Development of 3D Subsurface Models for Landslide Investigation Using Spatial Interpolation Technique

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Abstract

Landslides events in Malaysia are often triggered by rainfall due to the tropical climate which has resulted in large numbers of casualties and massive economic losses. To prevent this disastrous events, subsurface investigation is essential to facilitate slope characterization and establish effective slope stabilization measures. This paper presents the integration of borehole drilling, electrical resistivity and seismic refraction method to characterize a residual soil slope in Malaysia. Borehole drilling was used to obtain soil stratigraphy, to locate groundwater level and to obtain undisturbed soil samples for geotechnical laboratory testing. The electrical resistivity method was adopted to measure resistivity distribution of the subsurface materials while seismic refraction method was used to measure the travel time of seismic waves refracted at the interfaces between subsurface layers of different velocities. A deterministic spatial interpolation technique was applied to develop three-dimensional (3D) subsurface models from the available two-dimensional (2D) data. The outcome from this study produced valuable subsurface information of the slope that enables potential failure zone and effective slope stabilization measure to be identified.

Keywords: Rainfall induced landslide, subsurface characterization, slope stabilization, spatial interpolation, 3D subsurface model.

1 Introduction

The National Slope Master Plan of Malaysia has reported that rainfall has been recognized as the major triggering factor of slope failure worldwide and also in Malaysia (Public Works Department of Malaysia 2008). The tropical climate in Malaysia that experiences Southwest monsoon from May to September and Northeast monsoon from November to March contributes to the abundant rainfall annually. Therefore, it is not uncommon for steep soil slopes to remain stable for a long period, whereas some gentle slopes may fail after several heavy rainfalls (Li et al. 2005). Rainfall induced landslides are commonly triggered by rainwater infiltration that increases the groundwater table or degree of saturation in the soil mass. This increases the pore water pressure subsequently loss of shear resistance in the soil mass leading to landslide. Slope stability analysis is carried out regularly to assess the level of safety of the slope.

Site characteristics such as subsurface and groundwater information are essentially utilized as important input for stability analysis. Borehole drilling is a conventional and widely used method to obtain subsurface information such as stratigraphy, groundwater level and sampling of the study area. However, borehole drilling only offers a single point well data and is invasive to the surrounding. For a large area, additional boreholes are required and this will incur additional cost to obtain

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representative data. Therefore, geophysical methods such as electrical resistivity and seismic refraction can be the integral approaches to characterize the slope due to the advantages of being non-invasive, able to cover a large study area and less time consuming. The objective of this study is to enhance the conventional approach in developing subsurface models for slope stability assessment and the stabilization measures. Subsurface models in the form of 3D perspective were developed based on the results from borehole drilling, electrical resistivity and seismic refraction methods respectively.

2 Geological Information and Subsurface Investigation

The study area is generally underlain by graphitic quartz mica schist from Kajang Formation that mainly consists of dark grey to black carbonaceous quartz–muscovite schist interlayer with thin bands and lenses of orange to buff quartz–muscovite with minor intercalation of marble and phyllite (Manap et al., 2014). Observation on the outcrops indicates that intense weathering processes have taken place with weathering grades ranging from Grade III to VI. Based on the historical core samples obtained at the depths of 9m to 20m, the rocks in this area consist of interbedded sandstone, shale and actinolite schist (Ahmed et al. 2011).

Figure 1 shows the location of the borehole drilling, electrical resistivity and seismic refraction survey carried out at the site. A total of 17 boreholes drilling were conducted to determine the geological structure such as the thickness, sequence and extent of the soil strata, to determine groundwater conditions, to conduct in-site test such as standard penetration test (SPT) and to obtain disturbed and undisturbed soil samples for laboratory tests (e.g. particle size distribution, Atterberg limits test and consolidated undrained triaxial test). Rock coring was carried out when a rock layer was encountered. Total recovery ratio (TCR) and rock quality designation (RQD) were recorded for each core run to determine the quality of the rock samples.

Nine resistivity survey lines were performed to measure the resistivity distribution of the subsurface material. The principle that lies behind this method is by injecting electrical current into the ground through two electrodes and the potential difference is then measured through two potential electrodes. From the results of current and potential difference measurements, the variations of electrical resistivity value for the measurement point can be obtained. Since the ground resistivity is related to various geological parameters such as fluid content, degree of saturation and porosity, the variations in electrical resistivity may indicate the variations in composition, layer and contaminant levels. Table 1 shows the resistivity values of some type of common rocks and soil materials.

Six seismic refraction survey lines were carried out to map the seismic velocity of the subsurface geology. The seismic refraction method is based on the measurement of travel time of seismic waves refracted at the interfaces between subsurface layers of different velocity (Burger, 1992). Seismic energy is provided by a source generated by the sledgehammer impacting a metallic plate located on the ground surface. Energy radiates out from the shot point, either travelling directly through the upper layer, or travelling down to and then laterally along higher velocity layers before returning to the surface. This energy is detected on surface using a linear array of receivers known as geophones spaced at regular intervals (Redpath, 1973). Data are recorded on a seismograph and the first-arrival times for each shot position are analyzed. Table 2 shows the typical v_p for various types of earth materials which is useful as a guide for results interpretation.

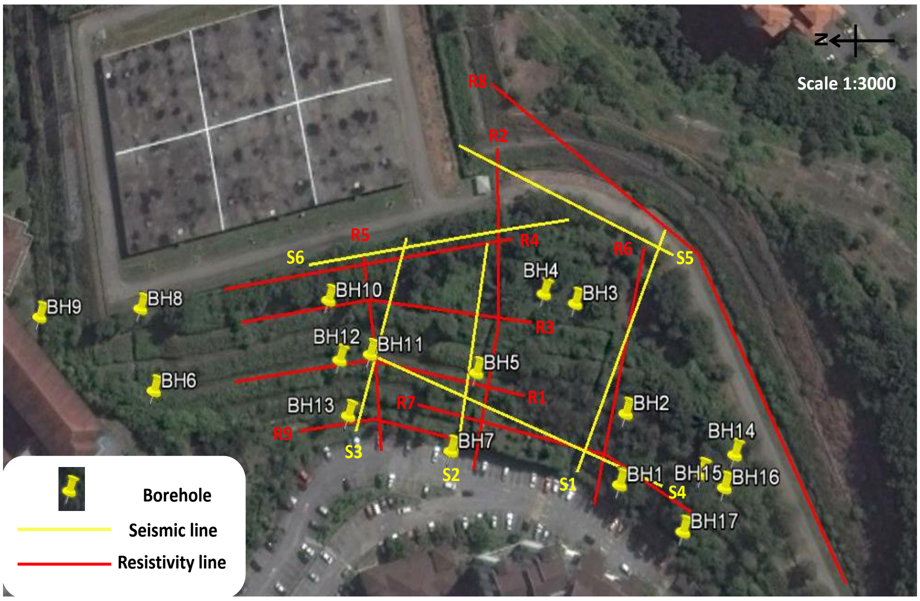

Figure 1: Location of boreholes, resistivity lines and seismic lines

Table 1. Resistivity of some common rocks and soil materials (Keller and Frischknecht 1966)

Material	Resistivity (Ωm)
Alluvium	10 to 800
Sand	60 to1000
Clay	1 to 100
Groundwater (fresh)	10 to 100
Sandstone	$8 - 4 \times 10^3$
Shale	$20 - 2 \times 10^3$
Limestone	$50 - 4 \times 10^3$
Granite	5000 to 1,000,000

Table 2. Typical propagation velocities of seismic waves through different types of geological media (Reynolds, 2011)

Medium	Velocity min (m/s)	Velocity max (m/s)
Air depending on temperature	310	360
Weather soil	100	500
Gravel, dry sand	100	600
Loam	300	900
Wet sand	200	1800
Sand loose	200	2000
Clay	1200	2500
Water depending on temperature	1430	1590
Sand and gravel (near surface)	400	2300
Sandstone friable	1500	2500

Sandstone dense	1800	4000
Sandstone (medium to strong)	1400	4500
Chalk	1800	3500
Shale	2000	4100
Limestone	2500	6000
Marl	2000	3500
Gypsum	4500	6500
Ice	3100	4200
Granite	4000	5700
Metamorphosed rock	4310	6360

3 Development of 3d Subsurface Model

Three different 3D subsurface models presenting the stratigraphy, P-waves velocity (v_p) and electrical resistivity were developed based on the results from boreholes drilling, electrical resistivity and seismic refraction. 3D models are able to present the spatial variation in the vertical, lateral and perpendicular directions along the survey line. However, 3D geophysical surveys are still a subject of active research at the present time thus not routinely used compared to the 2D survey (Loke, 1999). The cost for 3D geophysical survey is relatively higher and more time consuming due to the data acquisition for a large study area. Therefore, a simplified and less time-consuming approach is adopted in this study to develop the 3D models from the available 2D survey data.

The 3D stratigraphy, resistivity and v_p models were developed by using a solid modelling algorithm where the resistivity and v_p values were interpolated for fixed X, Y and Z coordinates. Numerous spatial interpolation methods have been developed and applied to various disciplines especially for meteorological data (Chai et al., 2011). Some of the examples are inverse distance weighting (IDW), kriging, nearest neighbour (NN), trend surface analysis (TSA), local polynomial (LP), etc. Each method has its own advantages and disadvantages and thus the optimal interpolation method is selected depending on the objectives of the study (Chen and Liu, 2012). The technique utilized in this study to perform spatial interpolation is the IDW method. This method assumes things that are close to one another are more similar than those that are farther apart and the local influence will diminish with distance (Li, 2008). The values of the unknown points are calculated with a weighted average of the values available at the known points. Hence, greater weights are assigned to points closest to the prediction location. A computer program named RockWorks15 was used to perform the IDW spatial interpolation to produce the 3D models. To evaluate the performance of the computed IDW model, coefficient correlation (R) was also determined. R value of 1 indicates a perfect correlation while a value of 0 indicates no correlation between the measured and computed data.

4 Results and Discussion

This section presents the results of the subsurface investigation by borehole drilling, electrical resistivity and seismic refraction. Figure 2 shows the results of the multi borehole logs plotted in 3D according to their positions on site. This result is further interpolated into a solid 3D stratigraphy model using the IDW method as presented in Figure 3. The 3D stratigraphy model indicates that the types of soil encountered at the site are silt, gravelly silt, clay, and sand. However, silt appears to be

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the dominant soil that is present. Sand exists at the top layer for about 1m from the surface while traces of gravelly silt and clay are also randomly encountered at the study area. In addition, rock was encountered at five boreholes namely BH3, BH5, BH6, BH9 and BH16 at the depth of 7.5m, 11m, 12m, 4m and 8.4m respectively.

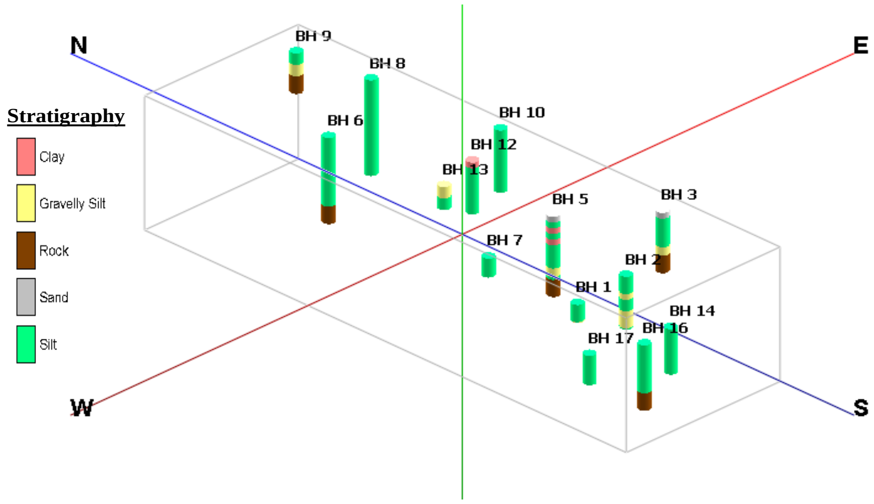

Figure 2: 3D multi boreholes log model

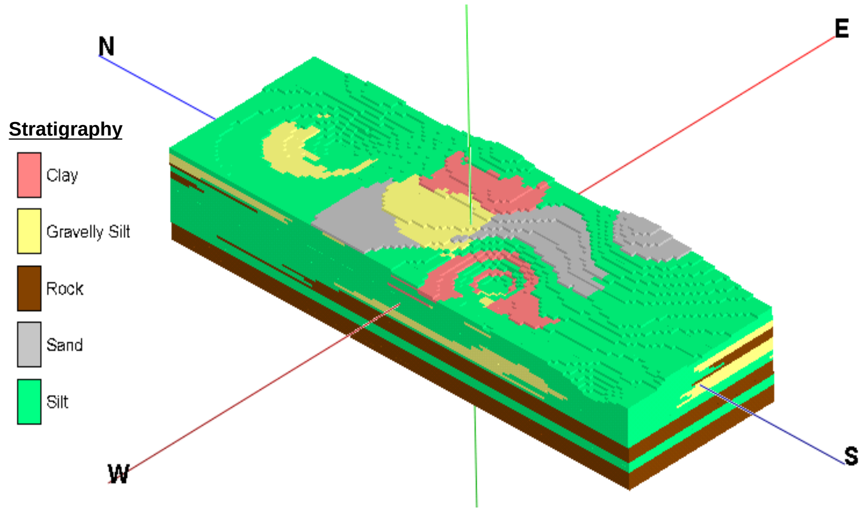

Figure 3: 3D stratigraphy model

Figure 4 shows the 3D resistivity model developed using the IDW spatial interpolation method. It can be observed that the model can be divided into two zones namely wet and dry zone. The wet zone indicated by blue colour scheme exhibits low resistivity values ranging from 10Ωm to 300Ωm and may indicate the presence of high water content or high seepage activities. The dry zone has higher resistivity values ranging from 300Ωm to 100000Ωm and this indicates that the soil within this zone is relatively dry with no seepage flow activities. Due to the high water content in the wet zone, rainfall events may increase the existing pore water pressure subsequently trigger failure. Hence, this area can be delineated as the potential failure zone. The robustness of the developed 3D resistivity model was measured through the correlation coefficient between the observed and computed resistivity. The correlation coefficient obtained was 0.791 and this indicates a satisfactory performance between the observed and computed resistivity values. Hence, the 3D resistivity model has a reliable accuracy to provide the indication for potential failure zone with high water bearing.

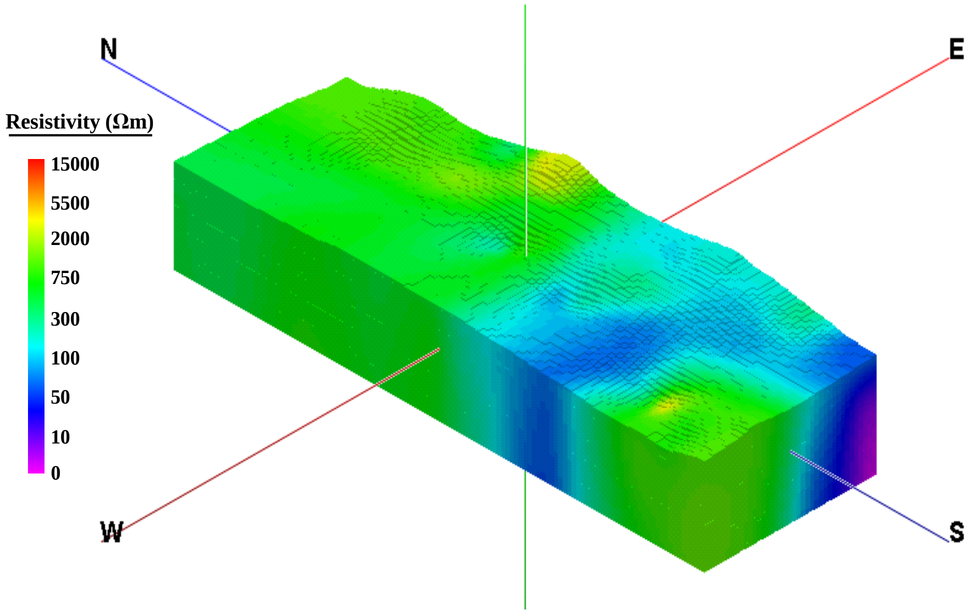

Figure 4: 3D resistivity model of the study area

The 3D v_p model presents seismic velocity distribution of the site is shown in Figure 5. The accuracy of the model is considered good indicated by the correlation coefficient value of 0.872. Generally, the site possesses the v_p value of approximately 1500m/s. In comparison with the 3D resistivity model, the water bearing zone coincides with the intermediate v_p zone of 500m/s to 1000m/s. This suggests that the identified zone consists of lower density or high porosity materials thus is prone to slope failure. Based on this subsurface investigation and developed 3D models, horizontal drains are proposed to be installed at the toe of the slope within the delineated high water bearing zone. This stabilization measure aims to discharge the high groundwater table subsequently reducing pore water pressure build-up. The flowrate measurements recorded the value of 115 ml/s during the dry season demonstrating the effectiveness of the horizontal drains as shown in Plate 1. This study has shown that the integration of borehole drilling, electrical resistivity and seismic refraction has provided useful information to characterize and remediate landslides.

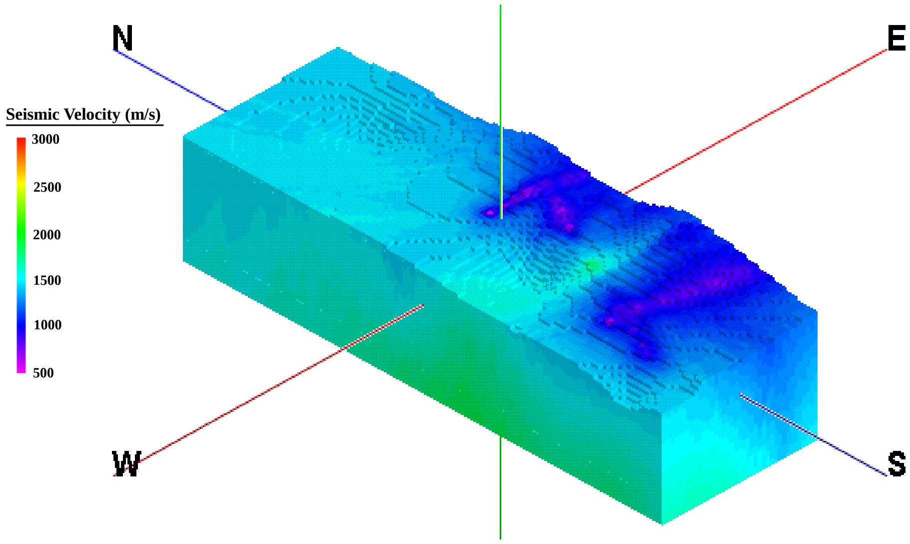

Figure 5: 3D v_p model of the study area

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Plate 1: Continuous discharge of groundwater from the horizontal drains on site

5 Conclusions

3D subsurface models of the stratigraphy, electrical resistivity and seismic velocity were successfully developed to characterize the study area using IDW spatial interpolation technique. The 3D stratigraphy model shows that the study area generally consists of silt with plasticity ranging from intermediate to very high plasticity. The 3D resistivity model indicates a high water content zone with the resistivity values ranging from 10Ωm to 300Ωm. The seismic velocity zone of 500m/s to 1000m/s in the 3D seismic velocity model also indicates low density and high porosity soil layer. These results demonstrated that the areas which consist of both characteristics of high water content and intermediate seismic velocity are prone to slope failure. Hence, an effective remediation measure can be proposed with such comprehensive subsurface investigation.

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