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Integrated Geophysical Models for Interpretations of Heterogeneous Subsurface Environments

(Model Geofizik Bersepadu untuk Tafsiran Persekitaran Bawah Permukaan Heterogen)

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ABSTRACT

Near-surface characterization can be vulnerable to misinterpretation due to limited resolution and methodological limitations. Validation from different parameters is necessary to substantiate the results and reduce errors during interpretations. This research aims to develop an alternative integrated method of a 2-D cross-plot model to enhance subsurface interpretations based on the model's criteria, resulting in better geological interpretation. Geophysical methods such as electrical resistivity and seismic refraction are utilized in a test model and a case study area to observe the capabilities of the integrated method approach. The goal of this study was to cluster two or more different parameters into a single model for a direct presentation of the subsurface model. This includes the characterization of subsurface properties, data integration using cross-plot analysis, and the development of a 2-D cross-plot model. This method visually represents the relationship between two or more attributes, allowing for the identification of anomalies. In the test model, the lithology consists of sandy silt derived from granitic residual soil, whereas in the case study model, it was dominated by weathered granitic residual soil with the presence of saturated zones. The 2-D cross-plot model provides a comprehensive interpretation where Quadrant, Q1 shows the vulnerable zones for sliding mass bodies. The plane weakness was successfully identified based on the cross-plot model as the weathered zone, and subsurface features were determined. The estimated volume of mass movement was successfully calculated for the case study area based on the determination of the sliding plane. The integrated method of cross-plot analysis along with the development of 2-D cross-plot models proves to be an informative approach for subsurface characterization and enhances subsurface imaging.

Keywords: Creep; cross-plot; resistivity; seismic refraction

ABSTRAK

Pencirian permukaan cetek boleh terdedah kepada salah tafsir disebabkan oleh resolusi terhad dan had metodologi. Pengesahan daripada parameter yang berbeza diperlukan untuk mengesahkan keputusan dan mengurangkan ralat semasa tafsiran. Penyelidikan ini bertujuan untuk membangunkan kaedah alternatif bersepadu bagi model plot-silang 2-D untuk meningkatkan tafsiran subpermukaan berdasarkan kriteria model, menghasilkan tafsiran geologi yang lebih baik. Kaedah geofizik seperti keberintangan elektrik dan seismik pembiasan digunakan dalam model ujian dan kawasan kes kajian untuk memerhatikan keupayaan pendekatan kaedah bersepadu. Matlamat kajian ini adalah untuk mengelompokkan dua atau lebih parameter berbeza ke dalam satu model untuk persembahan langsung model subpermukaan. Ini termasuk pencirian sifat subpermukaan, penyepaduan data menggunakan analisis plot-silang dan pembangunan model plot-silang 2-D. Kaedah ini secara visual mewakili hubungan antara dua atau lebih atribut, membolehkan untuk mengenal pasti anomali. Dalam model ujian, litologi terdiri daripada pasir berlodak daripada tanih baki granit manakala dalam kajian kes, ia didominasi oleh tanih baki granit terluluhawa dengan kehadiran zon tepu. Model plot-silang 2-D menyediakan tafsiran yang komprehensif dengan kuadran, Q1 menunjukkan zon terdedah untuk badan jisim gelongsor. Kelemahan satah telah berjaya dikenal pasti berdasarkan model plot-silang sebagai zon terluluhawa dan ciri subpermukaan telah ditentukan. Anggaran isi padu pergerakan jisim berjaya dihitung untuk kawasan kes kajian berdasarkan penentuan satah gelongsor. Kaedah bersepadu analisis plot-silang bersama-sama dengan pembangunan model plot-silang 2-D terbukti sebagai pendekatan bermaklumat untuk pencirian bawah permukaan dan meningkatkan pengimejan subpermukaan.

Kata kunci: Keberintangan; plot-silang; rayapan; seismik pembiasan

INTRODUCTION

Subsurface characterization can be vulnerable to misinterpretation due to limited resolution and methodological limitations. Proper subsurface characterization requires a wide range of data and observations, and validation from multiple parameters is essential to substantiate the results and minimize errors during interpretation. Complex geological structures or heterogeneous subsurface environments require comprehensive methodologies including data classification, processing, and interpretations. The variation in the topsoil composition has a negative impact on causing extensive and severe damages, leading to foundation failure (Abdelrahman et al. 2021). These issues arise due to the absence of subsurface geological data, often caused by structural features or horizontal differences in stratification (Fat-Helbary, El-Faragawy & Hamed 2019). It is essential to gather comprehensive geological information to gain a better understanding of subsurface behaviors. This process should encompass site characterization to comprehend soil materials and conditions adequately. Multiple techniques exist for examining the geometry and properties of the near-subsurface, broadly classified into intrusive methods (involving boreholes, soil sampling, and laboratory testing) and non-intrusive methods (geophysical methods) (Kayode, Arifin & Nawawi 2019; Yordkayhun 2021; Zaid et al. 2023). Although intrusive methods are commonly employed, they can be costly and necessitate accessible areas. Geotechnical approaches offer valuable data on the mechanical and hydraulic characteristics of the near-subsurface, but their drawback lies in providing information only at specific points within the subsurface (Marcato et al. 2012). Geophysical methods like 2-D resistivity and seismic refraction are crucial for characterizing the subsurface. The methods represent complementary approaches in providing high spatial subsurface resolution associated with the sensitivity of geophysical parameters. Indeed, geophysical methods offer the advantage of being less invasive and capable of providing comprehensive information over a larger volume of soil, which helps overcome the point-scale limitations of geotechnical measurements. The effectiveness of these geophysical methods relies on the existence of significant contrasts in the physical properties among various lithological units (Pazzi, Morelli & Fanti 2019). This contrast allows for better discrimination and characterization of subsurface features, making geophysical techniques a valuable tool in subsurface exploration and assessment. These techniques leverage the differences in physical properties to identify spatial variations in parameters, lithological boundaries, moisture content distribution, and assess the formation and growth of fractures (Pazzi, Morelli & Fanti 2019; Whitley et al. 2021; Zakaria et al. 2022). However, geophysical interpretation may have inherent ambiguity and limited resolution, making it necessary to complement it with correlated geological-engineering information or results from other geophysical measurements (Fisseha, Mewa & Haile 2021). Such cases of deep geological structures or complex reservoir of groundwater or hydrothermal, or geological disasters required a detailed information of geological, mechanical, and hydrogeological properties. Commonly, the interpretations are riley on the qualitative measurement of the inverted models depending on the visual analysis of individuals' datasets. To enhance this interpretation, cross-plot analysis with the development of a 2-D cross-plot model is introduced based on the integration of resistivity/chargeability and velocity values. This method is a visual representation of the relationship between two or more attributes that are used to visually identify the anomalies (Austin et al. 2018; Zakaria et al. 2022). This research work was focused on high-resolution subsurface imaging of geophysical approaches. The preliminary work involved conducting a desk study of the methodologies (test model) with the conceptualize of framework before data acquisition. The geophysical data underwent extensive processing and modelling included data reduction, filtering, qualitative analysis and interpretation. Acquiring multi-geophysical methods with cross-plot of co-located measurement for each datasets reduces the uncertainty in ground model with different sensitivity of geophysical properties. The goal of this method is to cluster two or more different parameters into a single model for direct presentation of subsurface model. The cross-plot model is used to improve the geophysical interpretation of the subsurface and exploit different sensitivities of different methods. The model approaches was implemented in assessing the capabilities to visualise the subsurface structure for slope instability.

MATERIALS AND METHODS

STUDY AREA

Test Model (USM-Rumah Tamu)

The study involves in two areas which are USM-Rumah Tamu and Lojing-Cameron Highland as test model and cases study, respectively. A test model at USM-Rumah Tamu is used to validate the propose method of cross-plot. In general, this method of cross plotting used appropriate pairs of attributes and cluster together allows straightforward interpretations. 2-D resistivity and seismic refraction data were utilised as cross-plot by dividing two individual thresholds of resistivity and velocity. However, defining appropriate threshold values was one of the challenges faced in this work. A borehole record was used to validate the results by analysing the bore log parameters. As the preliminary work, a study area of USM Rumah Tamu was chosen as the test model to validate the method. Table 1 and Figure 1 show the detailed of the survey with a schematic diagram. The cross-plot analysis was implemented at the critical slope area to define the failure plane and estimate the volume of mass sliding.

Case study (Lojing-Cameron Highland)

The study area is situated along the Gua Musang-Cameron Highland highway, featuring slopes with angles ranging from 34° to 35°. This area covers a portion of the Western Belt Main Range, which predominantly consists of granite (Figure 2). Additionally, there are several enclaves of metasedimentary rocks within this region (Raj 2009). The Main Range Granite extends from the western part of the state, spanning western Kelantan up to the state boundaries of Perak and Pahang, as well as the international boundary between Malaysia and Thailand. As reported by Rahman and Mohamed in 2001, Kelantan's igneous rock formations are distributed along the state's western and eastern borders, known as the Main Range Granite and Boundary Range Granite, respectively. The geomorphology of the area shows a reserved forest surrounded by mountainous landscapes. Most of the land in this region is used for farming plantations, making agriculture a crucial part of the local economy. However, a significant issue arises from the fact that many of these plantations are established on slopes, leading to potential ground instability. To investigate this problem, data was collected along the hill-slope topography adjacent to the highway (Figure 2). This particular study site was selected due to the identified instability caused by creeping activities. Through field observations, it was evident that the surface condition of the slopes had been severely disturbed by ongoing creeping activities, with some sections of the soil having already slid. These creeping activities are believed to have affected an estimated soil area measuring approximately 20 meters in length and 30 meters in width from the surface. Consequently, these activities result in a downward movement of the soil, leading to damage on the roads due to the influence of gravity. Furthermore, the instability of the ground motion has caused damage to the concrete drainage at the top of the terrace, making it easier for water to seep into the ground.

In this case study, surveys of 2-D resistivity and seismic refraction were conducted along lines on the terrace of the cut slopes and parallel to the slope's surface (Figure 2). For 2-D resistivity, four survey lines (LR1-LR4) each measuring 100 m in length were installed. The ABEM SAS4000 system and electrodes with a spacing of 2.5 m were used to acquire the data. The data acquisition protocol employed the Wenner-Schlumberger array. Meanwhile, four 115-m 2-D seismic refraction survey lines (LS1-LS4) were implemented, with a geophone spacing of 5 m. The seismic waves were recorded using the ABEM Terraloc MK8 seismograph. Table 2 shows the parameters of the survey lines.

The selection of the minimum electrode spacing and survey line lengths was based on the research objectives and the area's accessibility. Paying attention to the application of survey line arrays during data acquisition is crucial, as it significantly impacts the depth of investigation.

TABLE 1. Geophysical survey of USM-Rumah Tamu

Method	Electrode/Geophone spacing (m)	Total length (m)	Protocol
2-D Resistivity	1.5	60	Wenner-Schlumberger
Seismic refraction	2	46	-

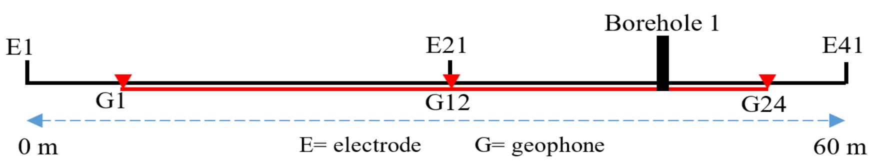


FIGURE 1. Schematic diagram of the layout USM-Rumah Tamu

For this research, the Wenner-Schlumberger array was chosen. Additionally, in geological areas where both geological structures are anticipated, this array provides a favourable compromise when compared to the Wenner array, offering a median depth investigation approximately 10% larger (Loke 2015). Moreover, this array exhibits slightly better horizontal coverage, making it wider in comparison to the Wenner array. The data was processed and interpreted using the Res2Dinv software, which generated a 2-D resistivity inversion model.

During seismic refraction, refracted waves were recorded, and several stacking techniques were applied to increase the signal-to-noise ratio. This involved repeatedly striking the striker plate to produce energy. A total of seven shot points were acquired, providing a dense velocity distribution. Among these, five shot points were inline, while the others served as positive and negative offsets. The inclusion of offsets is crucial for delineating the last layer of the media as it directly impacts the depth of penetration. For more comprehensive information about the seismic refraction layout, please refer to Table 2. The data later processed in Optim software to produce seismic models.

METHODS

Cross-plot analysis offers an alternative approach to integrating various geophysical parameters of co-located measurement. It provides a visual representation of the relationship between two or more attributes, aiding in the visual identification of anomalies (Austin et al. 2018; Hayashi & Konishi 2010; Inazaki & Hayashi 2011). The resistivity and seismic refraction data were subjected to cross-plotting, dividing them into two distinct thresholds known as quadrant limits. Each study area is divided into distinct limit quadrants based on the distribution of

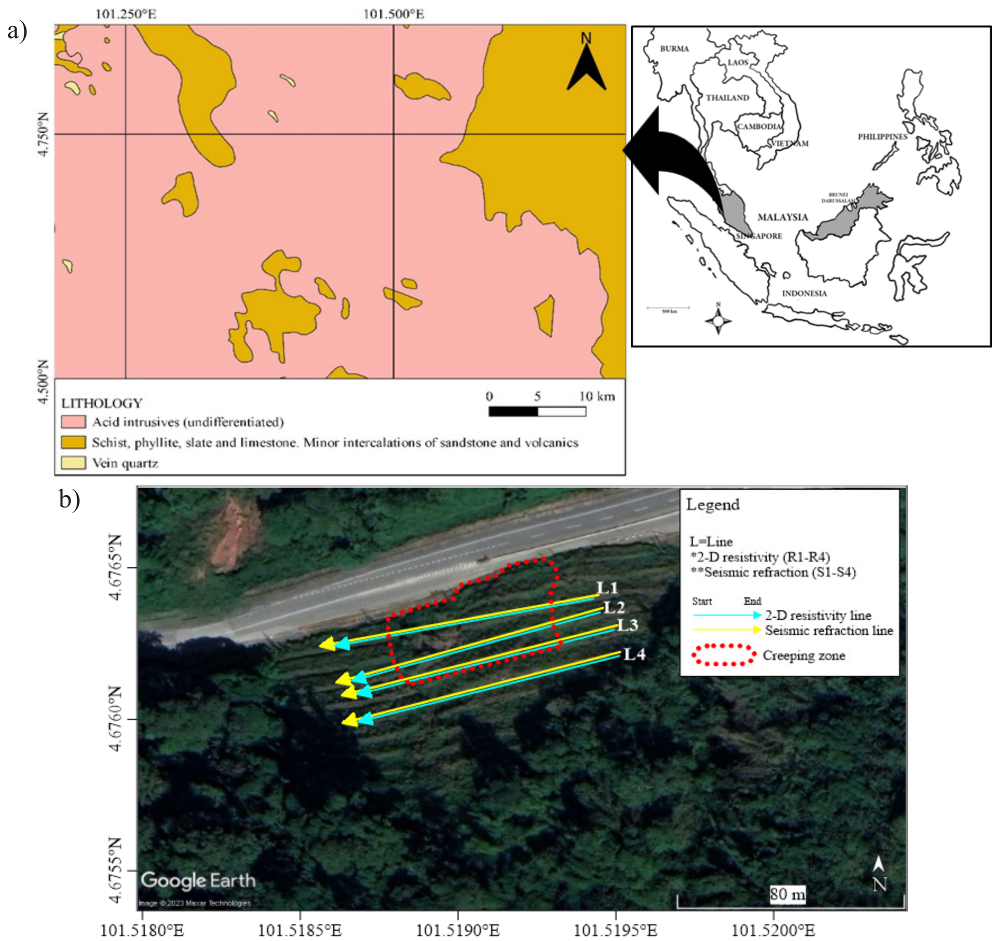
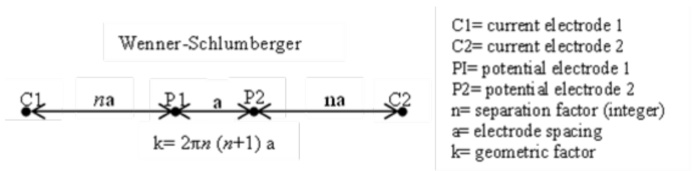
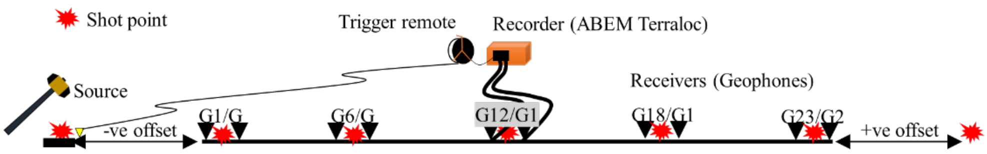


FIGURE 2. Study area; a) General geology of study area (simplified from geology of Peninsular Malaysia, modified after Tate et al. 2009); and b) Survey lines of the study area

TABLE 2. Geophysical survey of Lojing-Cameron Highland

Method	No. of line	Total length	Electrodes/geophones spacing	Array
2-D resistivity	4 (LR1-LR4)	100 m	2.5	Wenner-Schlumberger
Seismic refraction	4 (LS1-LS4)	115 m	5	-
Geometry layout of Wenner-Sclumberger array for resistivity				
Geometry layout of seismic refraction				

resistivity and velocity values determined by geological conditions and lithology. Thus, this method combines two parameters - resistivity and seismic values - derived from geological information. The datum point for each dataset was analysed and found to be nearly in the same position, facilitating the creation of a cross-plot model. The datum point for each result was rearranged in the geometry correction based on the x (distance) and y (elevation), which are in the same position. Subsequently, the gathered data underwent graphical and datum point analysis, with insignificant data being filtered out. Its objective is to amalgamate these parameters into a unified model for direct representation of the subsurface. Instead of analysing the results from each method separately, four-quadrant (Q1-Q4) criteria based on the ranges of electrical resistivity and seismic velocity were introduced. An illustration of a cross-plot criteria is shown in Figure 3 while Figure 4 present the workflow of 2-D cross-plot models. Based on the measured resistivity and seismic velocity at a given location, and where that point falls within the four quadrants (Q1-Q4), the soil type and the vulnerability of subsurface are estimated. The utilization of a cross-plot model enhances geophysical interpretation of the subsurface, exploiting the diverse sensitivities inherent in different methods. Through cross-plot analysis, similar areas and contiguous subsurface properties can be identified based on resistivity and velocity distributions.

RESULTS AND DISCUSSION

TEST MODEL

Figure 5(a) shows the initial models of 2-D resistivity and seismic refraction results. In borehole 1, the SPT-N value showed a variation in the range of 6-19 blows at a depth of <5 m, with soil dominated by silt. The recorded borehole showed increasing SPT-N values from 6-19 blows at a depth of 1.5-3 m, with soil consistency recorded as loose to very stiff material (Figure 5(b)). The resistivity value showed lower distributions at this depth range with values of <150 Ωm, whereas in the seismic profile, the velocity showed increasing values in the range of V_p =400-700 m/s. The SPT-N value showed decreasing soil stiffness from 19 blows to 14 blows at a depth of 3-9 m. The values showing the variation of soil material as sandy silt were present at a depth of 3 m, and silt at a depth of 6-7.5 m, and sandy silt to sand for a depth of 9-12 m. The P-wave velocity distribution is increasing with depth and ranges from 700-1200 m/s. The SPT-N values show increasing soil stiffness with 19-22 blows as very stiff to medium dense. Figure 5(c) shows the overlap between both sets of datum point distribution of 2-D resistivity and seismic refraction models. Both data sets were sorted according to the nearest location (x: distance; y: elevation/depth) of each datum point, as presented in Figure 5(d). The graphical analysis

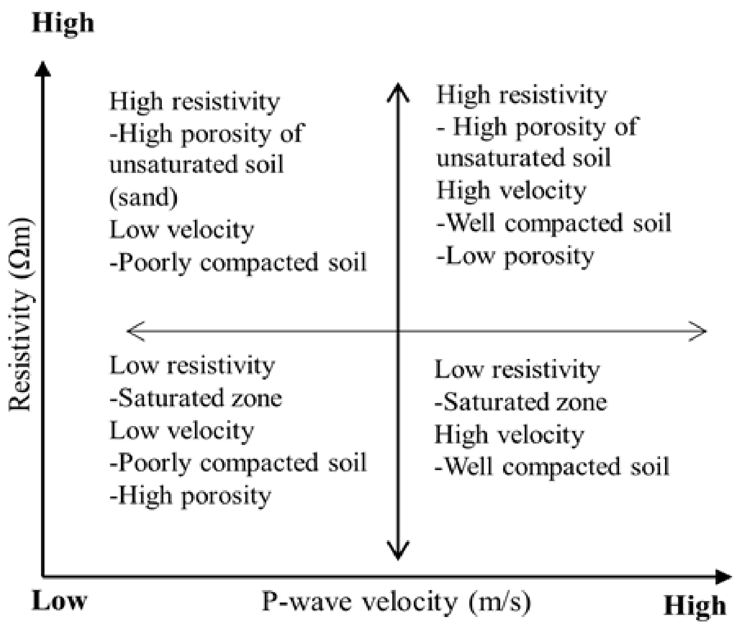


FIGURE 3. Schematic relationship of resistivity-velocity

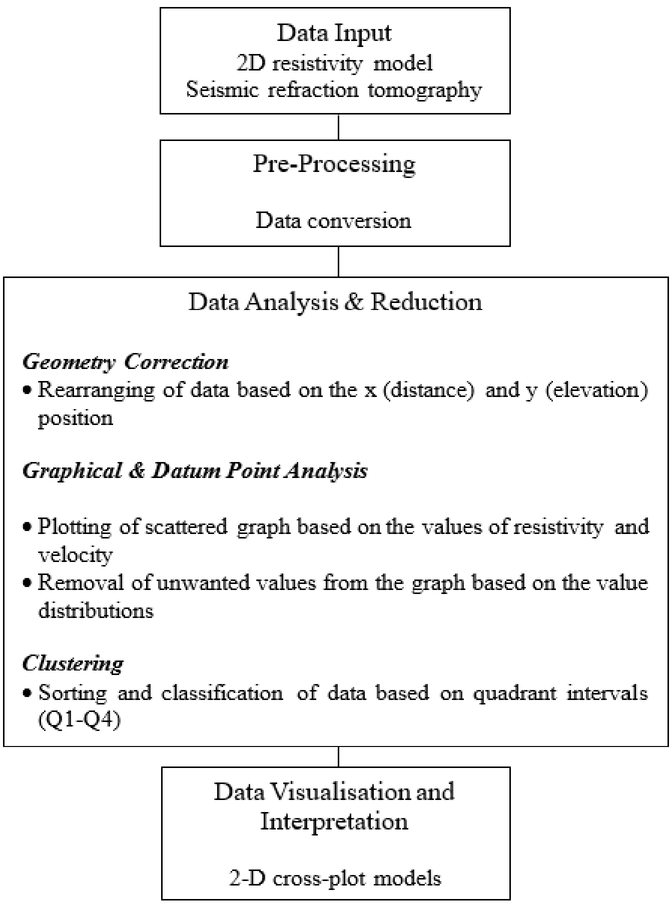
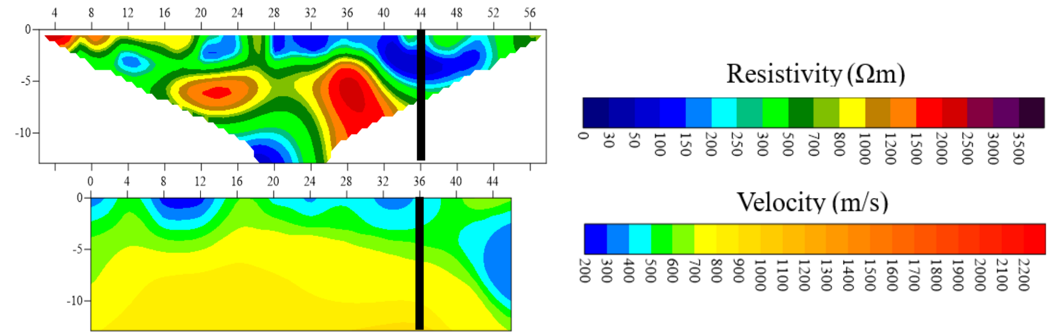
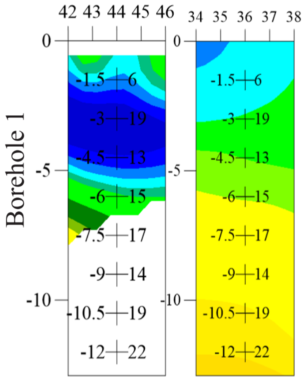


FIGURE 4. Workflow of 2-D cross-plot models

a)

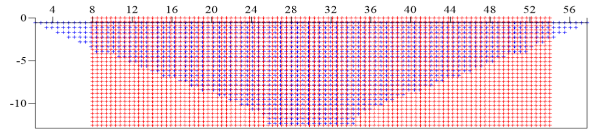


b)

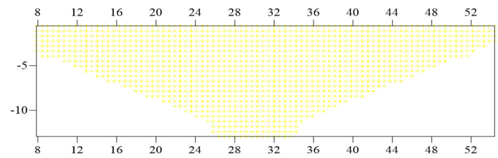


Depth	Soil description	Soil consistency	N-value	Type of soil
-1.5	N/A	N/A	6	N/A
-3	Stiff	High plasticity	9	sandy SILT
-4.5	Loose	N/A	8	SAND
-6	Stiff	High plasticity	10	sandy SILT
-7.5	Stiff	High plasticity	9	sandy SILT
-9	Stiff	High plasticity	11	sandy SILT
-10.5	Stiff	High plasticity	14	sandy SILT
-12	Very stiff	High plasticity	16	sandy SILT

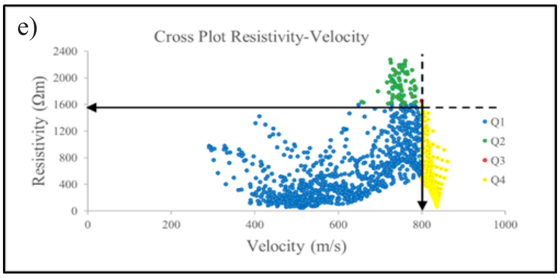
c)



d)



e)



Quadrant	Resistivity (Ωm)	Velocity (m/s)
Q1	<1600	<800
Q2	≥1600	<800
Q3	≥1600	≥800
Q4	<1600	≥800

f)

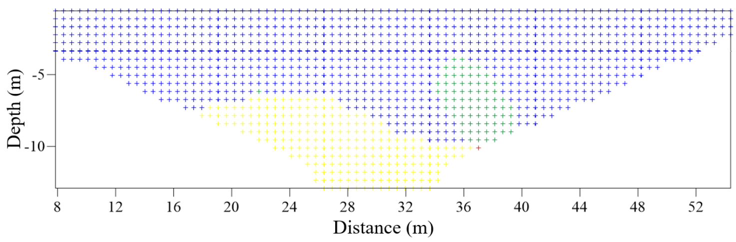


FIGURE 5. The cross-plot analysis based on the integration between 2-D resistivity and seismic refraction models; a) The initial models of 2-D resistivity and seismic refraction; b) The correlated geophysical result with borehole records; c) The overlapped datum point of both 2-D resistivity and seismic refraction; d) The cross-plot datum point of both methods after geometry correction; e) The graphical analysis based on threshold values; f) The example of final output of 2-D cross-plot model

between resistivity and velocity attributes was presented with the assigned threshold value, as shown in Figure 5(e). The threshold value was identified based on the correlated result with borehole records to classify the subsurface layer where resistivity of <1600 Ωm and velocity of <800 m/s were presented as the first (1st) layer of the profile. Above this threshold value was indicated as the second (2nd) layer or hard layer of the profile. Figure 5(f) shows the subsurface of the 2-D cross-plot model, where the 1st layer was classified in the first quadrant (Q1), while the hard layer was presented in the fourth quadrant (Q4). The results show that the integration of different geophysical attributes was successfully achieved based on the position of each data point. The integrated method of cross-plot analysis with the development of 2-D cross-plot model shows an informative method in characterization and enhances subsurface images.

CASE STUDY

Figure 6 shows the graph integration of resistivity and velocity data from line LR4&LS4 to line LR1&LS1. The data was divided equally into four quadrants: Q1, Q2, Q3, and Q4. The threshold values for V_p (velocity) and ρ (resistivity) were set at 600 m/s and 1500 Ωm, respectively, to represent the weathered zone for the soil creep. The quadrants were classified as follows: Q1 (<1500 Ωm, <600 m/s), Q2 (≥1500 Ωm, <600 m/s), Q3 (≥1500 Ωm, ≥600 m/s), and Q4 (<1500 Ωm, ≥600 m/s). The sorting analysis was then applied to extract the values according to their depth and position, aligning them inline with each other. The results were arranged according to the survey line numbering from LR4&LS4 to LR1&LS1, representing the top to bottom of the slope.

Figure 7(a) illustrates the results of the cross-plot analysis for LR4&LS4, with quadrant Q4 being the dominant feature in this profile. In quadrant Q1, lower resistivity (<1500 Ωm) and velocity (<600 m/s) indicate a potential zone for mass movements or, in this study, what we classify as mass creeping. The higher values observed in Q3 may suggest the presence of boulders, which play a significant role in triggering landslides, along with water flow movement in saturated zones. The integration of resistivity and velocity data using the cross-plot model shows that depths below 5 m correspond to lower values represented by Q1, identifying them as the slip surface of soil movement. Q1, characterized by low velocity and resistivity values, indicates poorly compacted soil or the presence of highly porous materials like sand. These areas are prone to experiencing landslide events or soil movements. On the other hand, Q3 represents higher resistivity (>1500 Ωm) and velocity (>600 m/s) values, suggesting the presence of hard layers or bedrock, as well as compacted soil with low porosity. The higher resistivity values coupled with low velocity indicate higher porosity in unsaturated materials (sand), contributing to landslides. Quadrant Q4 dominates these profiles, showing high velocity (>600 m/s) and low resistivity (<1500 Ωm) at depths exceeding 10 m, which indicates a stable subsurface condition. The low resistivity values in this quadrant may be indicative of saturation in the profile. The dashed black lines are marked as slip surface boundaries for a landslide to occur.

Figure 7(b) (LR3&LS3) presents a 2-D cross-plot model where Q1 dominates at depths less than 10 m, indicating a zone prone to landslides. The presence of poorly compacted soil with high porosity, such as sand, results in low resistivity and velocity values. Q4 is the dominant quadrant for this profile, representing stable conditions. In Q2, low velocity but high resistivity suggests the presence of boulders at shallow depths. The weathered zone thickness in Q1 is greater in comparison to LR4&LS4 due to active soil movement along this line. The continuous profile in Figure 7(c) for line LR2&LS2 also shows Q1 dominance, indicating active soil movement at depths below 10 m. The presence of boulders (Q2) at shallow depths acts as an additional trigger for failures. The low resistivity (<1500 Ωm) and velocity (<600 m/s) resulting from poorly compacted soil, such as sand or gravel, can induce soil slippage as the material's strength diminishes (Igwe 2015; Yalcin 2007). The presence of saturated zones and loose soil acts as catalysts for landslides (Noviyanto, Sartohadi & Purwanto 2020). High velocity and resistivity values in Q3 point to a boulder layer, while Q4 represents stable conditions in this study area. The sliding plane is observed in the profile at depths below 5 m, marked with a dashed black line. Figure 7(e) illustrates the 3-D orientation of the fence, including the sliding/failure plane, which was determined using the 2-D cross-plot model. The successful identification of the sliding plane is evident in this study area. Earlier, a comprehensive cross-plot analysis demonstrated the method's utility in classifying the target ground (Inazaki & Hayashi 2011). The quadrant system classifies different zones based on the distribution of attribute values, with Q1 indicating the vulnerable zone for the system.

The determination of sliding from 2-D cross-plot models is used to examine and estimate the volume of mass sliding. The information on the thickness of the sliding mass is utilized to compute the volume based on the elevation of the upper surface and lower surface. The volumetric calculation involves three methods: the Trapezoidal Rule, Simpson's Rule, and Simpson's 3/8 Rule. The final volume calculation examines the average of these methods. The details of the calculation are presented in Figure 8.

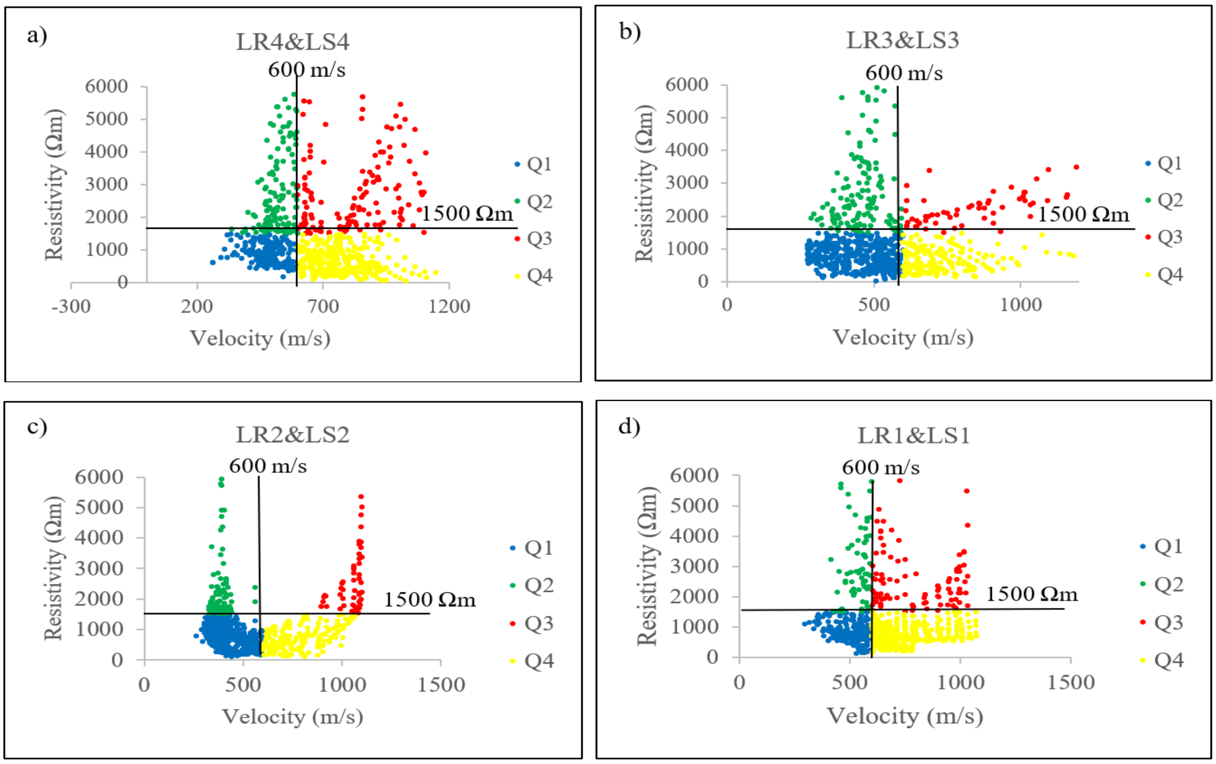


FIGURE 6. Graph integration of resistivity-velocity for the same X–Y location
a) LR4&LS4; b) LR3&LS3; c) LR2&LS2; d) LR1&LS1

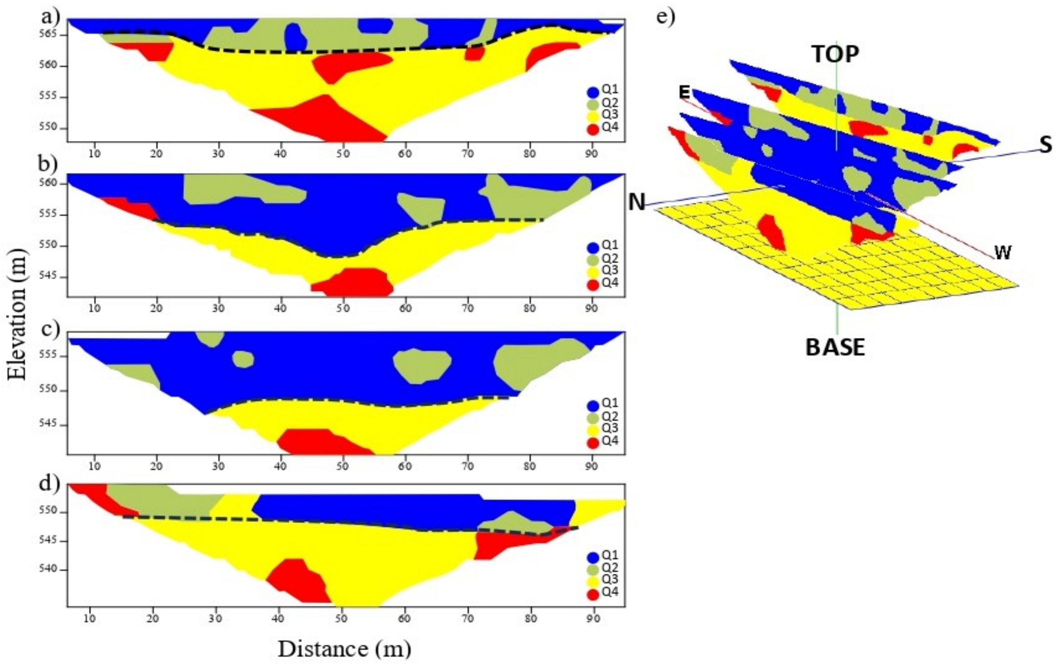
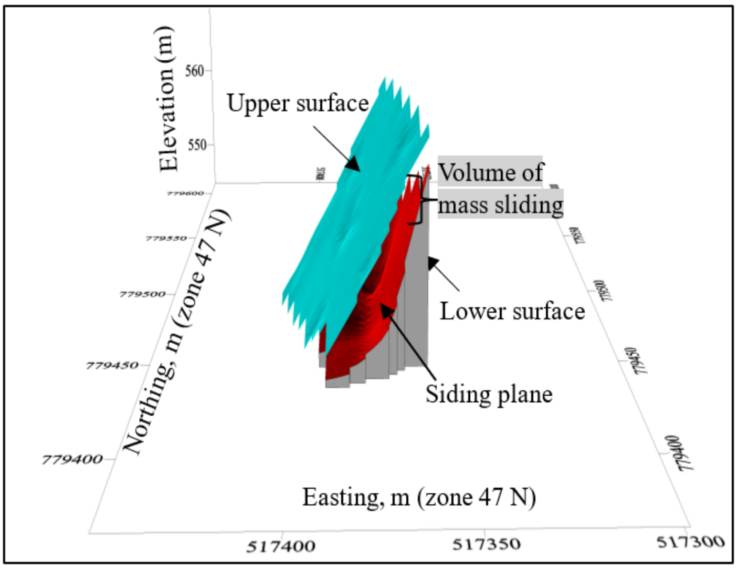


FIGURE 7. The 2-D cross-plot model; a) LR4&LS4; b) LR3&LS3; c) LR2&LS2;
d) LR1&LS; e) 3-D orientation of the models



The Volume and Area of Mass Sliding	
Lojing-Cameron Highland	
Volume	
Trapezoidal Rule:	13634.25
Simpson's Rule:	13706.72
Simpson's 3/8 Rule:	13630.81
Average volume (m3)	**13657.26**
Area	
Surface Area (m2)	1848.94

FIGURE 8. Volume calculation of mass sliding at landslide Lojing-Cameron Highland

The 2-D resistivity and seismic refraction results were combined using cross-plot analysis to resolve ambiguity in both anomalies. Weak zones suspected to be landslide areas with sliding planes were identified through the 2-D cross-plot model. Threshold values for the parameters in each study area were utilized to divide them into four quadrants. The first quadrant (Q1) is indicative of a higher risk of landslide events, characterized by lower resistivity and velocity values. In areas like Lojing, where mass creeping has occurred, factors such as loose materials (sand and gravel), the presence of boulders, and an accumulated saturated zone at the bottom part of the slope could trigger creep events. The lower resistivity and velocity resulting from poorly compacted soil, such as sand or gravel, may cause the soil to slip along the plane as its strength is reduced. The existence of a saturated zone and loose/weathered boulders acts as catalysts for landslides. On the other hand, high velocity and resistivity in Q3 indicate the presence of boulder/hard layers, while Q4 represents a stable condition for the study area.

CONCLUSIONS

This research aims to utilize integrated geophysical methods, with validation from different disciplinary fields, to provide highly accurate data to strengthen and enhance interpretations and data resolution. The integrated cross-plot analysis approaches, using the generated 2-D cross-plot model, could show direct visual representations of the relationship between the two attributes in identifying anomalies. The study provides insights into how spatial distributions of geophysical properties can be used to minimize uncertainty in ground models. Additionally, the cross-plot models between the integration of resistivity and seismic results show an informative technique in enhancing subsurface resolution. This research aims to utilize the integrated geophysical methods with validation from different discipline fields to provide highly accurate data to strengthen and enhance the interpretations and data resolution. The ability to define the subsurface of slope failure geometry, including the thickness of overburden, sliding plane, and other materials in failure mechanism on a large scale, including estimating the volume of mass sliding, is expected to demonstrate the successful implementation of the methods. The integrated cross-plot analysis approaches using the generated 2-D cross-plot model could show direct visual representations of the relationship between the two attributes in identifying the anomalies. The high data accuracy in defining the failure plane is a vital task in calculating or estimating the volume of mass sliding. In general, previous works relied on an individual or two/more methods in defining the subsurface geometry without stressed the elastic modulus of the materials. Those methods do not highlight the information on the sliding surface and overburdened materials in terms of resistivity and velocity distribution. The geological and geomorphological information with supported data from any discipline needs to be considered for providing detailed subsurface images. Providing high data accuracy of the surface and subsurface geometry of the slope failure to quantify slide mass volume and other subsurface characteristics for different landslides are an essential component of the landslide prediction and assessment.

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