Forensic Assessment on Ground Instability Using Electrical Resistivity Imaging (ERI)

Z A M Hazreek\(^{1,7}\), A T S Azhar\(^{2,8}\), M Aziman\(^{3,9}\), S M S A Fauzan\(^4\), J M Ikhwan\(^5\) and M A N Aishah\(^6\)
\(^{1,3,8}\) Faculty of Civil and Environmental Engineering, Universiti Tun Hussein Onn Malaysia, 86400 Batu Pahat Johor, MALAYSIA
\(^{2,7,9}\) Research Center for Soft Soil, Universiti Tun Hussein Onn Malaysia, 86400 Batu Pahat Johor, MALAYSIA
\(^{4,5}\) Geo-Structure Construction, MARA High Skills College, 86400 Batu Pahat, Johor MALAYSIA.
\(^6\) Geotechnical and Geo-Environmental Engineering, Kumpulan IKRAM Sdn Bhd, 43000 Kajang, Selangor MALAYSIA

E-mail: hazreek@uthm.edu.my

Abstract. Electrical resistivity imaging (ERI) was used to evaluate the ground settlement in local scale at housing areas. ERI and Borehole results were used to interpret the condition of the problematic subsurface profile due to its differential stiffness. Electrical resistivity of the subsurface profile was measured using ABEM SAS4000 equipment set. ERI results using electrical resistivity anomaly on subsurface materials resistivity shows the subsurface profile exhibited low (1 – 100 \(\Omega\)m) and medium (> 100 \(\Omega\)m) value (ERV) representing weak to firm materials. The occurrences of soft to medium cohesive material (SPT N value = 2 – 7) and stiff cohesive material (SPT N \(\geq\) 8) in local scale has created inconsistency of the ground stability condition. Moreover, it was found that a layer of organic decayed wood (ERV = 43 – 29 \(\Omega\)m & SPT N = 15 – 9) has been buried within the subsurface profile thus weaken the ground structure and finally promoting to the ground settlement. The heterogeneous of the subsurface material presented using integrated analysis of ERI and borehole data enabled ground settlement in this area to be evaluated. This is the major factor evaluating ground instability in the local scale. The result was applicable to assist in planning a strategy for sustainable ground improvement of local scale in fast, low cost, and large data coverage.

1. Introduction
Generally, forensic assessment in engineering is the investigation of materials, products, structures or breakdown components which may cause injury or property damage. The purpose of engineering forensic investigation is to identify causes of failure for rehabilitation or mitigation purposes or to assist a court in determining the facts of an incident. Engineering forensic assessment process normally begins with investigation and data collection related to the materials, products, structures or components that failed such as inspections, collecting evidence, testing and measurements, developing models, obtaining prototype model and conducting experiments. Meanwhile, geotechnical forensic engineering involves analysis of a project, site conditions, or construction from a geotechnical point of view which can be performed during the design phase (e.g. checking calculations and engineering assumptions) or during or after the construction of the project (e.g. providing quality assurance or
address issues that arise during or after construction). Common related issues involving geotechnical forensic evaluation were ground settlement, slope instability, foundation failure, excavation failure, collapsible soil, soil corrosion, etc. Forensic geotechnical engineering is growing increasingly important in most of the countries where the foundation failures may lead to litigation and even criminal action [1]. Previous classical instruments related used in ground settlement assessment were based on borehole data [2,3,4]. However, the efficiency of the conventional drilling data will decreased due to its high cost, time consuming and limited data coverage. A further constraint on conventional technique was the drilling data will represent only single point information (1-D) at the actual drilling location thus enables some degree of uncertainties due to the boring interpolation especially in a complex geological area [5,6,7]. Hence, lots number of drilling point was needed in order to obtain higher accuracy of the results thus linearly influencing cost, time and duration of the project. Moreover, drilling method will increased site damageability due to its destructive approach during the field measurement. As a result, the solutions to these challenges will require multidisciplinary research across the social and physical sciences and engineering [8]. Hence, geophysical method offers the chance to overcome some of the problems inherent in more conventional ground investigation techniques [9]. Geophysical techniques contributes several advantages such as it can be performed fast and low cost and has the ability to cover greater areas more thoroughly [10,11,12,13].

Several geophysical instruments already applied in slope failure assessment such as remote sensing [14], and seismic methods [4]. However, those geophysical techniques experienced several limitations due to its physics fundamental constraint such as hidden and thin layer, inadequate sources, noisy and involve lots of data reduction thus promoting to increase the results ambiguity. Moreover, the standard performance of individual geophysical method always depends on fundamental physical limitation (e.g. penetration, resolution, and signal to-noise ratio) [15]. Nowadays, electrical resistivity imaging (ERI) has greatly being improved in term of survey coverage, field measurement, processing techniques thus applicable to resolve complex geological structure compared to the previous sounding approach [16]. Previous geotechnical application of ERI has widely related to the subsurface characterization due to the detection of overburden materials, boulder and bedrock [17]. Hence, this study performed a field ERI to investigate the problematic subsurface profile with particular reference to ground settlement thus enabling the enhancement of the ERI prospect as a promising alternative tool in ground instability assessment.

2. Materials and Methods

2.1 Geologic setting
The general geology of Malaysia has been well documented [18]. Bedrock of this area was formed by intrusive rock which possibly consists of acid intrusive of granitic rock as referred to Figure 1. In general, the present of this type of rock exhibits geology structures, namely joint and fault. Those geological discontinuities may highly possibly presents at the studied area thus provide a weak zone due to the surface water seepage, groundwater carriage, and water storage in rock formation. During the field observation, it was found that this area was formed by granite rock which being confirmed thru field observation at the nearest existing rock outcrops. However during the localize site observation, there is no indication of geological structure exposed on the surface since the actual localize of the 2-D ERI survey location was historically located on a fill material by approximately 6 meter of embankment height. Based on existing borehole results, this area consist of a clay, silt, organic decayed wood, sand and gravel.
2.2 Electrical resistivity method
Electrical resistivity imaging (ERI) was performed using the ABEM Terrameter SAS 4000, combined with ES 10-64 electrode selector. A single line of electrical resistivity was performed across the problematic study area. Testing configuration was based on Schlumberger array using two (2) resistivity land cables, forty one (41) numbers of electrode and forty two (42) numbers of jumper cable. Equal electrode spacing of 3.0 m was used for all 41 electrodes producing total electrical resistivity survey length of 120 m. Field arrangement of the electrical resistivity imaging was given in Figure 2. Schlumberger array was used during the data acquisition since it able to provide dense near-surface cover of resistivity data. As reported by [19], the array provides a good vertical resolution and can give a clear image of groundwater and sand-clay boundaries as horizontal structures. Furthermore, the array able to provide greater depth of subsurface profiles within limited spaced area during the resistivity data acquisition. Raw data obtained from data acquisition were firstly being processed using commercialize RES2DINV software of [20] to provide an inverse model that approximates the actual subsurface structure. The inversion algorithm of RES2DINV was used to process the data, as proposed by [21] in order to obtain the 2-D resistivity section. Finally the 2-D electrical resistivity image and borehole SPT (N) result was presented using commercialize SURFER 9 software.

Figure 1. Geology of the study area [18].

Figure 2. Field arrangement of electrical resistivity imaging (ERI).
3. Results and Discussions

All results representing electrical resistivity and borehole information was given in Table 1 and Figure 3 respectively. Result from localize electrical resistivity value (ERV) and borehole data was analyzed and presented in Figure 3. Due to ERV limitation, borehole result was used to verify the ERI result and interpretation. The properties of ERV can be found to be dissimilar even for the same particular type of geomaterial in many past references. Moreover, conventional reference tables of geomaterials used for anomaly interpretation sometimes was difficult to decipher due to its wide range of variation and overlapping values [22]. As a result, a strong verification is vital to explained its behaviour which otherwise have been traditionally conclude based on a qualitative approach depending on the experience of the expert [23]. Soil resistivity value can be varied due to the variation of soil physical properties such as moisture content, densities, void ratio, porosity and grain size fraction [23,24,25,26,27,28]. Moreover, the success at any site investigation works is based on the integration of method [29].

| Depth, m | Lithology description                  | Standard penetration test, SPT (N) value | Electrical resistivity value, ERV |
|----------|----------------------------------------|----------------------------------------|----------------------------------|
| 0.00 - 0.30 | Top soil: CLAY with sand                | -                                      | -                                |
| 1.50 - 1.95 | Soft to firm CLAY with gravel           | 4                                      | 59                               |
| 3.00 - 3.70 | Soft to firm CLAY with gravel           | 4                                      | 55                               |
| 4.50 - 4.94 | Organic Decayed Wood                   | 15                                     | 43                               |
| 6.00 - 6.45 | Organic Decayed Wood                   | 9                                      | 29                               |
| 7.50 - 8.20 | CLAY                                   | 5                                      | 24                               |
| 9.00 - 9.45 | Very soft CLAY                         | 2                                      | 24                               |
| 10.50 - 11.20 | CLAY with sand                      | 3                                      | 26                               |
| 12.00 - 12.45 | Soft to firm CLAY with sand         | 4                                      | 30                               |

Figure 3. Electrical resistivity section with localize SPT (N) and ERV.

A line of electrical resistivity imaging (ERI) was performed exactly on the existing ground settlement at the housing area. The ongoing settlement has affected the existing nearby
structure thus creating hazardous to the living community. Generally, it was found that the subsurface profile consist of weak materials (1 – 100 Ωm) and moderately stiff material (> 100 Ωm) as shown in Figure 3. The resistivity image has successfully map the subsurface profile with a maximum depth of up to 24 m using 3 m of equal electrode spacing and Schlumberger array. The existing of low resistivity anomaly detected within the image was possibly due the presence of fine soil percolated with water. Most of the low ERV has been generated due to the presence of clay, sand and silt material consists of different concentration of water content. According to [30], clay and saturated silt, sandy clay and wet silty sand, clayey sand and wet silty sand will produce electrical resistivity value which varied from 0 – 500 Ωm. Most of the image has been dominated by weak material except at the very shallow middle portion of the image which indicates a minor or thin layer of medium stiffness material. Furthermore, verification thru borehole results (BH) and correlation analysis of ERV and BH was found to be in a good agreement. According to Figure 3, groundwater (ERV < 29 Ωm) was detected at depth of ≈ 7 m which been confirm thru borehole result (groundwater level = 7.44 m). According to [31], ERV for natural water in sediment was varied from 1 – 100 Ωm.

Figure 4 shows a further specific analysis of localizes SPT (N) and ERV result in order to investigate the potential zone and caused of the ground settlement occurred in the studied area. According to Figure 4, SPT (N) value has recorded at soft to firm layer (N = 4) at depth of 1.5 m and 3m. Then, SPT (N) value was drastically increased to firm layer (N = 15 & 9) at depth of 4.5 m and 6 m. After that, SPT (N) value was decrease consistently to firm and very soft layer (N = 5 & 2) at depth of 7.5 m and 9 m. Finally, it was found that the SPT (N) value was slightly increased from soft to firm layer (N = 3 & 4) at depth of 10.5 m and 12 m. As referred to Figure 3, ERV has revealed a significant relationship to the SPT (N) value. It was found that the ERV graph trend was close enough to the SPT (N) graph trend due to several reasons. At depth of 1.5 m and 3 m, ERV was recorded highest (59 Ωm & 55 Ωm) due to the existing of coarse soil (gravel) mixing with clay soil as proved by borehole result. Hence, it was proved that the existing of gravel has greatly influence the increment of the ERV compared to the rest of ERV analyzed. Then at depth of 4.6 m and 6 m, ERV was recorded high (43 Ωm & 29 Ωm) due to the existing of organic decayed wood which been verified using borehole data. It was strongly believed that the detection of previous dumping decayed wood layer within the subsurface profile (ERV = 43 – 29 Ωm at depth of 4.5 – 6.45 m) has contribute to the settlement problem of this area. Organic decayed wood may also act as a weakness zone due to its ability to absorbed water thus promoting the settlement occurrences. A projection layer of organic decayed wood (dotted pattern with brown anomaly colour) was able to be predicted using the electrical resistivity imaging result as shown in Figure 3. After that, ERV was continuously decreased (5 Ωm & 2 Ωm) at depth of 7.5 m and 9 m due to the domination of fine soil (clay). Finally, it was found that the ERV has slightly increased (3 Ωm & 4 Ωm) at depth of 10.5 m and 12 m due to the existing of sand particle.

Electrical resistivity value (ERV) was determined by measuring the potential difference at points on the ground surface which caused the propagation of direct current through the subsurface [32]. ERV can be influenced by several factors such as the concentration and type of ions in pore fluid and grain matrix of geomaterials via the process of electrolysis where the current was carried by ions at a comparatively slow rate [33]. In contrast to the coarse soil (sand and gravel), fine soil such as clay consists of high mineral composition (e.g: kaolinite, illite, montmorillonite and vermiculite) due to the rock mineral (feldspars and micas) weathering thus assisting the ease of the current propagation within the soil medium. A soil’s
electrical resistivity value generally varies inversely proportional to the water content and dissolved ion concentration as clayey soil exhibit high dissolved ion concentration, wet clayey soils have lowest resistivity of all soil materials while coarse, dry sand and gravel deposits and massive bedded and hard bedrocks have the highest ERV [11]. ERV was influenced by the soil grain size based on the general relationship that the field ERT was linearly proportional to the amount of coarse soil and inversely proportional to the fine soil content ($\rho \propto \text{CS}; \rho \propto 1/\text{FS}$) [34, 25]. A decrease of ERV was results from an increase of metal ions or inorganic elements in geomaterials [35]. Finally, this study has successfully demonstrated the applicable of ERI in ground instability assessment thus contributing to the decision making regarding the suitability approach of stabilization, remediation or mitigation in this area.

4. Conclusion
The problematic subsurface profile due to ground settlement was successfully being investigated using electrical resistivity imaging (ERI). The geometry and electrical resistivity anomaly distribution has been determined by analyzing ERI data obtained along the settlement zones and the result has shown a good correlation with borehole data. This finding has proved that this approach was applicable to detect and predict the weak features in order to assist the conventional borehole data. ERI was successfully mapped the ground instability which able to extend the surface information observed during the physical mapping. The mechanics and physical characteristics of ground settlement can be easily recognized. The determination of shape and depth of the subsurface weak material which promote the ground settlement are easier and cheaper than with conventional borehole method. The information from the ERI was useful as a decision making regarding the most suitable rehabilitation and mitigation approach which may applied afterward. This geophysical method is suitable for our sustainable ground investigation since it can reduce time, money and compliment others conventional method especially by its 2-D surface technique of investigation. The application of ERI in conjunction
with borehole and geological information was effectively being applied to the evaluation of the ground settlement due to its ability to detect the weak layer within the subsurface profile.

Acknowledgment
This work was funded by Universiti Tun Hussein Onn Malaysia (IGSP from Vote U258 and FRGS from Vote 1455). Many thank are due to all research members for their tremendous work and cooperation.

References
[1] Poulos H G 2008 A Framework for Forensic Foundation Engineering From Failure to Understanding: Proc. International Conference on Forensic Engineering (London, 2008)
[2] Anastasopoulos I 2013 Building damage during nearby construction: Forensic analysis, Engineering Failure Analysis. 34 252-267
[3] Russo G, Abagnara V, Poulos H, Small J 2013 Re-assessment of foundation settlements for the Burj Khalifa, Dubai Acta Geotechnica. 8 3-15
[4] Pando L, Pulgar J, Gutiérrez-Clavero M 2012 A case of man-induced ground subsidence and building settlement related to karstified gypsum (Oviedo, NW Spain), Environmental Earth Sciences. 68 507-519
[5] Abidin M H Z, Ahmad F, Wijeyesekera D C, Saad R, Baharuddin M F T 2013 Soil Resistivity Measurements to Predict Moisture Content and Density in Loose and Dense Soil Applied Mechanics and Materials. 353-356 (2013) 911-917
[6] Godio A, Strobbia C and De Bacco G 2006 Geophysical Characterisation of a Rockslide in an Alpine Region, Engineering Geology. 83 273-286
[7] Mauritsch H J, Seibert R, Arndt R, Römer A, Schneiderbauer K and Sendhofer G P 2000 Geophysical Investigations of Large Landslides in the Carnic Region of Southern Austria, Engineering Geology. 56 373-388
[8] Fragaszy R, Santamarina J, Ameikudzi A, Assimaki D, Bachus R, Burns S, Cha M, Cho G, Cortes D, Dai S, Espinoza D, Garrow L, Huang H, Jang J, Jung J, Kim S, Kurtis K, Lee C, Pasten C, Phadnis H, Rix G, Shin H, Torres M and Tsouris C 2011 Sustainable development and energy geotechnology — Potential roles for geotechnical engineering KSCE Journal of Civil Engineering. 15 611-621
[9] Clayton C R I, Matthews M C and Simons N E 1995 Site Investigation (UK: Blackwell Science Ltd)
[10] Khatri R, Shrivastava V K and Chandak R 2011 Correlation between vertical electric sounding and conventional methods of geotechnical site investigation Int. Journal of Advanced Engineering Sciences and Technologies. 4 042-053
[11] Liu C and Evett J B 2008 Soils and Foundation (New Jersey: Pearson International)
[12] Cosenza P, Marmit E, Rejiba F, Jun Cui Y, Tabbagh A and Charlery Y 2006 Correlations between geotechnical and electrical data: A case study at Garchy in France Journal of Applied Geophysics. 60 165-178
[13] Godio A, Strobbia C and De Bacco G 2005 Geophysical characterisation of a rockslide in an alpine region Engineering Geology. 83 273-286
[14] Herrera G, Álvarez Fernández M I, Tomás R, González-Nicieza C, López-Sánchez J M and Álvarez Vigil A E 2012 Forensic analysis of buildings affected by mining subsidence based on Differential Interferometry (Part III) Engineering Failure Analysis. 24 67-76
[15] Mauritsch H J, Seibert W, Arndt R, Römer A, Schneiderbauer K and Sendhofer G P 2000 Geophysical Investigations of Large Landslides in the Carnic Region of Southern Austria Engineering Geology. 56 373-388
[16] Loke M H, Chambers J E, Rucker D F, Kuras O, Wilkinson P B 2013 Recent developments in the direct-current geoelectrical imaging method Journal of Applied Geophysics. 95 135-156
[17] Saad R, Muztaza N M and Mohamad E T 2011 The 2D Electrical Resistivity Tomography
(ERT) Study for Civil and Geotechnical Engineering Purposes Electronic Journal of Geotechnical Engineering. 16 1537-1545

[18] Mineral and Geoscience Department Malaysia, Geological Map of Peninsular Malaysia 1985 Ministry of Natural Resources and Environment.

[19] Hamzah U, Yaacup R, Samsudin A. R and Ayub M S 2006 Electrical imaging of the Groundwater Aquifer at Banting, Selangor, Malaysia Environmental Geology. 49 1156-1162

[20] Loke M H, Acworth I and Dahlin T 2003 A comparison of smooth and blocky inversion methods 2-D electrical imaging surveys Exploration Geophysics. 34(3) 182–187

[21] Loke M H and Barker R D 1996 Rapid least squares inversion of apparent resistivity pseudosection using a quasi-Newton method Geophysical Prospecting. 44(3) 131–152.

[22] Solberg I L, Hansen L, Ronning J S, Haugen E D, Dalsegg E and Tønnesen J 2011 Combined Geophysical and Geotechnical Approach to Ground Investigations and Hazard Zonation of a Quick Clay Area, Mid Norway Bulletin of Engineering Geology and the Environment. 71 119-133

[23] Abidin M H Z, Wijeyesekera D C, Saad R and Ahmad F 2013 The Influence of Soil Moisture Content and Grain Size Characteristics on its Field Electrical Resistivity Electronic Journal of Geotechnical Engineering. 18/D 699-705

[24] Hazreek Z A M, Aziman M, Azhar A T S, Chitral W D, Fauziah A, Rosli S 2015, The Behaviour of Laboratory Soil Electrical Resistivity Value under Basic Soil Properties Influences Earth and Environmental Science. 23 1-9

[25] Abidin M H Z, Saad R, Ahmad F, Wijeyesekera D C and Baharuddin M F T 2014 Correlation Analysis Between Field Electrical Resistivity Value (ERV) and Basic Geotechnical Properties (BGP) Soil Mechanics and Foundation Engineering. 51 117-125

[26] Abidin M H Z, Ahmad F, Wijeyesekera D C and Saad R 2014 The Influence of Basic Physical Properties of Soil on its Electrical Resistivity Value under Loose and Dense Condition, Journal of Physics: Conference Series. 495 1-13

[27] Abidin M H Z, Ahmad F, Wijeyesekera D C, Saad R 2014 Small Soil Embankment Electrical Resistivity Value on its Array, Moisture Content and Density Influences Int. Journal of Geology. 8 9-18

[28] Abidin M H Z, Ahmad F, Wijeyesekera D C, Saad R, Baharuddin M F T 2013 Soil Resistivity Measurements to Predict Moisture Content and Density in Loose and Dense Soil, Applied Mechanics and Materials. 353-356 911-917

[29] Benson R C, Yuhr L and Kaufmann R D 2003 Some Considerations for Selection and Successful Application of Surface Geophysical Methods: The 3rd Int. Conference on Applied Geophysics (Orlando, Florida 2003)

[30] Lee T S 2002 Slope Stability and Stabilization Methods: Geologic Site Investigation (New York: John Wiley & Sons Inc.)

[31] Telford W M, Geldart L P and Sheriff R E 1976 Applied Geophysics (Cambridge: Cambridge University Press)

[32] Burger H R, Sheehan A F and Jones C H 2006 Introduction to Applied Geophysics (New York: W.W. Norton & Company)

[33] Griffiths D H and King R F 1981 Applied Geophysics for Geologist and Engineers-The Element of Geophysical Prospecting (Oxford: Pergamon Press)

[34] Abidin M H Z, Saad R, Ahmad F, Wijeyesekera, D C and Baharuddin M F T 2014 General Relationship between Field Electrical Resistivity Value (ERV) and Basic Geotechnical Properties (BGP) Int.Journal of Integrated Engineering. 6(1) 23-29

[35] Jung Y, Lee Y and Ha H 2000 Application of Electrical Resistivity Imaging Techniques to Civil and Environmental Problems Use of Geophysical Methods in Construction