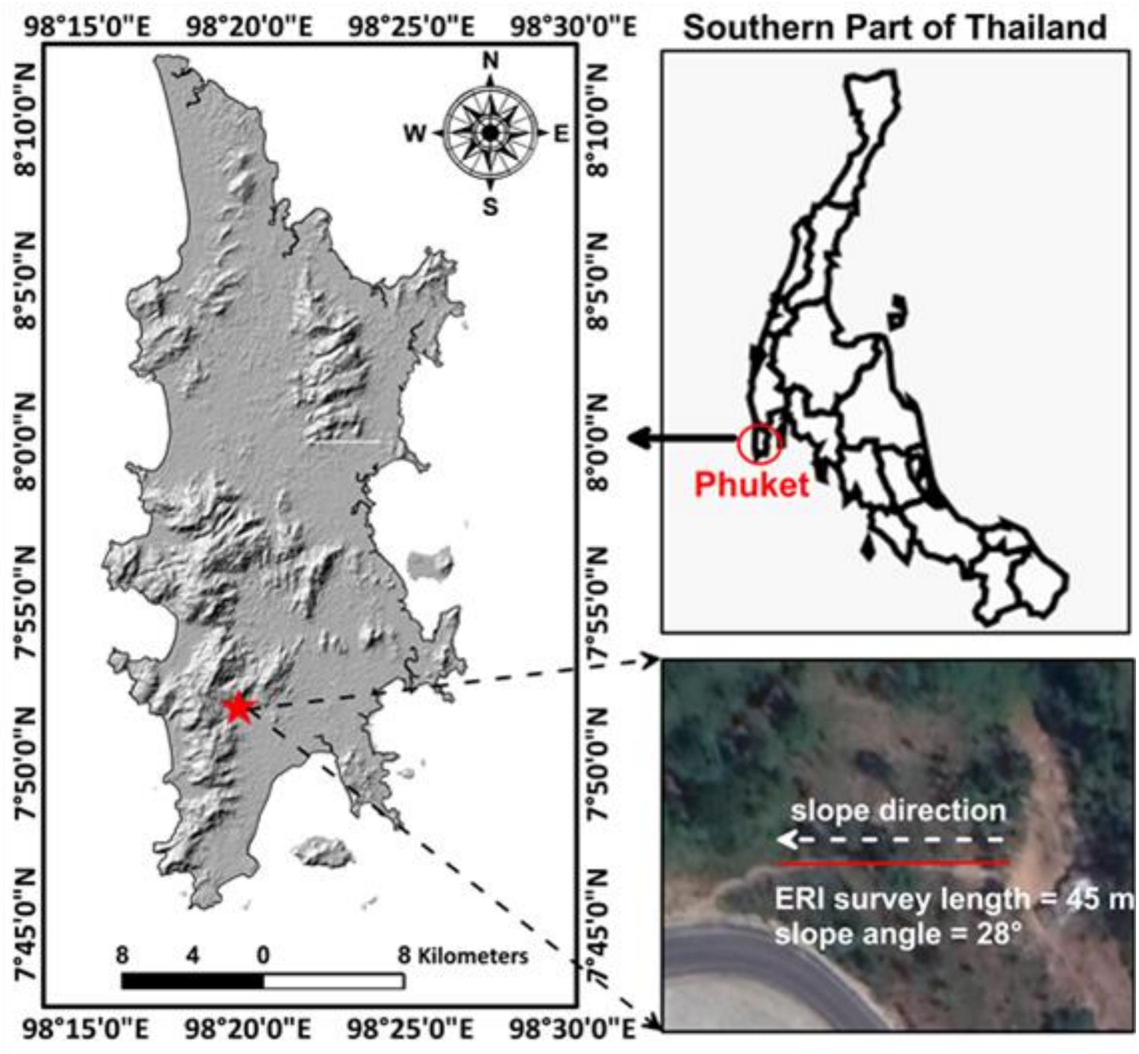

Figure 1 Study Area of Phuket Landslides at Chalong district showing the ERI survey profile

3. METHODOLOGY

3.1 ERI Data Acquisition

ERI's high geo-electrical sensitivity to subsurface conditions makes it particularly useful for investigating sub-surface conditions. In this study, ERI was conducted to observe changes in water saturation and topographical features. The study area was visited in September 2018 during the pre-monsoon period to investigate the landslide geometry with respect to the resistivity contrast between the susceptible sliding mass and the bedrock. An AGI Superstring R2 resistivity meter, which is a multi-electrode system with 31 automatic switching electrodes, was used for collecting the resistivity data. The ERI data were collected along a profile of 45 m (Figure 1) following the slope with an inter-electrode spacing of 1.5 m, which allowed probing down to a depth of 9 m. A GARMIN-portable GPS was used to synchronize the location of the survey profile. In the survey, 135 data measurements were taken in a Wenner configuration, which is an attractive array due to its high signal strength (Eissa et al., 2016) in order to obtain a 2D-ERI resistivity section.

The apparent resistivity data were inverted to obtain true resistivity along the profile using EarthImager 2D software (AGI, 2009) in order to generate a 2D profile of the resistivity distribution.

The software also divided the resistivity data into a number of rectangular blocks, then the blocks were optimized in an iterative manner reducing the difference between the measured and calculated resistivity values. After two iterations the root mean square (RMS) error was less than 3%, and a geo-electrical model along the profile was constructed and interpreted using a common colour code to map entrapped water pockets in the active landslide in the study area. The geometry of the susceptible landslide, i.e., the depth and lateral continuity of the sliding surfaces, was found from the ERI result.

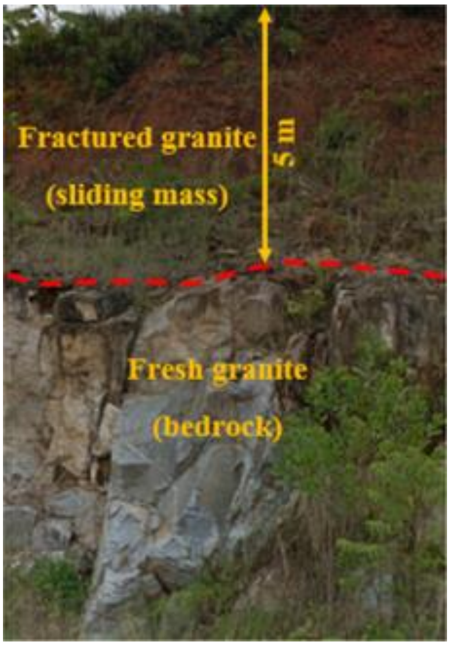

Figure 2 Exposed Geological Section in the study area

3.2 Slope Modelling

In this research, a landslide in the study area was simulated using the commercial software GeoStudio (Geo-slope International Ltd., 2017) by conducting slope stability analyses. The program SLOPE/W in GeoStudio is a finite element-based method of calculating and modelling slope stability. SLOPE/W allows limit equilibrium analysis of slope stability using the Morgenstern-Price method (Morgenstern and Price, 1965) to compute the FS taking into consideration the stages of normal inter-slice and shear forces to satisfy both force, FS_f, in Eq. 1 and moment equilibrium, FS_M, in Eq. 2. Then the FS of the Morgenstern-Price method is obtained by the calculation of FS_f and FS_M giving the result from the iterative procedure shown in Figure 3.

$$FS_f = \frac{\sum[c'\beta R+(N-u\beta)R\tan\emptyset]}{\sum Wx-\sum Nf+\sum kWe\pm\sum Dd\pm\sum Aa} \quad (1)$$

$$FS_M = \frac{\sum c'\beta\cos\alpha+(N-u\beta)\tan\emptyset\cos\alpha]}{\sum N\sin\alpha+\sum kW-\sum D\cos\omega\pm\sum A} \quad (2)$$

where c' is the effective cohesion, β is the slice base length, R is the radius for a circular slip surface, N is the normal force at the slice base, u is the exerted pore-water pressure, ϕ is the friction angle, W is the weight of the slice, x is the horizontal distance between the center of moment and the centerline of the slice, f is the perpendicular distance between the center of moment and the normal force, kW is the horizontal seismic load applied through the centroid of each slice, e is the vertical distance from the centroid of each slice to the center of rotation or to the center of moment, D is an external point load, d is the perpendicular distance between the center of moment and the point load, A is the resultant external water force, a is the perpendicular distance from the resultant external water force to the center of moment, α is the slice base inclination angle, and ω is the angle of the point load from the horizontal (always measured counter-clockwise from the positive X-axis.)

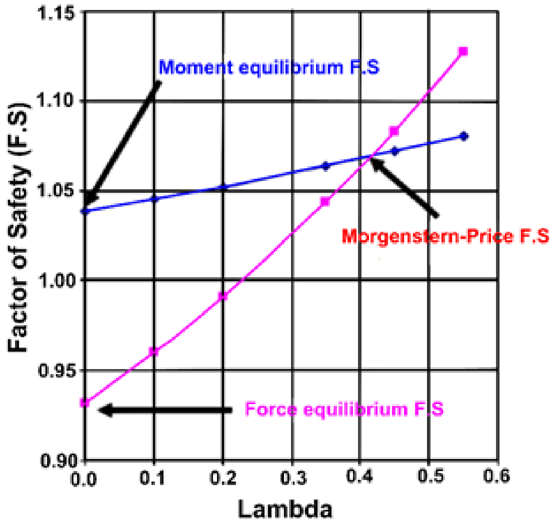

Figure 3 Morgenstern-Price factor of safety

The slope model was set up in two dimensions based on the following assumptions: 1) the slope failure is in a single layer, 2) the mode of failure is circular, 3) the maximum depth of failure is equal to the soil depth, 4) the bedrock is assumed to be an impermeable layer, 5) the landslide mass consists of homogeneous and isotropic ($k_x = k_y$) materials, 6) transient state-conditions are applied by piezometric head, 7) the assigned piezometric head is equal to the soil permeability. Further, the model layers were set up based on the exposed geological section after erosion near the study area as shown in Figure 4.

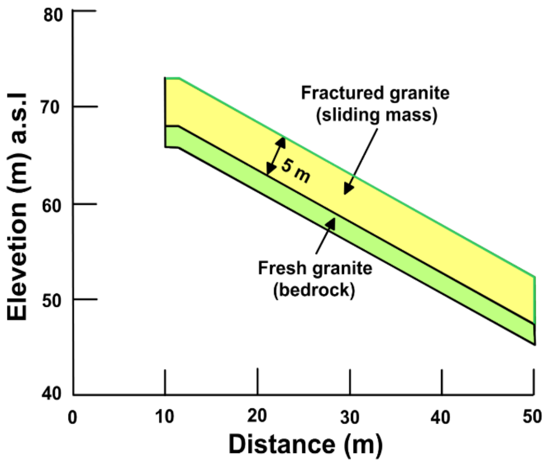

Figure 4 Model geometry for slope stability modelling

The data including, 1) effective cohesion, 2) unit weight, and 3) effective friction angle, used in this study were obtained from a report of the field investigation conducted by Soralump et al. (2011); Soralump (2010); Thaiyuenwong and Mairaing (2010); Mairaing and Thaiyuenwong (2010); Mairaing et al. (2006). The data were used in modelling the slope stability as detailed in Table 1. The slope stability conditions were evaluated using the assigned piezometric head values and the FS computed by the model for the landslide decreases after each piezometric head increase. For the slope stability simulation, a half-sine inter-slice force function was used in this study and the model thus concentrated on the inter-slice shear forces towards the middle of the sliding mass. Finally, the slipping surface was fully determined on the slope model, and was validated by the sliding surface found from the result of the ERI field observation.

Table 1 Input parameters for slope stability simulation

Geotechnical Parameter	Sliding Mass Conditions	
	Unsaturated	Sarturated
Unit weight, γ	16.35 kN/m^3	18.78 kN/m^3
Effective cohesion, c'	23.70 kPa	1.10 kPa
Effective friction angle, $\varnothing$	35.36°	37.68°
Matric suction friction angle, $\varnothing^b$	-	27.12°
Specific gravity, G_s	2.638	2.638
Void ratio, e	0.903	0.903

4. RESULTS AND DISCUSSION

4.1 Landslide Geometry Interpretation by ERI

The result of the ERI aimed at identifying locations susceptible to future landslides conducted in the study area gave very informative results delineating the landslide geometry. The ERI pattern showed the resistivity section along the survey profile (Figure 5), which was along the direction of the landslide movement, and had a resistivity range of 150 – 2600 Ωm with a low misfit of 2.23 %. The ERI of the survey profile distinguished three main materials in the slope. The first material in the upper layer is the main part of the landslide mass and is characterized by fractured granite, constituting a susceptible zone with a range resistivity of 200 – 600 Ωm. The second material, which is in the lower layer consists of fresh granite with a resistivity range of 800 – 1000 Ωm, while the final material is boulders (resistivity >1000 Ωm) which are exposed at the surface along the slope. A comparison of the ERI profile and the exposed geological section after erosion near the study area corresponded well to the ERI result. Moreover, the ERI result was in good agreement with the geological section studied by Giao et al., (2008) as detailed in Table 2.

The vulnerability of this slope is evident from the ERI section and the presence of fractured granite in a pocket overburdened by boulders at the top of the slope may lead to a landslide in future after heavy rainfall and the water content derived from rainfall is the key parameter in causing sliding. The contact between the fractured granite and boulders on the top of the slope appears to be the sliding surface, which is indicated by a red dashed line in Figure 2. The depth of the sliding surface was observed to be approximately 2.5 m. It should be noted that changes in resistivity due to temperature effects were not taken into account in this study because the temperature effects are much smaller than the effective changes in electrical conductivity (Lehmann et al., 2013).

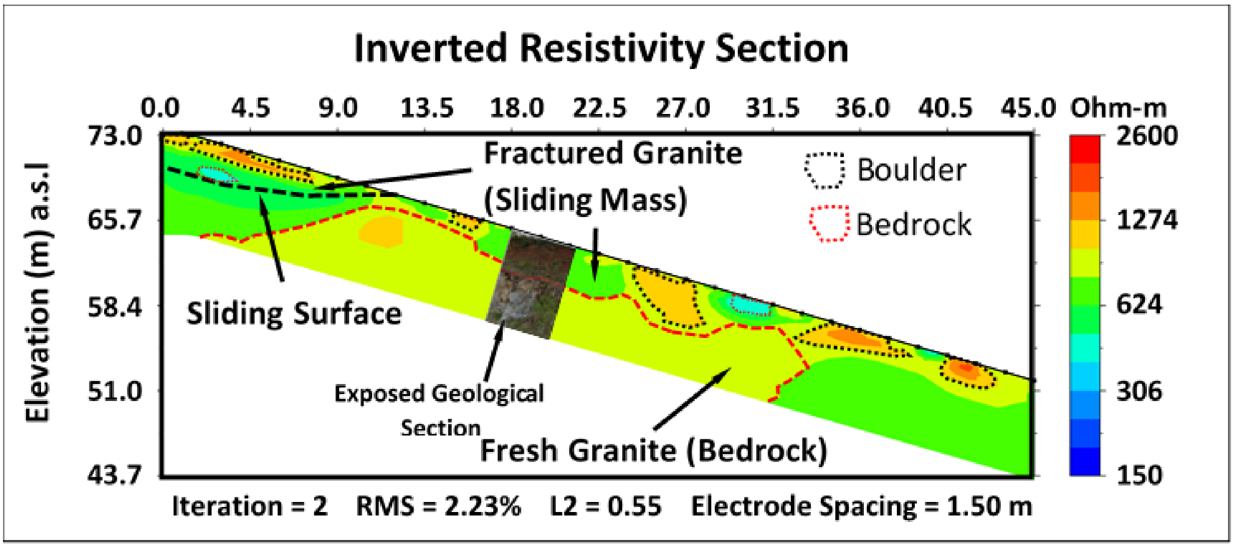

Figure 5 Interpretation of 2D-ERI showing the sliding surface of the susceptible landslide

Table 2 Resistivity range of Phuket granite (Giao et al., 2008)

Material	Resistivity Range (Ωm)
Granite residual soil (no corestones)	< 300
Completely weathered granite soil (<50% corestones)	300-600
Granite soil (50-90% block of rock)	600-1000
Granite bedrock (90% fresh granite)	1000-1800
Fresh granite	> 1800

4.2 Simulation of Slope Stability

The result of the slope stability simulation illustrates the critical sliding surface and the respective FS on the slope condition observed, as shown in Figure 6. The calculated depth of the sliding surface in the model differed by approximately 0.1 m from that estimated from direct observation. The simulation indicates that the failure will be initiated at the top of the slope from where the sliding mass will move down the slope. Although, the FS was higher than unity, which denotes a stable slope, in normal conditions (i.e., FS = 4.092 with no rainfall or water infiltration), the FS decreased (Table 3) after the groundwater level rose when the input conditions of the model were varied to include rainfall. A decreasing FS reflects the softening of the sliding surface induced by water infiltration, and the slope is, therefore, prone to be unstable during heavy and prolonged rainfall.

The parameters, taken into account in the simulation of the slope model included unit weight, friction angle, cohesion, and slope angle, because these parameters constitute the basic slope stability modelling parameters. Nevertheless, slope stability analysis is characterized by numerous uncertainties due to limited sampling, discrepancies in methods used to establish soil properties in a laboratory and during in-situ testing, and other unknown or uncertain factors. Therefore, in order to validate the sliding surface and the

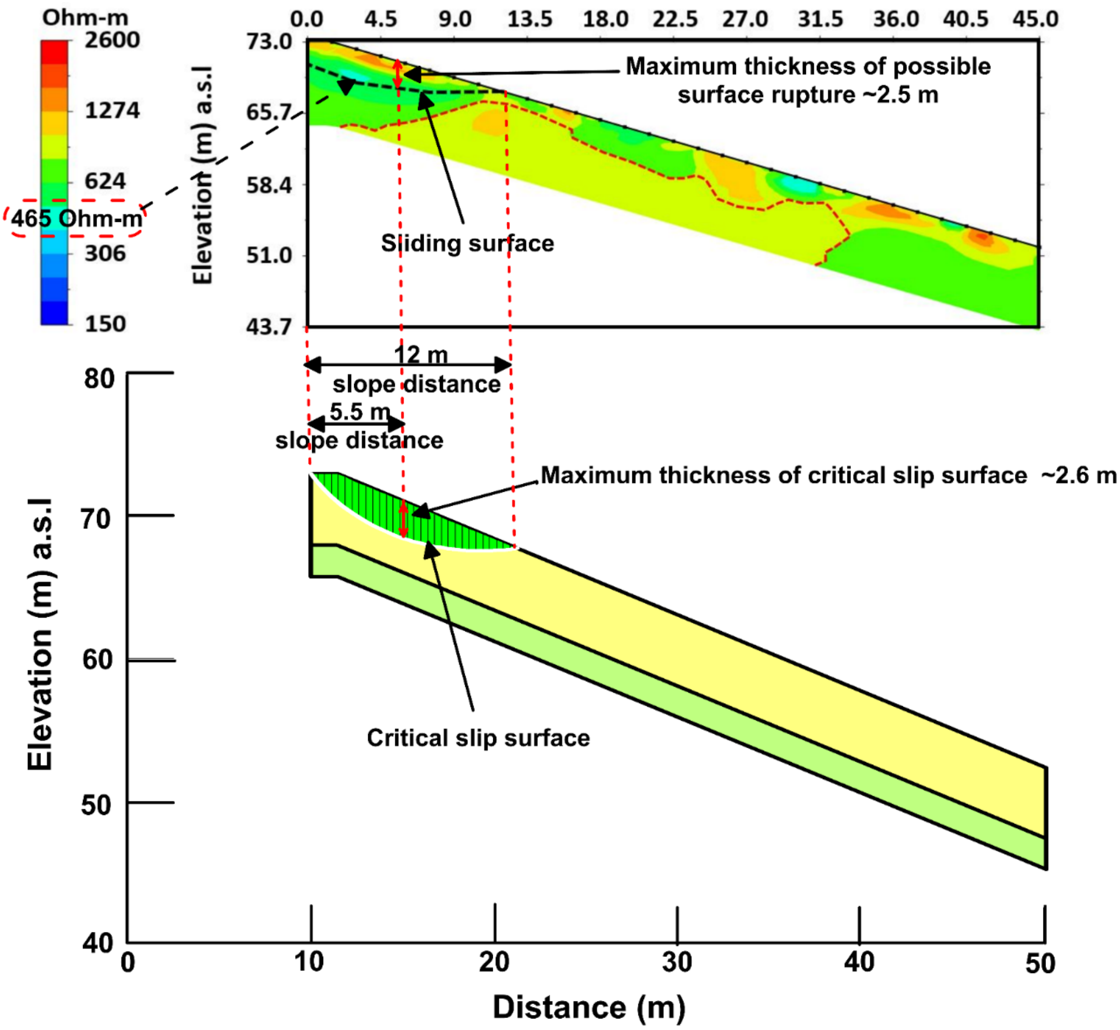

Figure 6 Sliding surface and thickness of sliding mass from slope stability modelling comparing with 2D-ERI

thickness of the sliding mass, the ERI profile investigation results were compared with the results calculated by slope modelling, as shown in Figure 6 and the two results were found to be in good agreement. However, the model created is limited to slope stability analysis and for a more accurate picture, seepage analysis, which simulates pore pressure distribution in natural slopes, should be conducted in order to create a more comprehensive model and provide better results.

Table 3 Comparison of increase in piezometric head and factor of safety

Piezometric head from surface	Factor of safety	
	Not Reconstruction	Reconstruction
No piezometric head	4.092	4.073
3 m	2.439	2.490
2 m	2.039	2.010
1 m	1.565	1.447

4.3 Reconstruction of Model Geometry Using ERI

In investigating the geometry and sliding mechanism of a complex subsurface body data must be collected from various depths in order to recognize and assess the sliding surface of a potential landslide and to create a model of the geometry of the landslide. However, drilling boreholes alone is not sufficient to establish the subsurface geometry and 2D-ERI is better able to identify the subsurface geometry, including the possible sliding surface and the thickness of the sliding mass, as well as mapping entrapped pockets of groundwater potentially contributing to the landslide.

In this study, the model of the subsurface geometry of the landslide was initially based on data relating to soil layers established from boreholes, then the 2D-ERI was used to reconstruct the model of the subsurface geometry as shown in Figure 7.

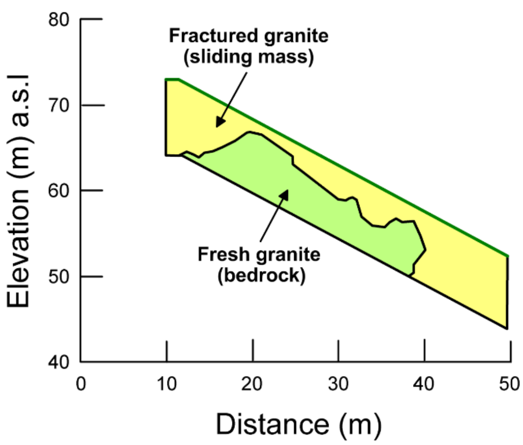

Figure 7 Reconstruction of model geometry using 2D-ERI

After producing a new slope model incorporating the complexity of the subsurface geometry, the simulation result (Figure 8) showed that the re-calculated FS was 4.073. Similarly, the thickness and the sliding surface of the landslide were also re-simulated as shown in Figure 8 and the results showed no great change in either the thickness or the sliding surface compared from the previous simulation without the reconstruction of the model geometry. Nevertheless, the FS of the reconstructed modelling simulation, especially when the piezometric head was increased, was significantly different from the simulation results without model geometry reconstruction as shown in Table 3 and Figure 9, the FS of the reconstructed model was less than the FS result from the slope modelling without the reconstruction of the model geometry when the piezometric head was input in the model. Consequently, the most important result is that the model geometry of the landslide simulation seems to result in the over-estimation of the FS. Therefore, the reconstruction of the model geometry is essential to prevent the over-estimation of the FS in slope stability modelling.

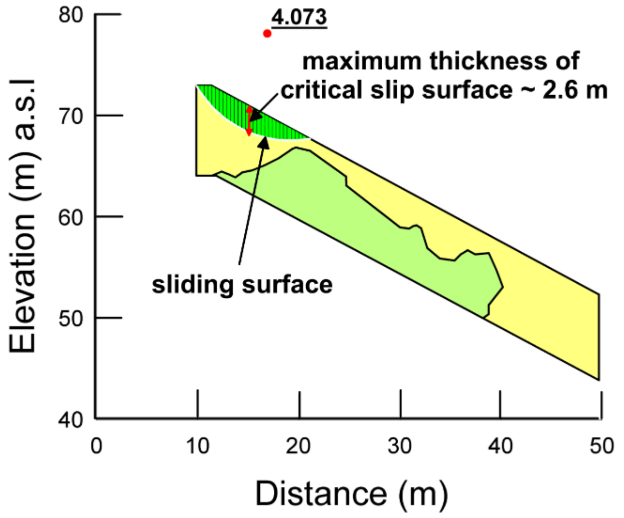

Figure 8 Simulation result of reconstructed model

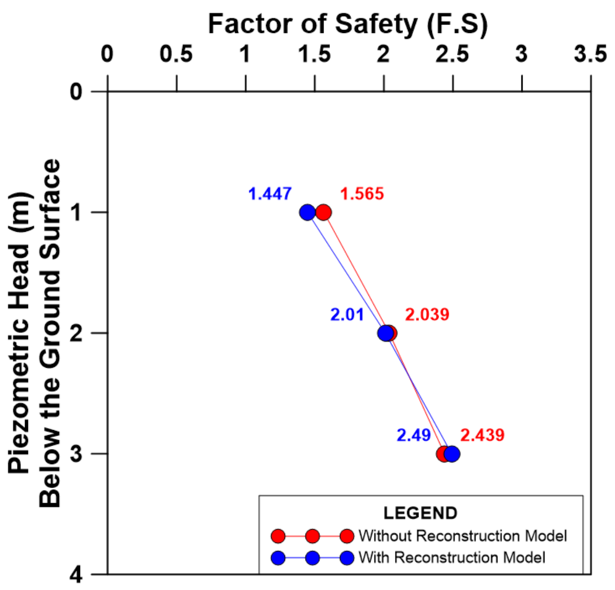

Figure 9 Comparison of simulated FS between reconstructed and non-reconstructed models

5. CONCLUSION

The unplanned and rapid urbanization of Phuket have contributed to an increased risk of landslides as the areas used for building expands from the flat regions to open slopes. The local government in Phuket has found it impossible to investigate all the areas which may be prone to the risk of landslides for many reasons, including, 1) they might not be aware of the increased danger of landslides in urban areas, 2) they might have other priorities, 3) they may lack the financial and technical resources necessary to develop mitigation programs, 4) they may not have the capacity to respond to and address the landslide risk (ADPC, 2008). However, ERI provides an easy method for investigating whether open slopes are susceptible to landslides based on the determination of the sliding surface and the geometry of the landslide, and it would be prudent to adopt ERI and slope stability modelling as a useful tool for landslide risk assessment in Phuket. In this study, ERI was used to validate the sliding surface and thickness of a sliding mass derived from the simulation results of a slope stability model. In addition, the reconstruction of the model geometry using ERI was carried out to simulate the slope stability under the condition of increasing piezometric head (i.e., rainfall) in the study area. The FS results show that the reconstruction of the model can help to avoid the over-estimation of the FS. Finally, the integrated method used in this pilot study would enable an early warning system incorporating, slope monitoring to be put in place, and this combined with the dissemination of information and educational campaigns would lead to a reduction in the impact of landslides. However, for a better understanding of the causes of landslides, slope failure mechanisms and the subsurface hydrology still need to be studied and incorporated into slope modelling, and this needs to be combined with simulations incorporating seepage and slope stability analyses. Therefore, further research is needed in order to fully understand potential slope failure during rainfall.

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