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Research paper

Slope Stability Analysis of Granitic Residual Soil Using SLOPE/W, Resistivity and Seismic

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Abstract

There are many factors that influence slope failure such as natural disasters and human activities. Amongst the major causes are the rise of groundwater and infiltration of prolonged and antecedent rainfalls. Together with its geographical condition; high lands and mountains, Malaysia is prone to have landslides especially at the Main Range area where most of the soil is residual soil. This study investigated a slope which had a history of landslide due to circular failure landslide using Slope/W, resistivity and seismic surveys to determine the physical and mechanical properties of the on-site materials. Based on the resistivity survey, the existence of groundwater level has been detected at a depth of 10.0 m from the ground level. Seismic analysis showed that the subsurface area was made up of Weathered Granite Grade VI (sandy soil) which is loose to medium dense. SLOPE/W analysis showed that the factor of safety (FOS) was 0.186 which was unstable for slope stability condition. The assessment showed that the slope condition is still not stable despite slope stabilization measurement using cement grouting. It is proposed that erosion control measures on the slope surface should be implemented to prevent recurrent of slope failure and to ensure slope stability.

Keywords: *Slope stability; slope failure; Slope/W; Resistivity; Seismic*

1. Introduction

Slope failure can be attributed to climatic event that affect the stability of the slope which results in mass movements that can develop into landslides. The phenomena of slope failure usually occur due to many factors such as the physical nature of the ground material, extreme weather conditions, limited vegetation cover, excessive water and inadequate drainage [1]. Apart of that, hill–site developments and rapid growth of population in the urban area particularly at hilly areas can also influence the stability of a slope due to the disturbance in the surrounding environments [2-3]. The two major factors that determine slope stability are the angle of the slope and the strength of material on it. The slope is more unstable if the slope is steeper. Each slope is different in term of geology and soil composition. Slope failure can lead to landslides that can cause tragedy in human lives and destroy properties and infrastructures within the affected area resulting in economic loss and massive damage [4].
Landslides and slope failures can be prevented by assessing the slope condition and the underneath ground using geophysical methods. Heavy rainfall is one of the most significant triggering factors for the occurrence of slope failures in the tropical region [5-6]. The mechanism of rainfall induced slope failure by reducing matric suction in soil which in turn reduces the soil shear strength, and subsequently triggers the slope failure. Furthermore, heavy downpour may cause a perched water table with positive pore-water pressure develops in the soil slope, which will further decrease the shear strength of soil and eventually make the slope increasingly susceptible to failure [7]. Malaysia has experienced many cases of slope failures and landslides in the past years due to climate change, global warming and also rapid development [8]. Slope failure due to rainfall is very common in Malaysia, being a tropical country which is characterized by high average annual rainfall and humidity [9-10]. During heavy rain, infiltration of rain water into the soil will make the soil become saturated, thus reduces the shear strength and decreases the friction between the soil grains which can initiate mass movement down the slope.
Slope safety control measures are important to evaluate the safety of slopes and mitigate the risks of slope failure. The past incident of slope failure can be highly prone to another episode of slope failure [11]. Slope stability can be determined from the soil's characteristic based on observations at site and laboratory test, SLOPE/W analysis and factor of safety (FOS) for slope [12]. Previous study showed that the FOS is important for the analysis of slope stability [13].
The purpose of this investigation of geophysical survey was to provide preliminary subsurface information of the study area that was previously affected by slope failure and landslide, and was rehabilitated using cement grouting, but the condition of the slope has yet to be assessed. In this study, the type of soil and rock, the value of SPT-N and RQD, as well as the groundwater table were evaluated using resistivity and seismic surveys. For slope stability analysis, SLOPE/W was used to calculate the factor of safety (FOS). The geotechnical assessment work consists of one line of resistivity survey and seismic survey respectively, as well as laboratory tests. The laboratory tests conducted were the particle size distribution test, specific gravity test, Atterberg limits test and shear strength test.

2. Experimental

2.1. Study Area and Geology

The study area was located in Perak which is indicated in Figure 1. The geology of study area is dominated by igneous activity consisting of granitic rocks that include quartz, feldspar and mica, but due to weathering, the strength of granite was alleviated. The site was composed of intrusive rocks, largely Biotite Granite made up of fine, medium and coarse-grained granites. This intrusive rock is part of Dinding's pluton in Main Range granitoid province. Radiometric dating shows that this rock age was 213 Megaannum (Ma). Most of the granites that were exposed in this area have undergone several degree of weathering process. The exposed rock layer of the slope area has the weathering grade of Weathered Granite Grade IV to VI.

The geophysics surveys including resistivity and seismic studies were conducted along the line located at 4°23'37.4" N latitude and 101°36'13.6'' E longitude on the slope to obtain the subsurface information. Table 1 showed the coordinates of the survey line. A slope failure has occurred two years ago due to heavy rainfall and landslide. After the incident, slope rehabilitation was implemented by constructing retaining wall using soil nailing method and cement grouting to reinforce the slope since the method was effective and economical [14]. Figure 2 showed the treated slope using soil nailing method.

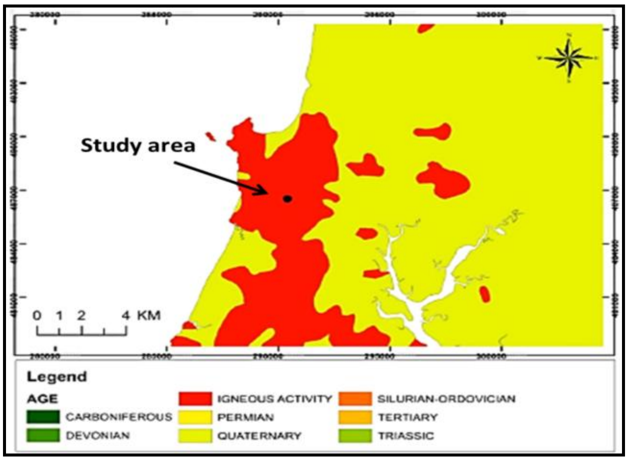

Fig.1: Geological map of study area

Table1: Coordinate and elevation of geophysics survey line

Line	Point (Electrode)	Coordinate RSO (meter)		Coordinate WGS (degree (°), minute ('), second ("))		Elevation (meter)
		North	East	Latitude	Longitude	
LINE 1	1	486463.471	290257.685	4°23'36.66"N	100°36'14.80"E	216
	C	486486.200	290257.779	4°23'37.40"N	100°36'13.60"E	195
	41	486471.084	290199.451	4°23'36.90"N	100°36'11.71"E	184

Fig. 2: Treated slope using grouted nails and cement grouting

2.2. Resistivity Study

Electrical resistivity method is considered a popular geophysical technique in electrical exploration that can create images of the subsurface that is measured from the spacing of current and potential electrodes, potential difference and injected current [15]. It is a non-invasive method that is used for surface exploration, subsurface characterization and monitoring. Resistivity measurements are based on the potential difference in resistivity between the variance sub-surface materials. The measured potential depends on the distance between the electrodes, the volume of current introduced in the ground, the type of array and the sensitivity of the measuring tools. The resistivity images were recorded in two dimensional forms, where the elevation from the sea level is represented by y-axis and the length of the survey line of the electrodes is represented by x-axis. This resistivity survey was able to predict and identify the type of soil and rock beneath the ground to a depth of 22.5 m.

Wenner-Schlumberger Array was used in this study area using the arrangement carried out with a multi-electrode resistivity meter system (ABEM SAS4000 Terrameter). The arrangement of 41 electrodes for a 2-D electrical survey and the sequence of measurement were used to build up a pseudosection. The total length for this survey line was 120 m with 3.0 m interval and obtained 22.5 m of maximum depth. The captured data will be deciphered into geo-resistivity images represented by a default color code. The depth of the geo-resistivity images recorded depends on the spacing of the electrodes and length of the survey. The longer the survey line, the deeper images can be recorded.

The recorded data by electrical imaging is a raw data that will be transferred to the data processing computer called RED2DINV software. The resistivity method basically measures the resistivity distribution of the subsurface materials such as soil profile, depth, contour, and groundwater level. The results from the resistivity survey will be compared with the standard result in the resistivity and conductivity values of some of the typical rocks and soil materials. A 2-D resistivity model versus depth/elevation was generated from the resistivity data and finally translated by Res2Dinv software.

2.3. Seismic Survey

Seismic methods are based on elastic wave also known as seismic, shockwave or acoustic waves of the earth's surface that is transmitted through the refraction of the sub-surface materials [16]. The wave is refracted on boundaries characterized by different rock types and densities, and physical properties. Seismic refraction is based on the first arrival of a signal that travels through a layer with a higher velocity. The seismic image was recorded in the form of two dimensional axes, where y-axis represents the travel time of seismic wave (ms-1) and depth below ground level (m) and x-axis represents the length of survey line where the geophones were installed.

A 24 channel ABEM Terraloc Mark 6, geophones for S-wave and P-wave and hammer were used for this study. Seismic survey was conducted using a 120 m in length with 5.0 m geophones spacing. A 4.5 kg hammer was used to produce pressure waves with seven points of impact from hammer towards steel plate to obtain proper readings. Energy will transmitted from the shot point, either by travelling directly through the upper layer or travelling down to and then laterally along higher velocity layers (refracted arrivals) before returning to the surface. This energy is detected on the surface using a linear array of geophones. Observation of the refracted signals provides information on the depth profile of the refractor. The raw data was captured by wave imaging from ABEM Terraloc Mark 6 and processed using software program called Interpex Seismic Refraction Interpretation Software (IXRefraX).

2.4. Slope W Analysis

SLOPE/W calculates the value of Factor of Safety (FOS) for various shear surfaces and the software can produce more than one angle of slopes and identify different type of soils. Factor of safety (FOS) is defined as the ratio of the shear strength to shear stress along a critical failure surface [17]. Analyses must be based upon a model that accurately represent site subsurface conditions, and ground behavior when using SLOPE/W software. Analysis of stability is mostly conducted using Bishop Method as shown in Eq. (1).

The factor of safety (FOS) is therefore chosen as a ratio of the available shear strength to that required to keep the slope stable. Table 2 shows the guideline for limit equilibrium of slope, which represents the condition of slope based on its FOS value. These values of FOS will be compared with FOS value obtained from SLOPE/W to get the condition of slope. If the value of FOS is 1.0, the slope is in a state of impending failure. The required factor of safety ranges between 1.25-1.5. In general, the value of FOS with respect to strength that is acceptable for the design of a stable slope is 1.5.

$$FS = \frac{1}{\sum_i W_i.\sin\alpha_i}\sum_i \frac{(c_i.b_i+(W_i-u_i.b_i)\tan\varphi_i)}{\cos\alpha_i+\frac{\tan\varphi_i.\sin\alpha_i}{FS}}$$

where;	
ui	pore pressure within block
ci, φi	effective values of soil parameters
Wi	block weight
αi	inclination of the segment of the slip surface
bi	horizontal width of the block

Table 2: Guideline for limit equilibrium of a slope

Factor of Safety	Details of Slope
<1.0	Unsafe
1.0 – 1.25	Questionable safety
1.25 – 1.4	Satisfactory for routine cuts and fills, Questionable for dams or where failure would be catastrophic.
>1.4	Satisfactory for dams / slope.

3.0 Results and Discussion

3.1. Resistivity Survey

Based on the resistivity survey, the existence of groundwater level has been found at a depth of 10.0 m from ground level. Generally, the subsurface is made up of sandy soil from weathered granite which range of resistivity value from 351 Ohm-m to 2670 Ohm-m. The stiff to very stiff layers of Sandy CLAY were interpreted 10.0 m below the surface around the tower with range of resistivity value 41 Ohm-m to 130 Ohm-m.

The Standard Penetration Test (SPT-N) and Rock Quality Designation (RQD) for soil and rock types in Table 3 have been interpreted at 1.5 m depth from the surface level based on the depth of borehole. This area consists entirely of weathered rock with RQD values of 25% to 50%, only a quarter of the area with RQD values of 50% to 75%. The stiff to very stiff soils were discovered at 10.0 m depth with SPT-N values 9 to 26.

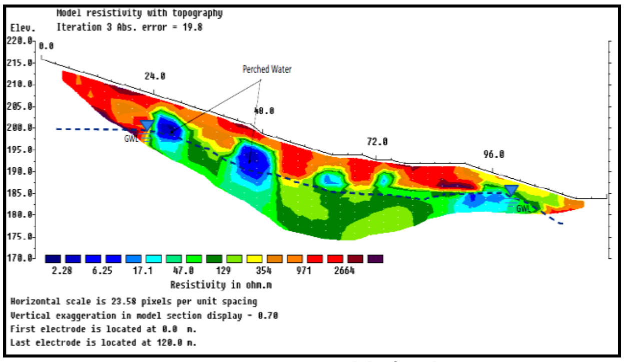

Fig.3: 2D Resistivity model of study area

Table 3: Summary of resistivity survey for Point A, B and C

Point	Max elevation obtained (m)	Min elevation obtained (m)	Elevation Water level (m)	Range of ohm at 1.5m depth	SPT-N value at 1.5m (if soil)	RQD value at 1.5m (%) (if rock)	Hard layer level, N>50 or RQD>1% (m)
A	195.0	177.5	192.5	351-360	-	25 - 50	NSL
B	202.5	185.0	195.0	351-360	-	25 - 50	NSL
C	192.5	180.0	185.0	2661-2670	-	50-75	NSL

3.2. Seismic Study

Seismic analysis showed that the subsurface area is made up by Weathered Granite Grade VI (sandy soil) which is silty to clavey sand materials with gravels. It also showed low velocity which was 500.0 ms-1. This indicates that the layer is a potential weak zone that is susceptible to slope failure. Weathered Granite Grade IV was discovered at 9.8 m depth with 1975.7 ms-1 of velocity value. This layer is a medium dense to dense overburden material. Detail of seismic result is shown in Table 4.

Table 4: Summary of seismic survey test

Depth (m, BGL)	Velocity (m/s)	Type of Soil	Consistency of Soil	SPT-N Value (Decourt, 1995)	Allowable Bearing Capacity (BS8004, 1986)
0 – 9.80	500.0	Top soil/Weathered Granite Grade VI	Loose to medium dense overburden material	4 - 30	75 - 100
9.80 – 12.50	1975.7	Weathered Granite Grade IV	Medium dense to dense overburden material	10 - 50	100 - 300

Note: BGL = below ground level

3.3. Laboratory Results

Laboratory testing can analyze characteristic of soil to identify soil classification and the strength of soil. Type of soil can be categorized by particle size distribution using sieve analysis test. Direct shear box test or triaxial unconsolidation undrained (UU) test was used to measure the shear strength parameters such as the cohesion value and friction angle. The summary of laboratory tests results is tabulated in Table 5.

Table 5: Summary of soil classification and mechanical properties

Type of test			Result
Soil Classification Test	Particle Size Distribution	Gravel (>2mm)	28.53 %
		Sand (0.06-2mm)	11.96 %
		Silt + Clay (<0.06mm)	59.51 %
	Atterberg Limits	Liquid Limit (LL)	38.9
		Plastic Limit (PL)	32.1
		Plasticity Index (PI)	6.8
	Moisture Content (%)		12.3
	Specific Gravity		2.62
	Units Weight (kN/m³)		16.5
	Soil Classification Based on BSCS		Gravelly SILT of Intermediate Plasticity, MIG
Mechanical Properties Test	Direct Shear	Friction Angle (°)	21
		Cohesion (kN/m²)	0

3.4. Slope/W Analysis

SLOPE/W analysis was processed based on geophysics analysis; resistivity and seismic as well as laboratory testing. From this analysis, the slope was predicted to be unstable based on FOS value which was 0.186 according to the guideline of slope stability. Table 6 shows the parameters of SLOPE/W analysis that generates FOS as shown in Figure 4.

Table 6: Parameters of SLOPE/W analysis

No. of layer	Type of soil	Note	Unit weight	Cohesion	Friction angle
1	Weathered Granite Grade IV to V	Above groundwater level/perched water	16.5 kN/m^3	0.0 kN/m^2	21°
2	Saturated Sandy Clay (wet soil)	Below groundwater level/perched water	17.8 kN/m^3	5.25 kN/m^2	23°

From the geophysics analysis, Weathered Granite Grade V with RQD values of 25% to 50% was detected at the surface of the slope. The Sandy CLAY that has SPT-N values from 1 to 26 was discovered at 5.0 m to 10.0 m depth. Factor of safety for the slope was 0.186 which is less than 1.0 indicating the instability of the slope condition. The actual slope circle failure has already taken place at the study site and the soil nailing was installed to prevent further slope failure. The study area was also experiencing soil erosion on the surface due to the existence of small gully that has developed previously. Following these observations, erosion control measures should be carried out to prevent or reduce movement of eroded soil sediments off-site or land. The controls often involve the creation of a physical barrier, such as vegetation cover or rock, to absorb some of the energy of water that is causing the erosion.

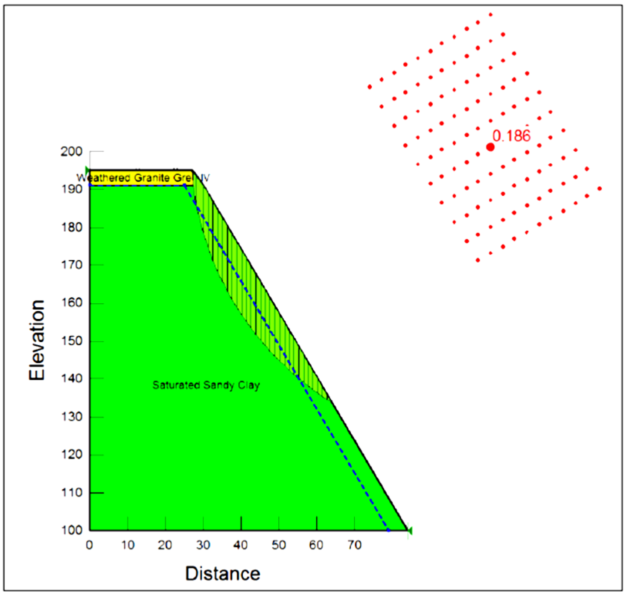

Fig.4: FOS model of study area.

Constant monitoring should be carried out on existing slope to prevent the recurrence of slope failures. Field monitoring provides the information and new insights on the condition of the slope [18]. The existence of groundwater level has been found at a depth of 10.0 m from ground level. During rainfall, the possible increase of groundwater level can reduce the strength of soil, thus this can affect the stability of the slope [19]. In previous cases of slope failures, a very high water table was identified as the most common cause of slope failure.

The stability of a soil-nailed system throughout its design life needs to be assessed. Its performance should not exceed a state at which failure mechanisms can form in the ground or within the soil-nailed system, or when movement of the soil-nailed system can lead to severe damage to its structural elements or nearby structures and facilities. For this area, the design of a soil-nailed system should be ensured that there is an adequate safety margin against all the perceived potential modes of failure. The environmental conditions should be investigated at the design stage to assess their significance in relation to the durability of soil nails. Appropriate measures should be applied to the soil nails such that an adequate safety margin of the soil-nailed system can be maintained throughout its design life. Doing so, the risk of slope failure in the study area can be minimized.

4. Conclusion

Slope stability analysis using geotechnical software provides an in -depth understanding of the physical properties of the subsurface factors that affect slope stability. From the study, it can be concluded that the value of plasticity of the soil material can affect the value of FOS. The results showed that the FOS value was less than 1.0 due to a decrease in cohesion and friction angle which indicated that the slope was not stable. The occurrence of groundwater at the slope area was detected by 2D electrical resistivity. This was further confirmed through the seismic velocity models that were developed using geophysical seismic refraction survey which is also an important geophysical method for slope stability studies. Through this assessment, the stability of the slope can be determined to prevent re-occurrence of slope failure and landslide.

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