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APPLICATION OF ELECTRICAL RESISTIVITY TOMOGRAPHY (ERT) FOR SLOPE FAILURE INVESTIGATION: A CASE STUDY FROM KUALA LUMPUR

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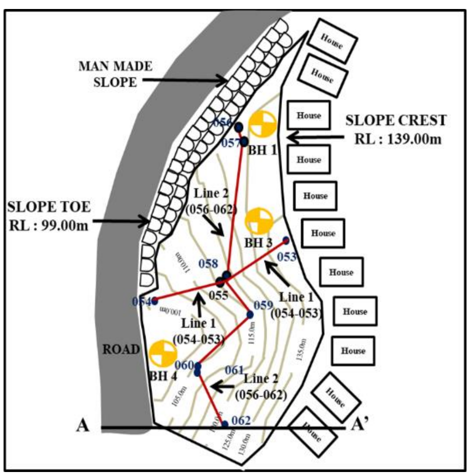
Graphical abstract



Abstract

Electrical Resistivity Tomography (ERT) is a commonly used tool in near surface geophysical surveys to investigate numerous geological, environmental, and engineering problems including landslides. In this study, an electrical resistivity survey was conducted at a landslide area, located in Bukit Setiawangsa, Kuala Lumpur, Malaysia. On 29th December 2012, a luxury hilltop bungalow was split into two when a 43m retaining wall was collapsed after a continuous heavy downpour. 2-D electrical resistivity survey have been acquired along two (2) profiles on the adjacent slope in an effort to mitigate the risks of instability, especially during the rectification work of the failed slope using a Schlumberger Array. It produced useful information about the geometry and characteristics of the study area. In addition, the 2-D resistivity method was performed to determine the behaviour of electrical resistivity underlying the slope areas and estimate the location of the failure surface. Four (4) boreholes were also drilled to obtain engineering properties of the study area such as soil classification, moisture content, soil hardness and SPT N-value. In order to develop the relationship between resistivity and engineering properties, a comparison between soil hardness and the resistivity value was made. Results from the ERT indicated the presence of zones with low resistivity values identified as percolated water in permeable loose soil, which was believed to be the potential slip surface. The findings of this study also showed that the electrical resistivity imaging coupled with borehole drillings were useful tools for the characterisation of slope failure via subsurface profiles and engineering properties of soil.

Keywords: Electrical Resistivity Tomography, borehole, SPT N-value, engineering properties, slope failure

Abstrak

Tomografi kerintangan elektrik (ERT) adalah alat yang biasa digunakan dalam kaji selidik geofizik berhampiran permukaan untuk penyiasatan pelbagai masalah geologi, alam sekitar, dan kejuruteraan termasuk tanah runtuh. Dalam kajian ini, satu tinjauan kerintangan elektrik telah dijalankan di kawasan tanah runtuh, yang terletak di Bukit Setiawangsa, Kuala Lumpur, Malaysia. Pada 29 Disember 2012, sebuah banglo mewah di puncak bukit terbelah dua apabila dinding penahan 43m runtuh selepas hujan lebat. Survei resistiviti elektrik 2-D telah diperolehi di sepanjang dua (2) profil di cerun bersebelahan dalam usaha untuk mengurangkan risiko ketidakstabilan, terutamanya semasa kerja pembetulan cerun yang telah gagal menggunakan teknik susunan elektrod Schlumberger. Ia menghasilkan maklumat yang berguna tentang geometri dan ciri-ciri kawasan kajian. Di samping itu, kaedah kerintangan 2-D telah dilakukan untuk menentukan kelakuan kerintangan elektrik yang mendasari kawasan cerun dan menganggarkan lokasi permukaan kegagalan. Empat (4) lubang gerudi juga telah dikorek untuk mendapatkan sifat kejuruteraan kawasan kajian seperti klasifikasi tanah, kandungan lembapan, kekerasan tanah dan nilai SPT N. Dalam usaha untuk mengkaji hubungan ciri-ciri kerintangan dan kejuruteraan, perbandingan antara kekerasan tanah dan nilai kerintangan ditentukan. Hasil ERT dipercayai menunjukkan kewujudan zon dengan nilai kerintangan rendah yang dikenalpasti sebagai air meresap di tanah longgar yang dapat dipercaya, yang dipercaya sebagai permukaan yang berpotensi untuk gagal. Penemuan kajian ini turut menunjukkan bahawa pengimejan rintangan elektrik ditambah dengan penggerudian lubang merupakan alat yang berguna untuk penciriran kegagalan cerun melalui profil bawah permukaan dan sifat kejuruteraan tanah

Kata kunci: Tomografi Ketahanan Elektrik, lubang gerudi, Nilai SPT-N, sifat kejuruteraan, kegagalan cerun.

1.0 INTRODUCTION

Slope failure is a complex geohazard that has negative consequences on the environment and socioeconomic. According to Petley *et al*. [1] and Marcato *et al*. [2], the investigation of slope failure usually requires boreholes to obtain information on the mechanical and hydraulic characteristics of the study area at a specific point of the subsoil. In order to overcome this problem, the application of the in-situ geophysical method has becomes a prime choice in providing continuous information incorporated on a greater soil volume besides offering a non-destructive method. Geophysical methods, particularly the Electrical Resistivity Tomography (ERT) have been extensively used for landslide investigation for the past 20 years (McCann and Foster [3]; Hack [4]; Suzuki and Higashu [5]; Lapenna *et al*. [6]; Jongmans and Garambois [7]; Drahor *et al*. [8]). The ERT can provide information on the behavior of electrical resistivity underlying the slope areas which is mainly controlled by the lithological nature and variation of water content. Over the past 15 years, the technology improvements in field data acquisition systems and the development of novel algorithms for tomographic inversion have made this technique as an attractive tool for studying slope failure as it provides useful information on the geometry and characteristics of the study area in a quick and cost effective manner (Stummer [9]; Dey and Morrison [10]; Loke and Barker [11]; Loke *et al*. [12]).

Many attempts were made by researchers to explore the phenomenon of electrical resistivity with soil properties. Campanella and Weemees [13] thoroughly discussed that the soil electrical resistivity was affected by its index properties. Griffith and King [14] also stated that the pore fluid and grain matrix of the geological materials greatly influenced the resistivity value.

Abu-Hassanein *et al*. [15] conducted an electrical resistivity survey on compacted clay and observed a positive correlation between electrical resistivity and soil index properties in which the electrical resistivity was also affected by the liquid limit and soil plasticity. Another research by Friedel *et al*. [16] considered that the soil parameters that were determined in grain size analysis could very well replicate the variety of resistivity values obtained from the site very well. The resistivity value can give vary due to the variation of soil physical state. In other words, the soil condition can strongly influence the resistivity value obtained on site because to the soil composition variation is relative to the quantity of geology material, air and water.

In relation to the soil type and gradation, it was found that clean gravel and sand had a relatively high resistivity, while the presence of silt and clay produced low resistivity values. Several studies were done to explore the relationship between the soil electrical resistivity and geotechnical parameters. Sudha *et al*. [17] established a linear relationship between the N-values obtained from the Standard Penetration Test (SPT) and electrical resistivity. However, the relationship was site specific as it was affected by the site geological formation. A thorough study conducted by Bhatt and Jain [18] on the correlation between electrical resistivity and water content of sand stated that electrical resistivity could be a good indirect predictor for water content. Mostafa *et al*. [19] pointed out that the changes in water content and fines content were reflected on the obtained electrical resistivity. As presented in the literatures, electrical resistivity could be considered as a promising quick and easy method for measuring water content, soil strength or the variation in them. Still, more efforts are needed to provide a wide range of local relations that is related to the site specific formations.

For this research, a case study was conducted at the Bukit Setiawangsa slope area using the 2D ERT technique along with two (2) profiles in order to investigate the subsurface conditions by determining the soil profile, locating the possible slip surface and identifying the areas with high water content. One (1) of the two (2) lines was along the axis of the slope failure, whereas the other line was across the axis. The obtained data was then matched with the borehole profile and the relationship between the resistivity values and the engineering properties of the soil was developed.

1.1 Basic Theory of Electrical Resistivity

Prior to outlining the methodology used, it would be gainful to describe the basic electrical resistivity theory. The electrical resistivity method relies on determining the resistance underneath the earth's surface. The measurement of resistance is normally made by allowing the current (I) to flow through the subsurface.

In this case, the electrical resistivity is calculated according to the following formula, which is based on Ohm's Law:

$$R = \rho\left(\frac{L}{A}\right)\Omega$$

Where ρ = Electrical Resistivity
L = Length in meters (m)
A = Area in square meters (m2)

When current (I) is applied into the ground and the potential difference between the two ends of the ground is measured using voltmeter in volts (V), the resistance (R) of the ground is equal to the ratio of the voltage applied to current (V/I). The resistance (R) of a conductor is directly proportional to length (L), and inversely proportional to the cross section area (A).

1.2 Geological Setting

Based on the geological map of Kuala Lumpur (Sheet 94) published by the Geological Survey Department of Malaysia, the Bukit Setiawangsa slope was underlain by the Hawthornden Schist of Silurian - Ordovician age, (Tate *et al*.) [20]. The location of the study area was indicated as in Figure 1. The Hawthornden Schist is made up of low grade metamorphic rock ranging from Quartz Mica Schists, Quartz Schists and Graphitic Schists. In general, the presence of these types of rock exhibits geology structures, namely faults, foliations, folds and joints. It is highly possible that these geological discontinuities may be present at the studied area, thus providing a surface water seepage underground, groundwater carriage, and water storage in the rock formation. However, during the electrical resistivity survey (along the resistivity survey line), there was not much indication of geological structure being exposed on the surface.

The topography of the study area is characterised by alternation of steep to gentle surfaces from the top to the bottom of the slope. In general, the bottom of the slope is much steeper than the top. The slope ranges in gradient from 85°-30°. From plan view, the study area is a semicircular-convex slope. The highest elevation is approximately 139m from the reduced level on the crest of the slope while the lowest point is 100m from the reduced levels at the toe of the slope. The most characteristic feature of the slope is the presence of a depression or V-shaped valley in the centre of the slope. This feature is believed to be a former gulley or relict landslide scar. Several houses are located on the crest of the Bukit Setiawangsa slope.

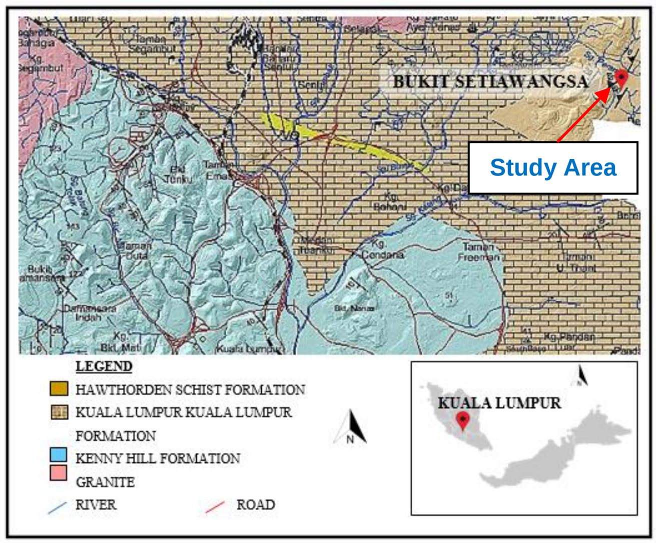


Figure 1 Geological map of Bukit Setiawangsa

2.0 METHODOLOGY

In this study, the borehole drillings were conducted prior to the resistivity survey. Therefore, the alignment of resistivity lines was proposed based on the location of the boreholes as in Figure 2. Figure 3 shows the side view of the failure area.

2.1 Borehole Drilling

Four (4) boreholes were drilled to determine the soil properties using Rotary Wash Boring Method at different locations of the slope failure area. However, only two (2) boreholes, namely BH1 and BH3, located near to the resistivity survey line as shown in Figure 2, were chosen due to the significant data observed. Standard Penetration Test (SPT) was conducted to determine the bearing capacity of the soil. Disturbed and undisturbed soil samples taken from the boreholes were used for physical and mechanical purposes in the laboratory.

2.2 Electrical Resistivity Tomography (ERT) Measurement

The resistivity measurement covered two (2) intersected lines (Line 1 and Line 2 in Figure 2. The resistivity of Line 1 (L1) was laid out from the down slope to the up slope by intersecting Line 2 (L2) which was approximately near to the centre of both lines. The resistivity survey of L1: 054 – 053 was performed using 2.5 m of equal electrode spacing with a total profile length of 100 m while the resistivity survey of L2: 056 – 062 was performed using 5.0 m of equal electrode spacing with a total profile length of 200 m. The estimated depth of penetration was varied up to 22m depth for L1, and 43m depth for L2 from the gently to steeply undulating ground level.

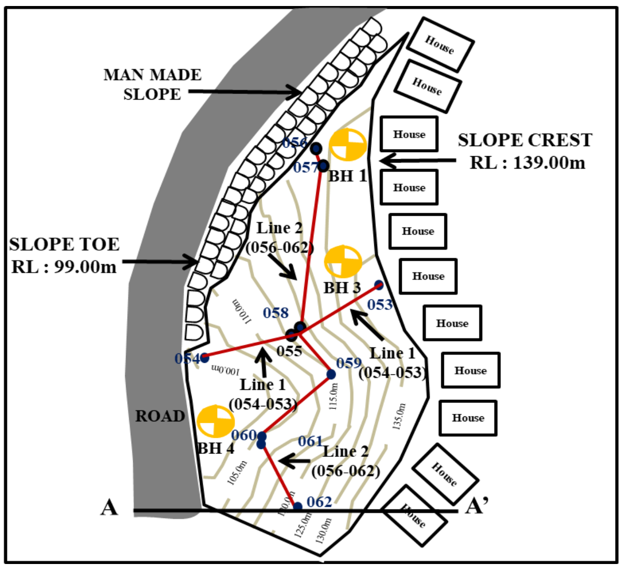


Figure 2 Plan view of the resistivity lines and borehole points arrangement

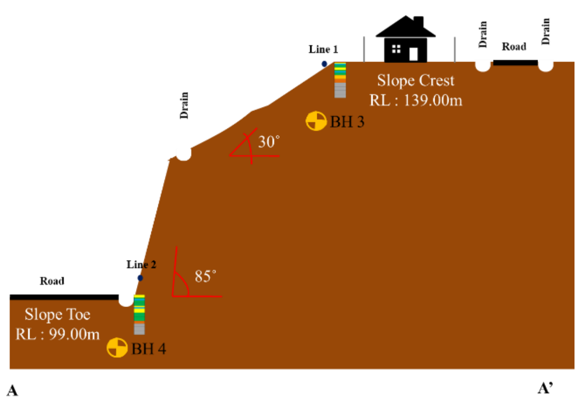


Figure 3 Cross section of line A –A', resistivity line, borehole points and soil profile

The Schlumberger Array was applied in this work due to its dense near-surface cover of resistivity data. In addition, the array was also able to provide a better vertical resolution and clearer image of soil formation for groundwater investigation as mentioned by Hamzah et.al. [21], therefore, provides greater probing depth of profiles within the limited space encountered during the resistivity data acquisition (field measurement). The Electrical Resistivity Tomography survey was conducted with the aid of the ABEM Self Averaging System (SAS) 4000 Terrameter, combined with ES the 10-64 electrode selector.

Data obtained from the field investigation was processed using the Res2Dinv software based on the study by Loke *et al*. [11], to provide an inverse model that approximated the actual subsurface structure. To obtain the resistivity section, the inversion algorithm and the Res2Dinv were used to process the data, as proposed by Loke and Barker [10]. The inversion routine used by the Res2Dinv programme was based on the smooth constrained method due to the target interest and site conditions. According to Loke and Barker [10], this programme divided the two-dimensional model used in the subsurface into a number of rectangular blocks. To minimise the difference between the measured and the calculated apparent resistivity values, the resistivity of the blocks was adjusted iteratively. The latter was calculated by the finite-difference method of Dey and Morrison [9]. From these resistivity images, the soil profiles were interpreted based on the resistivity value.

3.0 RESULTS AND DISCUSSION

3.1 Soil Properties

The engineering properties of the soils were obtained from the laboratory test and boreholes data. Table 1 and 2 show the soil classifications of BH 1 and BH3 obtained from the mechanical and hydrometer analyses and moisture content.

Table 1 Soil classification and moisture content of BH 1

Depth of borehole	Clay (%)	Silt (%)	Sand (%)	Gravel (%)	Moisture Content
1.00	6	50	26	18	17
2.00	10	44	31	15	30
2.50	3	53	37	7	24
4.00	12	63	20	5	34
6.00	10	75	13	2	30
9.00	7	52	23	18	12
10.50	6	69	23	2	26

Table 2 Soil classification and moisture content of BH 3

Depth of borehole	Clay (%)	Silt (%)	Sand (%)	Gravel (%)	Moisture Content
1.00	15	49	26	10	27
1.50	19	48	17	16	21
2.00	29	54	11	6	24
4.00	23	58	13	6	23
4.50	19	62	13	6	19
6.00	4	69	20	7	20
7.50	2	71	25	2	18

The boreholes data showed that the subsurface soil profile was not homogeneous. According to Table 2 and 3, the BH1 and BH3 comprised of high silt content and had an intermediate moisture contents. By referring to Figure 4, the electrical resistivity was found to decrease with the increase of fines content and moisture content. The hardness of the soil can be referred to in Table 3 and Table 4, in which for BH1, the SPT-N value was higher at depth above 6.00m, while for BH3 the SPT-N value was higher at depth above 7.50m, respectively. Thus, stronger soils were found in BH1 compared to BH3.

Table 3 SPT, N-Value of BH 1

Cumulative Depth (m)	Material Description	SPT N-Value
0-1.00	Topsoil: Medium brown silty SAND	33
1.00-2.00	Stiff, light pinkish brown striped with dark brown, sandy SILT with a little gravel	8
2.00-3.00	Very stiff, medium brown spotted with dark reddish brown, sandy SILT with a little gravel	37
3.00-4.00	Very stiff greenish brown dappled with dark brown, SILT	38
4.00-6.00	Hard, light brown streaked with greenish brown sandy SILT with traces of gravel	
6.00-7.50	Hard, light brown streaked with greenish brown clayey SILT with a little of sand and traces of gravel	50
7.50-10.50	Very dense, reddish brown sandy SILT with a little gravel	50
10.50-12.30	Very stiff, milky white brown striped with reddish brown sandy SILT with traces of gravel	50
12.30-15.30	Very poor, highly weathered and fractured, greenish brown, PHYLLITE	RQD 21%
15.30-16.80	Poor, moderately weathered and fractured, greenish grey, PHYLLITE	RQD 35%

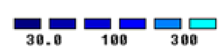
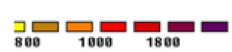
Table 4 SPT, N-Value of BH 3

Cumulative Depth (m)	Material Description	SPT N-Value
0-1.00	Soft, Medium brown, silty SAND	3
1.00-2.00	Stiff, reddish brown mottled with dark brown, sandy SILT with a little of gravel	8
2.00-3.00	Medium stiff, pale brown, clayey SILT with a little of sand and traces of gravel	5
3.00-4.00	Stiff, yellowish brown CLAY with gravel	8
4.00-6.00	Stiff, medium brown, sandy SILT with gravel	9
6.00-7.50	Very stiff, medium, sandy SILT with traces of gravel	32
7.50-9.00	Very dense, milky white dappled with medium brown, silty SAND with traces of gravel	50
9.00-16.50	Very poor, highly weathered and fractured, light greenish brown, PHYLLITE	RQD 8%

3.2 Electrical Resistivity Tomography Analysis

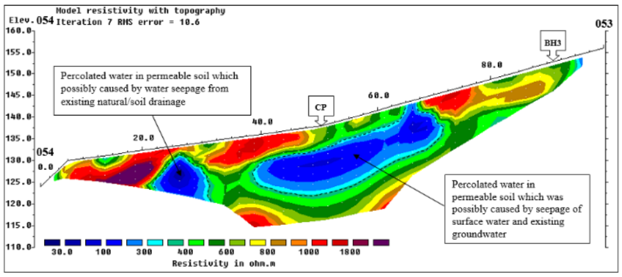
The profiles of the two-dimensional (2D) electrical resistivity section (resistivity subsurface image) are presented in Figure 4a and 4b respectively. The results of the 2D ERT gave the distribution of the electrical resistivity values. The resistivity contrasts, mainly due to the lithological nature of the terrains and water content variation were identified. The results of the 2D resistivity tomography obtained from the L1 and L2 surveys revealed three types of materials as tabulated in Table 5.

Table 5 Summary of resistivity value interpretation in Bukit Setiawangsa area

No	Resistivity value(Ωm)	Resistivity Legend	Interpretation
1	1-350		Water in soil (saturated to moist condition)
2	350-800		Weathered residual soil to moderately stiff of Meta-Sedimentary rock (Grade III, IV and V)
3	800 and above		Moderately weathered to very hard/fresh layer of Meta-Sedimentary rock (Grade I, II and III)

The permeable loose soil percolated with water was detected by the resistivity values ranging from 1 to 350 Ω.m. This resistivity value can be divided into two conditions which were saturated condition (1 – 150 Ω.m) and unsaturated condition/moist (150 – 350 Ω.m).

(a)



(b)

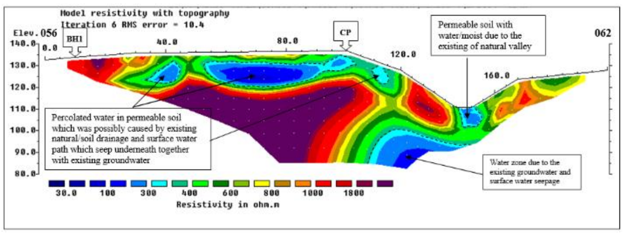


Figure 4 (a) 2D resistivity section for line 1 (East: 054 – West: 053) (b) 2D resistivity section for line 2 (North: 056 – South: 062)

The result for L1 has revealed that the resistivity tomography of the permeable soil percolated with water accumulation was mainly located at the centre and slightly down slope areas within the resistivity image produced while the result for L2 showed that the resistivity tomography for permeable soil percolated with water was mainly located at the left-hand side with a shallow depth and the right-hand side with some greater depths within the resistivity image produced. The low resistivity value obtained for the materials was due to the presence of a percolated water zone. This zone was possibly occurred due to the water seepage of the surface runoff and direct precipitation through the permeable subsurface materials together with its existing groundwater zone. The presence of the percolated water zone will possibly weaken the slope or soil erosion in this area. The water may seep through the permeable soil due to the existing natural valley and drainage. These natural features may allow the water to be heavily concentrated and seeped through the permeable subsurface materials.

The resistivity values that ranged from 350 to 800 Ω.m were interpreted as weathered residual soil to moderately stiff of Meta-Sedimentary rock. These materials were probably consisted of weathered materials from grade III, IV and V. Different grades of weathering soil can be found in a scattered distribution (mainly from the up slope to the centre and slightly down slope area with a various depths from the ground surface for L1 while for L2 the majority were at the left-hand side with a shallower depth and the right-hand side with some greater depths) within the resistivity images. The resistivity anomaly interpretation was verified using the borehole data (BH3). According to the BH3, the subsurface profile materials consisted of medium stiff of sandy silt at 5m depth and gradually shifted to the hard layer at the greater depth.

Finally, the resistivity values from 800 Ω.m and above can be interpreted as hard materials which may consist of gravel, boulder, dense and dry soil, non-cohesive soils and rock fractures. These materials were probably derived from the existence of weathered bedrock (Grade I, II and III). Based on the resistivity image produced in Figure 4a, the hard materials zone was located in a scattered distribution (mainly at the down slope and shallow depth of the subsurface profile) in a minor composition. Furthermore, the resistivity images in Figure 4a and 4b also show that the thickness of the existing hard materials varied by possibly up to 5 m and between 10-40 m, respectively. By referring to the geological map in Figure 2 and BH3 results, the type of rock presented in this area was identified as meta-sedimentary rocks with a particular reference to phyllite.

3.3 Determination of Slip Surface

Based on Figure 5(a), the L1 was believed to be highly exposed to slope failure or soil erosion since weak zone was detected. This weak zone was located underneath the centre and near the down slope of the image. This phenomenon may occur due to the surface water seepage which penetrates through the existing permeable material at the existing of natural drain/valley or water path.

According to the Figure 5(b), the L2 consisted of high resistivity anomaly at the left-hand side (10 m depth and beyond from the ground surface). That high anomaly was possibly derived from hard materials (gravel, boulder or bedrock). Hence, the left bottom part of the image was considered stronger compared to the other portions of the section. The localised weak zone was believed to be located at 10 m deep which started from the left side and increasingly thickened toward the right portion of the section. Hence, this part of the section had the potential to become a hazardous zone due to its low resistivity values. The boundary between high and low resistivity value can be interpreted as a weakness plane (slip surface) for any slope failures to occur. Hence, perhaps this area should be protected or strengthened with appropriate geotechnical ground stabilisation techniques in the near future.

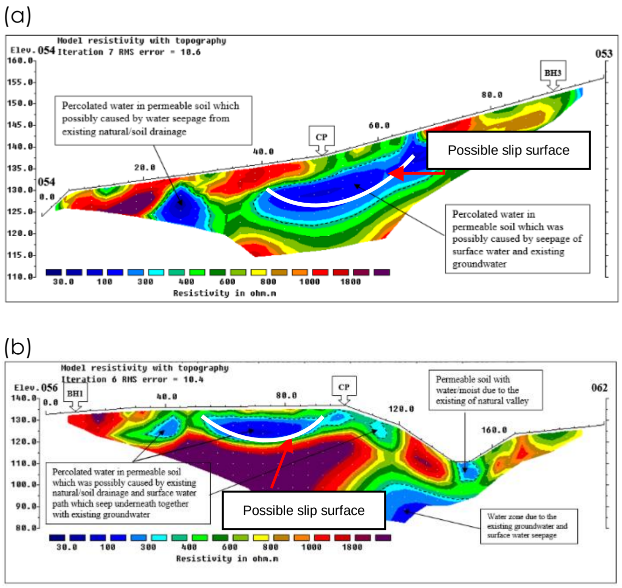


Figure 5 (a) 2D resistivity section for line 1 (East: 054 – West: 053) (b) 2D resistivity section for line 2 (North: 056 – South: 062)

3.4 Comparison of Resistivity and Soil Hardness Value

A comparison between the resistivity and soil hardness was made and tabulated in Table 6. It showed that the resistivity value increased with the increment of soil hardness and SPT N-value.

Table 6 Classification of soil hardness based on SPT N- and resistivity value

Soil hardness	SPT N-value	Resistivity value (Ω.m)
Soft	0-3	0-30
Stiff	5-9	30-100
Very stiff	32-50	100-400
Hard	>50	>400

Correspondingly, the results showed a good agreement between the resistivity and borelog profiles. In light of this, the subsurface with high resistivity values were interrelated to the hard soil as well as the low resistivity value which fitted to the soft soil material. Furthermore, the results were also similar with the findings in the literature by Hatta and Syed Osman [22] where a good correlation was found between the resistivity and soil properties. The obtained results demonstrated the possibility of using the electrical resistivity survey as a site investigation tool to extrapolate the soil formation in between the boreholes with a fair degree of accuracy

4.0 CONCLUSION

A case study on a slope failure from Bukit Setiawangsa, Kuala Lumpur was presented. On 29 December 2012, a luxury hilltop bungalow was split into two when a 43m retaining wall collapsed after a continuous heavy rainfall. 2-D electrical resistivity survey have been acquired along two (2) profiles on the adjacent slope in an effort to mitigate the risks of instability, especially during the rectification work of failed slope. This case study showed that the ERT verified by the boreholes and laboratory analysis of the soil samples with respect to grain size distribution and moisture content were a useful tools for the slope failure investigation. In this study, the inversion of resistivity data yielded information on the presence of saturated soil layers which could become the potential slip surface.

Moreover, the resistivity tomography method could be implemented to investigate the failure of wide areas with a minimum number of borehole drillings. A reliable result was obtained throughout this study from the ERT and geotechnical methods. The combination of these methods could be used as guidelines for the investigation of similar slope conditions.

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