



**GEOTECHNICAL RISK ASSESSMENT OF SUBSURFACE CAVITIES
IN LIMESTONE FORMATIONS USING 2D ELECTRICAL
RESISTIVITY TOMOGRAPHY (ERT) FOR INFRASTRUCTURE
DEVELOPMENT IN KAMPAR, PERAK DARUL RIDZUAN,
MALAYSIA**

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Abstract

Subsurface cavities in limestone formations poses hazardous risks to infrastructure from sudden ground movement, subsidence, and structural failure. These cavities form mainly from natural dissolution of carbonate rocks. Traditional methods like borehole drilling are costly, limited in resolution, and require many boreholes to cover large areas. To address this, the utilisation of 2D Electrical Resistivity Tomography (ERT) as a non-invasive geophysical technique to investigate potential subsurface voids at a proposed site in Taman Bandar Baru, Mukim Kampar, Daerah Kampar, Perak Darul Ridzuan, Malaysia. Three survey profiles (L-1, L-2, L-3) were conducted using a dipole-dipole array, and data were analysed with RES2DInv software to produce subsurface resistivity profiles. Geological formations identified through resistivity ranges revealed weakly consolidated soils, weathered or fractured limestone bedrock, and water-filled cavities, all indicating potential instability. A risk matrix applied to each profile confirmed that zones with groundwater activity and voids pose a high collapse risk to surface layers. The study highlights the value of early ERT and geotechnical risk assessments for guiding mitigation strategies, recommending continuous monitoring, adapted designs, and best practices to reduce hazards.

Keywords: electrical resistivity, geotechnical risk assessment, limestone formations, RES2DInv, subsurface cavities

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INTRODUCTION

Subsurface cavities in limestone formations pose significant hazards to infrastructure development, particularly in karst environments where dissolution of carbonate rocks by acidic groundwater creates sinkholes, voids, and underground channels (Zhang et al., 2018; Zhao & Shen, 2022). Human activities such as uncontrolled construction and urban drainage further accelerate cavity formation, making early detection critical. Traditional detection methods such as borehole drilling are costly, time-consuming, and limited in spatial coverage (Hossain et al., 2018; Estrada-Medina et al., 2012).

Electrical Resistivity Tomography (ERT) offers a non-invasive and cost-effective alternative for subsurface mapping. The technique injects electrical current into the ground via source electrodes and measures the resulting voltage difference, producing apparent resistivity values that are then converted into real resistivity using inverse modelling (Vanella et al., 2022). This enables identification and description of subsurface voids, alerting engineers to potential threats such as ground collapse and groundwater intrusion. ERT is particularly effective in water-rich soils due to their higher conductivity, making it advantageous for locating water tables and monitoring moisture changes (Vanella et al., 2021; Innocenti et al., 2024). It has been widely applied in civil engineering, hydrological studies (Paz et al., 2020), and environmental assessments (Abdul Rahman et al., 2016).

The main objective of this study is to evaluate the geotechnical risks of subsurface cavities in limestone formations using 2D ERT for infrastructure development in Kampar, Perak. Specifically, the study aims to: (1) identify the location of subsurface cavities using 2D ERT, (2) classify cavity risks using a geotechnical risk assessment framework, and (3) evaluate the potential hazards posed by these cavities on infrastructure development.

MATERIALS AND METHOD

This research was conducted in Taman Bandar Baru, Mukim Kampar, Daerah Kampar, Perak Darul Ridzuan, Malaysia. Figure 1 presents the location of the survey area. The mean elevation of the point above the mean sea level of the survey site is 205.00 m and located at approximate coordinates 4.323265 N and 101.146431 E.

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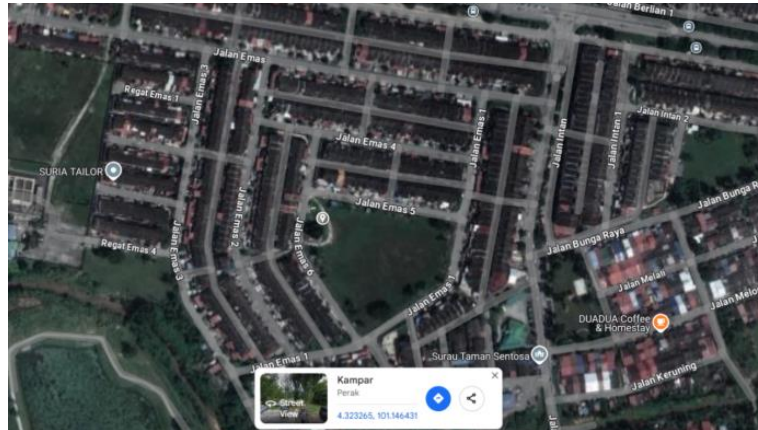


Figure 1. Location of the study area.

Regional Geology

Figure 2 shows the ground beneath the survey site constitutes a thick underburden of limestone. Geologically, Kampar, in the state of Perak, Malaysia consists mainly of areas of limestone dating back to the Devonian age (Metcalf, 2023).

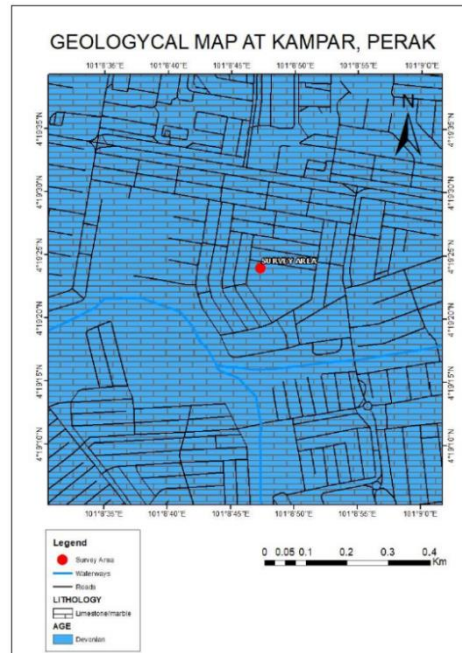


Figure 2. Geological map of Kampar, Perak Darul Ridzuan, Malaysia (Department of Mineral and Geoscience Malaysia (JMG), 2013).

The Devonian limestone in Kampar is especially famous for its quality assemblage of fossils, both conodonts and various marine organisms, for paleo-environmental and evolutionary studies (Hassan, 2021). These limestones are very soluble. Hence, during long-term dissolution with acidic water, they can form characteristic karstic features such as sinkholes, caves, and underground rivers. This results from more prolonged exposure of limestone to acidic water, and the dissolution of the rock takes place more slowly in most natural environments examining over geologic time.

Geological studies has also shown the presence of the Kampar limestone overlain by alluvial materials composed of layers of relatively younger sedimentary material. This stratigraphy has important implications for groundwater flow dynamics and ground stability, particularly in urban environment where the natural geology may be disturbed.

Field measurement

This study was conducted using the ASTM D6431-99 (2010) standard, Standard Guide for Using the Direct Current Resistivity Method for Subsurface Investigation. The electrical resistivity measurements were made with the ABEM Terrameter LS2 equipment (Figure 3).

Two multicore cables were used in the measurement process, the method injects an electrical current into the ground with two current electrodes, C1 and C2, and then measures the resulting voltage difference at two potential electrodes, P1 and P2. Each cable contained electrodes spaced 2.50 m apart. This results in a 100.00 m total length of the measurement line, with a maximum depth of about 25.00 m.

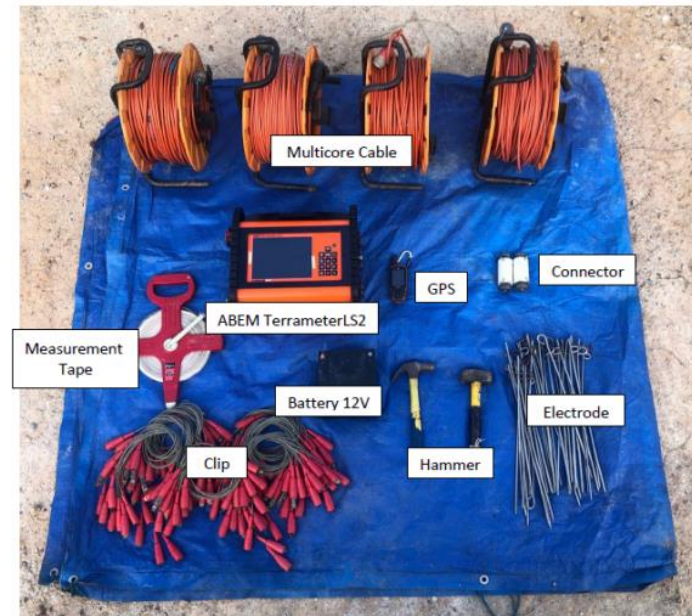


Figure 3. 2D Electrical Resistivity Tomography (ERT) equipment.

Equipment and Electrode Configuration

The measurements of resistivity imaging were made with an ABEM Terrameter LS2, the electrode array was arranged in the dipole-dipole (DD) configuration. This configuration has a much deeper extent of coverage and generally gives superior data quality, especially when targeting subsurface features at moderate to greater depths. As shown in Figure 4, the dipole-dipole (DD) method is well recognised for the possibility to provide resistivity variation within a broad depth range and deliver actual data even when the geological structure of the site is difficult. It is very effective when greater depth penetration is needed since, for deeper layers, higher sensitivity of the change in resistivity appears, and it is indispensable for the full subsurface mapping. The technique optimises the performance of the dipole-dipole (DD) tool in providing high resolution resistivity images.

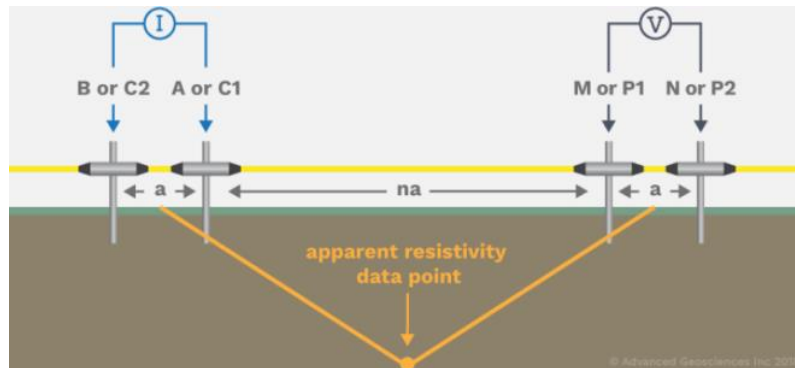


Figure 4. The arrangement of dipole-dipole (DD) array.

Methods of Data Analysis

The on-site data are initially converted into .DAT file format using S4Kwin, a software interface for ABEM Terrameter LS2 that digitises field manual measurements for further processing tasks. This data conversion is then analysed using RES2DInv software to facilitate inversion data-processing, converting field obtained apparent resistivity to produce 2D ERT output models comprising of in-depth visualisation of subsurface anomalies. Inversion data are computed based on standard and modified algorithm, such as least-squares inversion.

The generated surface and cross-section resistivity model visualises areas of subsurface interest that are prominent with other geology of the study area. Detailed visualised resistivity output profiles on subsurface condition in specific coordinates are extracted and redrawn in CorelDRAW to improve the graphical quality of the sectioned resistivity data plots.

The first approach in geotechnical risk assessment employs qualitative methodologies, which rely on expert judgement, experience, and the categorisation of hazards to determine risk levels and propose mitigation strategies. The second approach involves quantitative risk assessment, employing mathematical modelling, probabilistic analysis, and numerical evaluations to calculate risk indices, prioritise hazards, and inform decision-making.

These approaches, whether used individually or combined, collectively aim to safeguard safety, optimise competitiveness, and ensure the prosperity of geotechnical engineering projects by systematically identifying, assessing, and managing uncertainties throughout geotechnical design and construction stages. Modern advanced data-processing and modelling tools, when integrated with structured methodologies for risk assessment in geotechnical engineering, facilitate a proactive and systematic approach for the successful management of evolving hazards and their consequences.

Softwares

The most commonly used inversion program for processing 2D ERT data is RES2DInv, which transforms apparent resistivities into a subsurface resistivity model that can be interpreted in terms of geological structure and features.

Resistivity Value

Resistivity values in the field typically range from 1.00 Ωm to 3,000.00 Ωm , and are classified by material type as summarised in Table 1 to guide interpretation of subsurface geological conditions.

Table 1. Rock type resistivity value (Keller & Frishcknecht, 1996).

	
< 100.00 Ωm	Geological formation that has a high conductivity value (Clay/Silt/Phylite)/Void
20.00 Ωm – 150.00 Ωm	Geological formation that contained with groundwater
100.00 Ωm – 1000.00 Ωm	Other geological formation / Weathered material
> 1000.00 Ωm	Dry sand/Compacted material/Rock (Granite/ Conglomerate/ Sandstone)

Geotechnical Risk Assessment

Geotechnical risk assessment in this study integrates both qualitative and quantitative approaches, combining expert judgement with systematic identification of geological and hydrogeological hazard criteria as outlined in Table 2. It is crucial for the safety of civil engineering projects which it addresses uncertainties in subsurface soil and rock conditions using advanced methods involving geology, hydrogeology, etc. Furthermore, it also supports the identification and mitigation of geohazards by optimising the design compliance with standards to ensure the long-term sustainability and performance of structures such as foundations, retaining walls, and reinforced soil systems.

Table 2 revealed that geological factors such as the physical and structural properties of soil and rock were important in the risk of ground instability of the subsidence, collapse, and sinkhole. Groundwater, including its depth and fluctuations, was able to dissolve soluble rock, enable the formation of voids, reduce or remove support to overburden strata, and facilitate the possibility of collapse.

Table 2: Resistivity value and conductivity of some rocks, soil, and groundwater.

Criteria		Risk Level			
		1	2	3	4
Geology	Depth to bedrock (m)	>15	10 - 15	5 - 10	<5
	Soil Raveling Potential	CH	NH/CL	SC/SM/ML	SP/SW
	Soil Desiccation Potential	SP/SW	SC/SM/ML	MH/CL	CH
	Potential for Boulders	-	No cap rock	Cap rock	-
	Fracturing of top 5m of Rock	Unfractured	Slightly Fractured	Moderate Fractured	Highly Fractured
	Voids and Fissures in Soil	-	No	-	Yes
	Depth of Void (m)	>15	10 - 15	5 - 10	<5
	Proximity of Voids (m)	>30	15 - 30	3 - 15	<3
	History of Sinkholes, within 30 m	-	-	-	Yes
	Bedrock Orientation	Horizontal	Slight dip	Moderate dip	Steep dip
Groundwater	Depth to Groundwater (m)	>15	10 - 15	5 - 10	<5
	Groundwater Pumping History	Never	Stopped	Deep	Shallow
	Groundwater Flow in Voids	>30	15 - 30	3 - 15	<3

ANALYSIS AND DISCUSSION

Results

Based on Figure 5 shows the layout and configuration of the geophysical investigation in Taman Bandar Baru, Mukim Kampar, Daerah Kampar, Perak Darul Ridzuan, Malaysia. The ERT measurements were conducted using an ABEM Terrameter LS 2. The geophysical survey involved three parallel survey lines, labelled as L-1, L-2, and L-3, each extending 100.00 m in length. A total of five electrodes were installed in succession along each line at a uniform 25.00 m interval, starting at 0.00 m and ending at 100.00 m. The electrode array was arranged in the dipole-dipole (DD) configuration, it provides a greater depth of coverage, extending to depths of up to 25.00 m. Each electrode was positioned on a pre-marked to facilitate an exact spacing and alignment. A GPS unit was placed directly at the electrode location during electrode installation, and the corresponding geospatial coordinates were recorded in real-time.

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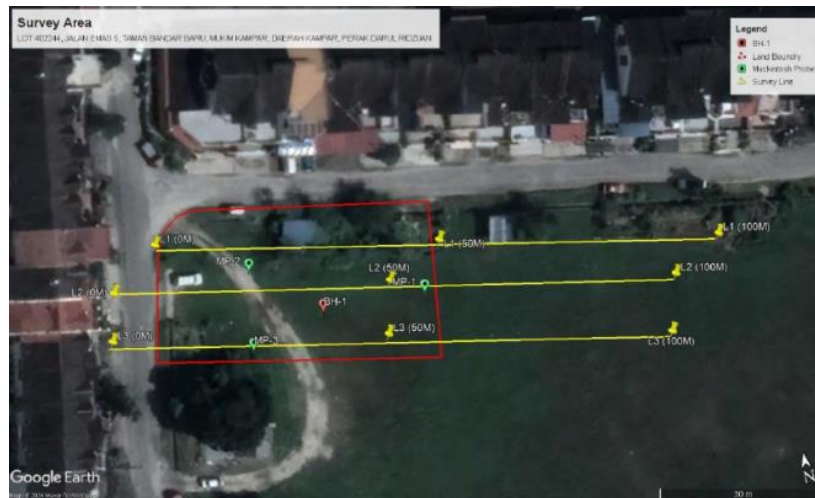
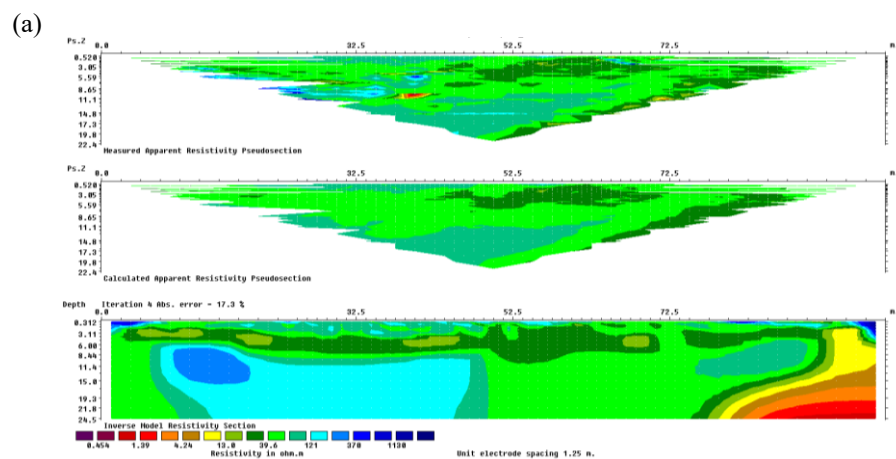


Figure 5. Layout of ERT survey lines location

Apparent Resistivity Pseudosection

The apparent resistivity pseudosection of survey lines, as shown in Figure 6 represents the raw field measurements of resistivity values obtained from the dipole–dipole electrode configuration. The colour distribution reflects variations in apparent resistivity with depth and horizontal distance along the survey line. Higher resistivity zones (warmer colours) may indicate compact or dry materials, such as limestone or gravel layers, while lower resistivity zones (cooler colours) are typically associated with clay-rich soils, water-saturated layers, or potential voids.



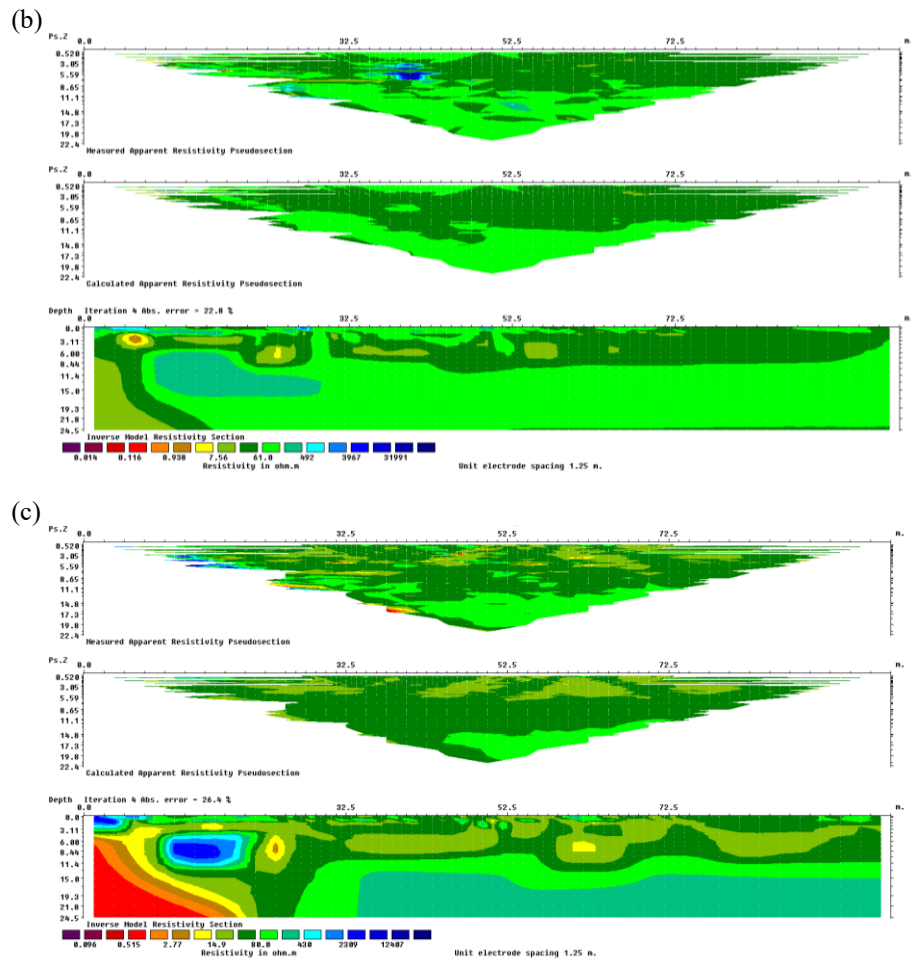


Figure 6. Apparent resistivity pseudosection of survey line (a) L-1, (b) L-2 and (c) L3.

Root-Mean-Square (RMS) Error

The inversion of all three survey lines produced RMS errors predominantly below 20%, confirming the reliability of the subsurface resistivity models generated using RES2DInv.

2D Electrical Resistivity Tomography (ERT) Imaging Profile

The interpreted geology of the profile is presented on Figure 7(a) with annotations of major hazards like possible cavities and stratigraphic boundaries. The inversion of all three survey lines was performed using RES2DInv. The inversion parameters were kept consistent for all survey lines to ensure comparable results.

The inversion process was carried out for seven iterations, with each iteration progressively improving the model fit between the measured and calculated apparent resistivity data. The final inversion models were selected after the seventh iteration, which provided the optimised subsurface resistivity imaging profiles. This imaging profile is almost identical to a similar one from an adjacent and parallel line surveyed 9.00 m away, thereby implying subsurface continuity of geology and confirmation of observed patterns.

The profile shows that the area subsurface condition is dominantly layered structured and underlain by loose alluvial deposit consist of-layered sandy soil composed of sandy-silt top soil, silty-clay sub soil and partly large boulder within its overburden. The sandy silt deposit has intermediate resistivity values of between 50.00 and 150.00 Ωm and is identified as partly saturated with fine sediments. The sandy silt constituted the upper 1.00 m thickness of its overburden of the sounding curve and is typical of material of normally unconsolidated regolith indicative of materials with fine sediment and excess surface water infiltration.

Underlying this overburden is a water-bearing silty clay of 7.00 m thickness with resistivity values between 0.00 and 50.00 Ωm . Materials such as these have very low resistivity typical of water saturated, poorly drained clayey lithologies. Silty clays are fine particles that permit high capillary saturation of the upper soil horizon typical of poor drainage. Underneath these materials next to the bedrock is a thin layer weathered sand sometimes with gravel that has high resistivity values ranging from 120.00 to 200.00 Ωm . These materials are very dried and characterised as well-drained material. These channels form a transition zone between normally porous poorly consolidated alluvial fill with underlying lithified material.

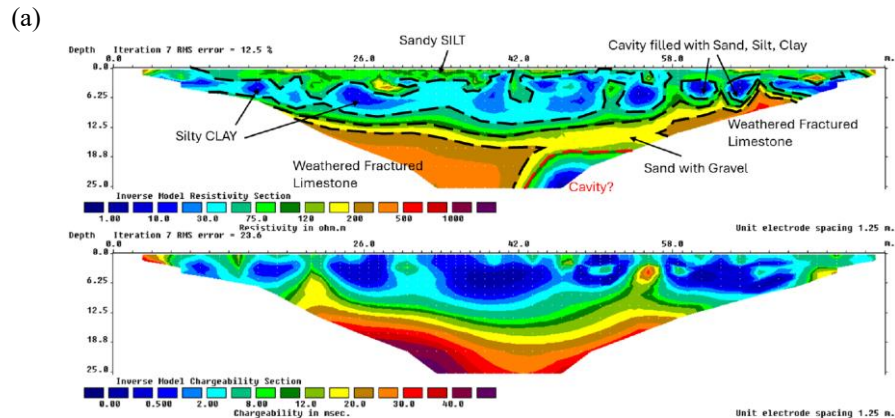
The lower part of the profile shows weathered, fractured limestone bedrock with a resistivity values of 300.00 Ωm to 1000.00 Ωm depending on the degree of fracturing and amount of groundwater present. However, undulating features are observed in the limestone at the depth of approximately 7.00 m along a horizontal distance between 58.00 m and 66.00 m: these features have been interpreted as infilled cavities- possibly karst features filled with sandy, silts and clay particles. Also, the feature seen at a depth of approximately 25.00 m between 42.00 m and 54.00 m along the survey line is interpreted as a zone of fractured limestone having very low resistivity interpreted as a possibly a large cavity or an area of high moisture accumulation.

Figure 7(b) shows the line L-2 reveals major subsurface geologic features. This indicated a rather fairly uniform geologic stratification similar to that of line L-1. The top layer is sandy silt with resistivity values ranging from 50.00 Ωm to 150.00 Ωm and thickness of 5.00 m. It appears due to the existence of lots of silty fine to medium sand sized particles in a comparatively dry

environment. The underlying layer is silty clay with very low resistivity values ranging from 0.00 Ωm to 50.00 Ωm in thickness of 7.00 m. The low resistivity of this layer indicates its high moisture content which is characteristic of clayey deposits. These may present geotechnical problems with potential settlement problems.

The overlying transitional sand and gravel layer between 120.00 Ωm to 200.00 Ωm , resistivity values higher than those of the wet low permeability media below occurs as a thin layer. The base of the profile is characterised with high resistivity from 300.00 Ωm to 1000.00 Ωm , which is interpreted as weathered and fractured limestone. This is a common formation of limestone found in a karst environment; the degree of fracturing and wetness reflects the condition of the weathered limestone under a possible influence of drying or compacting. The nature of the anomaly indicates karst mechanics (filled cavity) at least within the first 25.00 m under ground level.

The resistivity distribution shown in Figure 7(c) outlines the main stratigraphic contacts consistent with L-1 and L-2, comprising a sandy silt top layer (50.00 – 150.00 Ωm , ~5.00 m thick), an underlying silty clay layer (0.00 – 50.00 Ωm , ~7.00 m thick), a thin transitional sand and gravel layer (120.00 – 200.00 Ωm), and weathered fractured limestone bedrock (300.00–1,000.00 Ωm). A distinct anomaly is detected between 30.00 m and 34.00 m at approximately 25.00 m depth, interpreted as a void infilled with sand, silt, and clay — consistent with karstic dissolution features observed in the other survey lines.



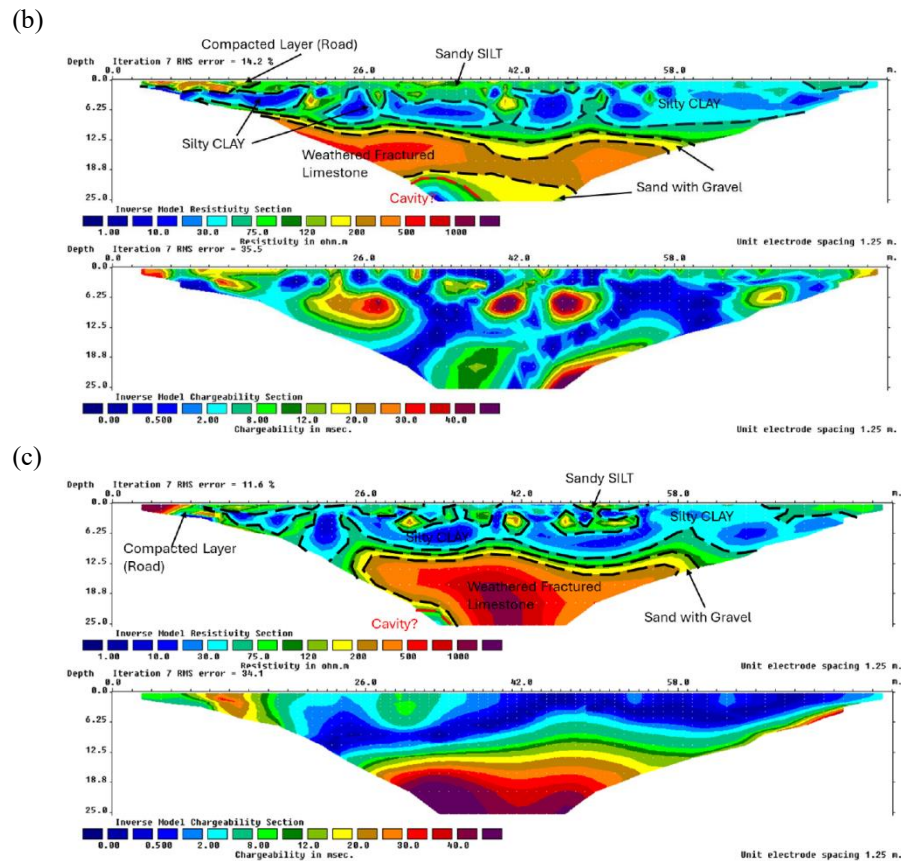


Figure 7. 2D ERT imaging profile section of survey line (a) L-1, (b) L-2 and (c) L-3.

DISCUSSION

Integrated Interpretation of Subsurface Stratigraphy

The 2D ERT imaging profiles as shown in Figure 8 extend to a maximum depth of approximately 25.00 m, and their interpretation is based on an integration of borehole logs, earlier research, and geological maps. All three survey lines (L-1, L-2, and L-3) run parallel to one another and are spaced roughly 9.00 m apart, producing broadly consistent resistivity responses that enable reliable correlation across the site. The resistivity results consistently identify four principal subsurface layers across all survey lines: sandy silt, silty clay, sand with gravel, and weathered fractured limestone.

Findings from the borehole summary based on Table 3 support the resistivity interpretation. The borehole data indicate that the site area is underlain by residual soils, up to about 14.50 m thick, consisting mainly of sandy silt and sand with Standard Penetration Test (SPT) values not exceeding N=5, pointing to very soft to loose ground conditions. At 14.50 m, limestone bedrock of the Kinta Limestone formation was encountered, overlain by the residual soils and alluvium. Between 16.50 m and 18.00 m, sandy gravelly material was recorded, interpreted as an infilled cavity within the limestone sequence. Below this, the limestone continues until about 23.00 m depth. Rock quality designation (RQD) results show that the recovered limestone cores are generally very weak and highly fractured, with an RQD of 0%, except for one core (C1) that showed a moderately fractured condition with an RQD of 25%. The integration of borehole and ERT data confirms the presence of two cavity types as shown in Table 3.

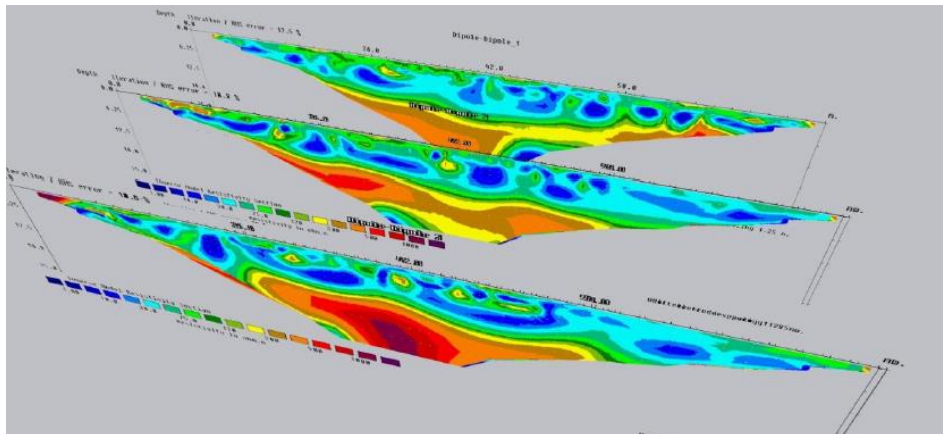


Figure 8. Fenced diagram of survey lines with views from south.

Table 3: Summary of Borehole Investigation Results.

Depth (m)	Material	SPT (N-value)	Remarks
0.00 – 14.50	Sandy silt / residual soil	≤ 5	Very soft to loose
14.50	Limestone bedrock (Kinta Formation)	—	Bedrock encountered
16.50 – 18.00	Sandy gravelly material	—	Infilled cavity
18.00 – 23.00	Limestone	—	Continues to depth

RQD: Generally 0% (highly fractured); C1 core = 25% (moderately fractured)

Geotechnical Risk Assessment

Based on the comparative analysis of risk assessments across three survey lines (Table 4), varying levels of geotechnical and hydrogeological risks were observed. Survey line L-1, with a depth to bedrock of 10 m to 15 m, indicates moderate to high-risk conditions. The soil types present categorised as SC/SM/ML, exhibit moderate raveling and desiccation potential. The existence of a cavity filled with loose material signifies high risk due to possible voids and fissures, compounded by fractured limestone contributing to instability. Groundwater is likely shallow between 10 m to 15 m with risk factors contributing to an overall risk score of 5 (very high).

Survey line L-2 displays even more severe conditions with a shallower depth to bedrock of less than 10 m, resulting in a high risk rating. Similar soil types are present, alongside a visible void at depth and evidence of fractured limestone supports a very high risk of collapse or sinkhole development. The depth of voids ranges between 10 m to 15 m with proximity less than 15 m heightening the risk score to 5 (very high), although the absence of boulders and sinkhole history mitigates some risk factors.

In contrast, survey line L-3 shows the least severe conditions with a depth to bedrock of around 15 m classified as low to moderate risk. The voids here, though present, are isolated, leading to a moderate likelihood status. Groundwater depth is somewhat deeper from 10 m to 15 m, maintaining a moderate risk rating but overall structural integrity appears better thanks to a well-defined compacted surface layer.

It is clear that geotechnical hazards associated with the presence of voids and fissures in the soil material at the site is significant, with all three lines experiencing high geotechnical risks. Voids are relatively shallow in survey line L-2 and L-3 with each of them being found close to the surface material. This relatively shallow depth of voids increases the probability of the ground surface experiencing a collapse due to the presence of voids.

Groundwater from anthropogenic means from pumping is prone to very little influence on the groundwater level given the difference in pumping height and deepest groundwater level of >100 m (water needing to travel to greater depth reduces flow rate into subsurface rock) and potential groundwater flow within voids can be characterised to be moderate, which is adequate for the expansion of voids and or facilitating the collapse of inadequately filled void spaces.

Based on the results of each respective risk assessment model developed for each survey profiles in the study, it can be concluded that L-1 and L-2 are more susceptible to risks of void formation because of their shallower bedrocks and shallower voids, with L-3 having comparatively better score results in terms of sinkhole formation.

Table 4: Comparison of risk level of survey lines.

Criteria		Risk Level		
		L -1	L -2	L -3
Geology	Depth to bedrock (m)	2	3	2
	Soil Raveling Potential	3	3	3
	Soil Desiccation Potential	2	2	2
	Potential for Boulders	1	1	1
	Fracturing of top 5m of Rock	1	2	1
	Voids and Fissures in Soil	4	4	4
	Depth of Void (m)	2	1	1
	Proximity of Voids (m)	1	1	1
	History of Sinkholes, within 30 m	1	1	1
	Bedrock Orientation	3	3	3
Groundwater	Depth to Groundwater (m)	2	3	2
	Groundwater Pumping History	1	1	1
	Groundwater Flow in Voids	2	2	2

Implications for Commercial Building Development and Mitigation Measures

The risk assessment indicates that the site presents significant geotechnical and hydrogeological risks, particularly along survey lines L-1 and L-2, where increase the potential for ground instability and sinkhole formation. These conditions are particularly critical for commercial buildings because ground movement may cause differential settlement and structural damage. The 2D ERT and borehole results can be used to determine appropriate mitigation measures which may include pressure grouting or cementitious filling of cavities and ground improvement. Moreover, an effective groundwater monitoring and drainage system should be implemented to control changes in groundwater conditions and minimise erosion of subsurface cavities. Construction activities such as excavation, dewatering, and heavy loading should be carefully controlled especially in high-risk areas. Furthermore, the continuous monitoring using inclinometers or piezometers should be considered during construction and throughout the building's service life.

CONCLUSION

The first objective was successfully addressed through the interpretation of resistivity profiles across three survey lines. Line L-1 revealed a distinct anomaly between 58 to 66 metres at approximately 7 metres depth, characterised by moderate resistivity values (300 Ω m – 1000 Ω m), indicative of fractured limestone and voids potentially filled with sand, silt, and clay. L-2 showed a deeper cavity between 30 to 37 m at about 25 m depth within the high-resistivity limestone, which could represent a significant karstic cavity. Meanwhile, for L-3 also detected a cavity between 30 to 34 m at a depth of 25 m with similar resistivity characteristics.

The second objective was to classify the geotechnical risk associated with these cavities as inferred by the ERT data. L-1 is classed as very high risk as the shallow voids, fractured bedrock and groundwater involvement all contribute to instability. Furthermore, L-2 is classed as very high risk due to the shallow bedrock, cavity volume and hydrogeological activity, which collectively enhance the probability of ground failure. While line L-3 exhibits similar geological characteristics, due to the relatively deep voids and well compacted surface, it is considered to be of high risk.

Engineering solutions such as pressure grouting and deep foundations are recommended for L-1 and L-2, while continued monitoring is advised for L-3.

REFERENCES

- Abdul Rahman, A., Nawawi, M., Saad, R., Abu-Rizaiza, A. S., Yusoff, M. S., Khalil, A. E., & Ishola, K. S. (2016). Characterization of active and closed landfill sites using 2D resistivity/IP imaging: Case studies in Penang, Malaysia. *Environmental Earth Sciences*, 75(4). <https://doi.org/10.1007/s12665-015-5003-5>
- Estrada-Medina, H., Graham, R. C., Allen, M. F., Jiménez-Osornio, J. J., & Robles-Casolco, S. (2012). The importance of limestone bedrock and dissolution karst features on tree root distribution in northern Yucatán, México. *Plant and Soil*, 362(1–2), 37–50. <https://doi.org/10.1007/s11104-012-1175-x>
- Hossain, S., Kibria, G., & Khan, S. (2018). *Site investigation using resistivity imaging*. CRC Press.
- Innocenti, A., Pazzi, V., Napoli, M., Ciampalini, R., Orlandini, S., & Fanti, R. (2024). Electrical resistivity tomography: A reliable tool to monitor the efficiency of different irrigation systems in horticulture field. *Journal of Applied Geophysics*, 105527. <https://doi.org/10.1016/j.jappgeo.2024.105527>
- Paz, M., Alcalá, F., Medeiros, A., Martínez-Pagán, P., Pérez-Cuevas, J., & Ribeiro, L. (2020). Integrated MASW and ERT imaging for geological definition of an unconfined alluvial aquifer sustaining a coastal groundwater-dependent ecosystem in southwest Portugal. *Applied Sciences*, 10(17), 5905. <https://doi.org/10.3390/app10175905>
- Vanella, D., Peddinti, S. R., & Kisekka, I. (2022). Unravelling soil water dynamics in almond orchards characterized by soil-heterogeneity using electrical resistivity tomography. *Agricultural Water Management*, 269, 107652. <https://doi.org/10.1016/j.agwat.2022.107652>
- Zhao, Z., & Shen, Y. (2022). Rain-induced weathering dissolution of limestone and implications for the soil sinking-rock outcrops emergence mechanism at the karst surface: A case study in southwestern China. *Carbonates and Evaporites*, 37(4). <https://doi.org/10.1007/s13146-022-00813-1>

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