Geophysical method exploration for slope failure investigation

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Abstract. A combination of seismic refraction survey, electrical resistivity method and integration with borehole method has been used for ground exploration to study the slope surface failure along the study area at Kayangan Height, Selangor. This study focuses on investigating the possible cause of the slope failure at the area. By necessity, non-destructive method like electrical resistivity test is the most suitable method as this method can determine the subsurface water conditions. Meanwhile, seismic refraction test is able to determine the type of subsurface layers and level of bedrock. Seismic refraction test can guide the borehole drilling works which can provide borelog data. Based on the study, seismic tomogram and 2D resistivity imaging results provide complementary information to each other. The existing geotechnical borehole logs refined both seismic and 2D resistivity results. Therefore, the study shows that the electrical resistivity test, seismic refraction test and borelog data in combination, could be an effective tool and cost effective for slope failure investigation.

1. Introduction

Other The consequences of individual slope failure are generally not as spectacular as the consequences produced by earthquakes, major floods, or other natural catastrophes [1]. In recent times, slope stability has become one of the most significant factors in geotechnical engineering [2]. Various methods have been implemented around the world. However, in Malaysia, the slope failure problems during monsoon seasons are yet to be solved. Among the various methods used to address the slope stability problem, geophysical methods are one of the more reliable methods for solving matter. Many geophysical tools exist to investigates slopes and to establish non-homogeneous material, boundaries and material’s properties. According to [3], [4], [5] and [6], geophysical method such as the seismic methods can be practically adopted to determine the internal distribution of materials within a slope, identifying sliding surface geometry, water effect on slope, landslide material physical properties and mass movement. Furthermore, geophysical methods can be applied in identifying thickness of the unstable slope, measure water content, as well as acknowledge the weathering grade of the soil or rock mass [7].

Seismic refraction is one of geophysical methods that is used to investigate the subsurface profiling via generating the arrival time and offset distance to identify the velocity value of the ground’s elastic disturbance [8]. This method is able to produce a continuous subsurface profile comprehensively in a relatively low cost within a short duration of time [9]. It produces P-wave velocity values which are able to measure the bedrock profiling approximately and also the geological features [5]. However, the effectiveness of seismic P-wave velocity is normally affected by density, lithology, porosity, lithification, pressure, fluid saturation and anisotropy of the geomaterials. According to [10], lithology,
Porosity and interstitial fluids of geomaterials can influence the success of interpretation of subsurface profile based on the seismic P-wave velocity contrast. Moreover, it is also able to characterize the properties, for example, material stiffness or compaction, geological layering and porosity [6].

Meanwhile, electrical resistivity imaging is one of the popular geophysical methods to investigate sub-surface strata. Many researchers use it to identify the bedrock depth of bedrock [11], [12], [13]. Electrical resistivity method functions by producing different values for different geological materials. Hence, the result depends mainly on variation in the amount of water content as well as amount of dissolved ion in water [14]. Other words, the method is used to acknowledge zones with different electrical properties which represent different geological strata [1]. These methods were also used to correlate subsurface material in between existing geotechnical borings at the study area. The drilling method will represent only single point information in the lateral space of actual drilling location. Thus, the main objective of this study was to investigate the possible cause of the slope failure by using seismic refraction test and 2D electrical resistivity imaging survey in combination with borehole data.

2. Methodology

2.1. Study Area
This study investigates the slope failure located at Kayangan Height, Selangor. According to the geological map Department of Mineral and Geosciences Malaysia, the study area is underlain by intrusive sedimentary rock. Referring to the geological map, the location falls under Kuala Lumpur Limestone which is overlain uncomfortably by the more gentle Carboniferous to Permian Kenny Hill Formation, which were estimated to be in the range of 1200 m to 1500 m thick that covered in several places notably towards the south of Kuala Lumpur, starting from Petaling Jaya and Puchong to Kajang and Putrajaya [15]. Based from the observation at the existing site, the failed downslope consisted of cut and fill (more fill than cut) slope on the previous slopes. As shown in Figure 1, the slopes slipped downward and flowed onto the roads.

![Figure 1: The slope failure at Kayangan Height, Selangor](image-url)
2.2. Field Test Layout
Throughout the study area surveyed (Figure 2), there are two survey lines of seismic refraction test and three survey lines of electrical resistivity test that was perpendicular of these. Meanwhile, six boreholes were drilled along the survey lines in the study area. The boreholes drilling were required to determine the soil and rock properties. Five boreholes were drilled at different locations of the slope failure area. However, only five numbers of the boreholes were chosen due to the significant data observed. The chosen BH1, BH3, BH4, BH5 and BH6 were located near to the seismic refraction and also resistivity survey lines as in Figure 2.

![Figure 2: Survey line of seismic refraction, electrical resistivity imaging and boreholes along the slope failure area at Kayangan Height, Selangor](image)

2.3. Seismic Refraction Survey
Seismic refraction survey produces the result of compressional wave (also known as primary velocity, \(v_p\)). The data are obtained achieved via site testing when the data are recorded by the ABEM Terraloc MK6 seismograph. The subsurface profile was investigated based on linear and delay time analysis. Test was conducted on site using 28 Hz vertical geophones, two refraction cables with 12-foot takeout, a sledgehammer and a steel plate. Each seismic line consisted of one overlapping geophone. The geophones are spread nominally within the spacing of 5 m for a total spread length of 115 m. There are five shot points used per spread as the distance is considered far enough to refract the deepest image. The first arrival times of the seismic data was picked and the seismic refraction data were processed using the OPTIM software [16].

2.4. 2D Electrical Resistivity Test
For 2D electrical resistivity test, there are several main equipments that need to be set properly in order to obtain the resistivity data. Each 2D resistivity survey line consisted of a single spread of 41 stainless steel electrodes nominally spaced 5 m apart for a maximum total spread length of 200 m. The pole-dipole array was used with roll-along technique. A least-squares inversion of the resistivity data was conducted using a finite element mesh with surface topography to generate a 2D model of resistivity versus depth or elevation.
3. Result

3.1. Seismic Refraction Velocity

The seismic tomogram represents approximate geological sections along the surveyed area. Each tomogram represents varying velocity as in Figure 3. The seismic tomography in Line 1 (SL1) consisted of two boreholes results, BH1 and BH6. The velocity value of Line 1 shows generally low velocities with values ranging from 300 m/s to 850 m/s at the depth of 0 m to 7 m below ground level. According to [17], the velocity values vary from 300 m/s to 1800 m/s indicating that the subsurface condition consisted of clay soils. From the borehole result in BH1, the site is underlined by clay at the depth of 0 m to 7 m. Similar to BH6, the subsurface condition was characteristic for clay soils at the depth of about 0 m to 7.5 m.

Meanwhile, the underneath layer of Line 1 has velocity values more than 3200 m/s which is considered as hard layer. By comparing BH1 and BH6, it shows that the hard layer was found approximately at the same depth which is at 7 m and 7.5 m respectively. The SPT N-value generally reached 50.

As shown in Figure 4, there is only one borehole (BH4) data situated on Line 2 (SL2). The borehole data reveals sand and clay soils at the depth of about 0 m to 12 m while it reaches hard layer at the depth of 12 m as per shown in Figure 11. The velocity value exhibits a range between 300 m/s to 1800 m/s which reveal that the subsurface condition is clay soils [17]. Besides, the velocity value more than 3200 m/s is considered as hard layer.

![Figure 3: The seismic tomography for SL1](image-url)
3.2. 2D Electrical Resistivity Imaging

Results of the 2D electrical resistivity imaging survey along the slope failure are presented in images as shown in Figure 5 to Figure 7 respectively. The 2D electrical resistivity images of the study area show the soil layers underneath the cable line. Each of the colours represents the different resistivity value. The value of the resistivity image could be referred to the resistivity index [2]. The resistivity value is marked by inverse model resistivity colours.

The 2D electrical resistivity image of Line 1 (RL1) shows that the subsurface consists of low resistivity value of below 200 ohm.m and interpreted as low stiffness or loose soil. It was underneath the line together with the location of the BH1 and BH4. Based on BH1 and BH4, the soil profile indicated silt, clay and sandy soils. Meanwhile, the hard layer from BH1 and BH4 was found to be different the depth of 7 m and 12 m respectively. Very low resistivity (< 30 ohm.m) is depicted with thickness at 5 m from the ground surface along the survey line which can be interpreted as saturated soil.

The saturated zone represented by blue colour is due to the soil having high moisture content which reduced the resistivity value. This is the area where the shallow slope failure occurred. It is because of the reduction in soil strength and it experience saturation. There are a lot of boulders with high resistivity value of >4000 ohm.m between BH1 and BH4. Besides, the resistivity image of Line 2 (RL2) shows that the subsurface dominantly consists of high resistivity value which is more than 1000 ohm.m. Consequently, the soil could be classified as stiff soil or hard material. This area is located along the toe of the slope. However, the presence of wet soil conditions in the survey line RL2 has resistivity values ranging from 100 ohm.m to 200 ohm.m. For resistivity image Line 3 (RL3), it shows that the subsurface layer consisted of high resistivity value which represent hard layer in the profile. However, a few cavities identified near the subsurface due to water presence produce values ranging from 100 ohm.m to 200 ohm.m. Nevertheless, overall strata are considered as hard layer as seen from the high resistivity values produced by this test.
Figure 5: The alignments of resistivity lines as per in site map for RL1

Figure 6: The alignments of resistivity lines as per in site map for RL2

Figure 7: The alignments of resistivity lines as per in site map for RL3
3.3. Borehole Data
Boreholes data are obtained from the borehole drilling test conducted at the site. It is a destructive site investigation method for identifying soil and rock properties. Standard Penetration Test (SPT) was carried out in the same location of the borehole in at 1.5 m of the drilling.

Referring to Figure 8 to Figure 10, it indicates the soil depth, soil description and SPT N-values for each borehole as observed in geotechnical boring logs.

**Figure 8**: SPT N-value of BH1 and BH3

**Figure 9**: SPT N-value of BH4
4. Discussion

This study investigates the integrated method to solve slope failure problem. Methods used are conventional borelog method and geophysical methods which are seismic refraction and 2D electrical resistivity. The results of all methods have been clarified. Conventional borelog method determined the SPT N-value and also the types of soil. Meanwhile, seismic refraction method is to identify the velocity value of subsurface layers. Other than that, 2D electrical resistivity imaging was used in the sub-surface water conditions. Apart from this, wetting surface can be determined. Therefore, by using all of these methods, this study is able to determine the factors that contribute to slope failure. 2D electrical resistivity method can clarify the water condition. Excessive water often leads to cavities in soil. This is an important factor that leads to slope failure. Based on 2D electrical resistivity conducted in the study, the weak zone was located at the lowest slope, where the lowest slope first failed, followed by the next upper slope. The saturated zone with high moisture content gives a significant influence on the resistivity value which caused the failure of the slope [18].

Another probable cause of slope failure due to slip circle/slumping caused by the slope being saturated with water as owing to the constant water flow at the slope base and water accumulation from long periods of rain in the previous month or so. It refers to rainwater infiltration causing saturation to the wetting surface of the area. Infiltration of water will be affected the soil strength of the slope stability. Basically, infiltration is the term applied to the process of water entry into the soil, generally by downward flow through all or part of the soil surface. During infiltration, water moves downward from the saturated zone to the unsaturated zone. Generally, humid tropical zone such as Malaysia experienced high rainfall, often seasonal with high temperatures over a long period [19]. Based on [20], intense rainfall will raise groundwater level rapidly surface of the ground and this would result in a sudden increase in pore pressure which would reduce the shearing resistance of geomaterial and finally lead to a failure.

The variation in weak zone and depth seen in this study may be due to the subsurface materials having gone through additional weathering process. According to [21], rates of weathering were influenced by rock characteristics (types of rock, mineral composition and rock physical condition) and climate (related to temperature and moisture). In a tropical climate country such as Malaysia, the weathering process is much more progressive due to the abundance of rainfall and moisture thus accelerating the transformation of homogeneous subsurface material into heterogeneous subsurface materials.

![Figure 10: SPT N-value of BH5 and BH6](image-url)
According to [22] and [4], the concept of using seismic refraction in locating weaknesses plane (slip surface/shear plane) is that the indicators for weakness are diverse such as a slipped mass will exhibit lower seismic velocity than those underlying in situ strata. The seismic refraction is capable of showing a weathered fractured material by low P-wave velocity while the high P-wave velocity represents the hard layer/bedrock. Hence, the results of all three methods can complement each other.

5. Conclusion
Based on the findings, it can be concluded that the likely downslope failure mechanism is retrogressive failure. The failure begins with the lowest slope. One of the factors that contribute to failure is the weakening of the slope’s soil strength. It is due to heavy and prolonged rainy period. The upslope failure on the other hand, was likely caused by the high groundwater level which weakened the slope. All these factors cause increase in moisture content making it prone to failure. As a conclusion, the seismic refraction test, 2D resistivity imaging survey presented a detailed image of the slope failure condition which is generally in good agreement with the borehole method.

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