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Utilizing Gravity Surveys for Subsurface Feature Identification in Foundation Planning

(Menggunakan Tinjauan Graviti untuk Pengecaman Ciri Subpermukaan dalam Perancangan Asas)

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ABSTRACT

Understanding the distribution and extent of solution features such as cavities and pinnacles in limestone bedrock is crucial for anticipating potential challenges and planning appropriate foundation solutions. This study employed microgravity surveying to complement available borehole data and map karst features, particularly cavities, within the limestone bedrock. The survey was conducted on a 5 m × 5 m grid interval, establishing a total of 91 stations. Reduced Bouguer and residual anomalies were contoured and plotted using the GEOSOFT Oasis Montaj Mapping system. Anomalies of interest were further analyzed through 2-D gravity modeling using PotentQ software to determine the dimensions of the causative bodies. The survey results, presented as Bouguer, residual, and Bouguer anomaly horizontal gradient maps, showed a small range of gravity values (-9.24 to -9.10 mGal), indicating minimal variation in limestone bedrock topography. Gravity highs were associated with shallow limestone bedrock, while isolated gravity lows suggested the presence of cavities. Horizontal gradient maps highlighted peaks corresponding to the edges of these cavities and potential channel-like features. Borehole data corroborated the microgravity findings, with bedrock encountered at depths between 9.6 m and 12.3 m indicating deeper bedrock towards the south. The 2-D gravity modeling suggested a sediment-filled cavity approximately 7 m thick and 15 m wide in an east-west orientation, aligning well with borehole data. The combined use of borehole data and microgravity surveying proved effective in characterizing subsurface karst features, providing valuable insights for foundation planning leading to safer and more efficient construction practices.

Keywords: Anomaly; Bouguer; cavities; limestone; microgravity

ABSTRAK

Pengetahuan tentang taburan dan ciri larutan seperti rongga dan puncak batu kapur adalah penting untuk meramal potensi cabaran dan merancang pembinaan tapak yang sesuai. Kajian ini menggunakan survei mikrograviti untuk melengkapkan data lubang bor yang sedia ada dan memetakan ciri karst, khususnya rongga dalam batuan kapur. Tinjauan dilakukan dengan sela grid 5 m × 5 m, berjumlah 91 stesen. Anomali Bouguer yang dikurangkan dan baki digambarkan menggunakan sistem pemetaan GEOSOFT Oasis Montaj. Anomali yang menarik dianalisis lebih lanjut melalui pemodelan graviti 2-D menggunakan perisian PotentQ untuk menentukan dimensi jasad yang menjadi punca. Keputusan survei yang diketengahkan sebagai peta anjakan Bouguer, baki dan gradien mendatar anjakan Bouguer mendedahkan julat kecil dengan nilai graviti (-9.24 hingga -9.10 mGal), menunjukkan variasi minimum dalam topografi batuan kapur. Anjakan graviti tinggi dikaitkan dengan batuan kapur cetek, manakala anjakan graviti rendah menunjukkan kehadiran rongga. Peta gradien mendatar menunjukkan puncak yang sepadan dengan tepi rongga ini dan ciri potensi berbentuk saluran. Data lubang bor mengesahkan penemuan mikrograviti dengan batuan kapur dijumpai pada kedalaman antara 9.6 m dan 12.3 m menunjukkan batuan kapur yang lebih dalam ke arah selatan. Pemodelan graviti 2-D menyarankan keberadaan rongga berisi endapan dengan ketebalan kira-kira 7 m dan lebar 15 m dengan orientasi timur-barat, sejajar dengan data lubang bor. Penggunaan data lubang bor dan survei mikrograviti terbukti berkesan dalam pencirian karst di bawah permukaan, memberikan maklumat penting untuk perancangan tapak yang lebih selamat dan cekap dalam amalan pembinaan.

Kata kunci: Anomali; batu kapur; Bouguer; mikrograviti; rongga

INTRODUCTION

Foundation problems in limestone are attributed to various solution features inherent in the rock, which are particularly well-developed in tropical karst (Abdeitawab 2013; Gómez & Martin 2012; Nouioua et al. 2013). These features include pinnacle bedrock profiles, cavities, overhangs, thin limestone slabs, and boulders. Limestone areas are highly susceptible to geohazards due to their tendency to undergo karstification, a process in which dissolution of carbonate rocks leads to the formation of underground cavities, sinkholes, and subsurface voids. These features pose significant risks to infrastructure, buildings, and human safety. The process of karstification has resulted in underground natural cavities that significantly impact people's lives, as they can cause severe damage to properties and infrastructure, including land subsidence, sudden sinkhole formation, highly fractured and building collapse (Gambetta et al. 2011; Youssef et al. 2016). Arisona et al. (2023) found that significant gravity lows are primarily caused by the infilling of hollows in limestone with low-density materials rather than by air-filled cavities. Ahmad and Noorliza (2004) utilized the microgravity method to detect subsurface cavities in Kuala Lipis, Pahang. The microgravity surveys identified four cavities at depths ranging from 3.77 to 6.50 meters, calculated using the half-width method. However, the depths were found to be shallower when compared with borehole results. Ahmad and Noorliza (2004) also noted that the most significant gravity low detected by the gravimeter was due to air-filled cavities, attributable to the high-density contrast between air and the host rock. In contrast, gravity highs were associated with pinnacles and subsurface topographic highs, as well as dense root systems. This study assumed that gravity lows were caused solely by cavities. Only anomalies larger than 0.1 mGal were considered significant. The gravity lows were attributed to cavities, with variations in magnitude indicating differences in size or depth. Similarly, positive anomalies were due to near-surface karst pinnacles or boulders, with the magnitude differences reflecting the size or depth of both cavities and boulders.

Beres, Luetscher and Olivier (2001) and Sobh (2013) also used microgravity method to detect subsurface cavities. Microgravity survey was conducted at very small area to increase the precision of data acquired. From residual bouguer anomaly map that was produced, an area with lower gravity reading ranging between -40 and 33 μGal was interpreted as near surface cavities. Previous study such as Ahmad and Norliza (2004), Gyesoon et al. (2010), and Neumann (1967) stated that subsurface cavities will produce very low gravity values in comparisons to the host rocks.

Foundation design and construction in limestone areas present unique challenges due to the geological characteristics of limestone, particularly in tropical regions like Malaysia (Ahmad & Norliza 2004; Muhamad Zaki 2019; Trepil Fouzie 2020). The complexity arises from the irregularities and solution features inherent in limestone formations. In Malaysia, notable limestone formations such as the Kuala Lumpur Limestone and the Kinta Limestone are characterized by pinnacle bedrock profiles, cavities, overhangs, thin slabs, and boulders. These features can significantly impact foundation stability and require specialized approaches to foundation design and construction (Branston & Styles 2003).

Several projects in Malaysia have successfully navigated the challenges of constructing foundations in limestone areas by adopting best practices and innovative solutions are Kuala Lumpur City Centre (KLCC) and Mass Rapid Transit (MRT) projects. The foundation design for skyscrapers in this area involved extensive geotechnical investigations and the use of bored piles to anchor structures securely into the limestone bedrock. The MRT projects in Kuala Lumpur utilized advanced ground investigation techniques and tailored foundation solutions to address the complex limestone geology. Conducting geophysical methods for foundation design in Kuala Lumpur involves a series of non-invasive techniques to investigate the subsurface conditions, which is crucial for effective foundation engineering. Given Kuala Lumpur's geological setting, which includes soft alluvial deposits, karstic limestone, and granite formations, selecting appropriate geophysical methods is essential for accurate subsurface characterization. Given Kuala Lumpur's complex geological setting, microgravity surveys are effective in detecting cavities and ensuring the stability of foundations in karstic areas. Therefore, this research intend to delineate subsurface anomalies, such as cavities and variations in soil and rock density that may impact foundation stability. Microgravity is known as non-invasive method, cost effective and provide detailed subsurface information, aiding in better foundation design and risk mitigation (Agus et al. 2015; Kim et al. 2003; Muhamad Zaki 2019; Trepil Fouzie 2020). Microgravity surveys primarily rely on the density contrast between an anomaly and its surroundings; thus, differences in density are used to detect cavities (Ahmad & Norliza 2004). Foundation design and construction in limestone areas in Malaysia demand a comprehensive understanding of geological conditions and meticulous planning. By leveraging geophysical investigation techniques, engineers can effectively manage the challenges posed by limestone formations, ensuring the stability, longevity of structures and more resilient infrastructure development.

GEOLOGY OF THE STUDY AREA

The large inland plain around Kuala Lumpur is underlain by unconsolidated sediments containing tin deposits. The alleviated areas are generally underlain by calcareous bedrock; the other bedrock types giving rise to hills which surround the lowlands. The thickness of the alluvium varies from a few metres to a few tens of metres. In places, where ‘troughs’ are developed along contacts between the calcareous rocks and granites, it may be much thicker (Mohamad Ayob 1970). Kuala Lumpur is underlain by extensive limestone bedrock formations, including the Kuala Lumpur Limestone (Figure 1). In each area, the limestone bedrock rises above the alluvial plains, forming limestone hills with steep to vertical slopes, known as mogote or tower karst. The Kuala Lumpur Limestone is overlain uncomfortably by the more gently folded Carboniferous to Permian Kenny Hill Formation, estimated to be about 1200 to 1500 m thick. The thickly bedded fine- to medium-grained quartzose sandstone is of a light yellowish colour. Feldspars are uncommon in the sandstone and heavy minerals recovered from friable crushed samples include well-rounded pink zircons with some tourmaline and opaque minerals (Hutchison & Tan 2009). It consists predominantly of carbonate rocks, mainly limestone and dolomite which have undergone various geological processes such as folding, faulting, and karstification (Hutchison & Tan 2009).

MATERIALS AND METHODS

A microgravity survey was conducted at the car park in front of the main entrance to Kompleks Budaya Kraf, Jalan Conlay, Kuala Lumpur. An underground tunnel for the Mass Rapid Transit Line 2 (KVMRT2) project is expected to pass through this location as part of its alignment. Additional subsurface data is required to ensure that their tunnel boring machine (TBM) does not encounter unexpected technical issues when passing through this location, which is underlain by limestone.

A number of boreholes have been drilled earlier at this site. The microgravity survey was conducted to supplement the subsurface information obtained earlier from boreholes. The primary objective of the survey was to map karst features (especially cavities) within the limestone bedrock. The survey had to be carried out at night as conducting the survey during the day was not permitted by the Management of the Kompleks Budaya Kraf. It was also preferable because the car park would not be occupied at that time. The site was also too close to the proposed MRT station where active construction activities was taking place which would have badly affected the precision of the gravity measurements.

FIELD PROCEDURE

The field data acquisition was carried out using a SCINTREX CG-5 Autograv gravity meter.

The survey was carried out on 5 m × 5 m grid interval. A total of 91 stations were established (Figure 2). The positions (in local Cassini projection) were precisely located, and the reduced level of all the gravity stations was determined by the survey team. The locating and marking of the gravity stations on the ground were supervised and commenced an hour earlier before the microgravity measurements.

A number of data correction still needed to be done in order to get the relative bouguer contour map because the gravimeter only gives raw observed relative gravities under the assumption that the earth was spherical and the measurement taken from the datum. This correction is known as gravity data reduction (Reynold 1997). One of the corrections used in this research was the drift correction. This correction was done due to the spring being affected by elastic creep throughout a certain amount of time. Therefore, a repeated measurement is needed to be taken at base station and subtracting the difference to all stations measured in-between the timeframe (Reynolds 1997).

A base station was established to monitor the drift of the gravity meter and was occupied at an interval of between 2 and 2.5 h. The measurements were repeated twice with a 30 s cycle and a 15 s delay was set as the measurement parameters for the gravity meters. Measurements were repeated at least twice each time the base station was occupied. Additional measurements were made if the two earlier consecutive measurements were not within the allowable error with tilt x and tilt y axis below 5 arcsec, value difference of the base measurement data must be below 0.005 mGal and acceptable standard deviations (SD) below 0.05.

Measurements at all other stations were made following similar procedure at the base station. To ensure data integrity, quality and consistency, repeat measurements were randomly made at previously occupied stations. The instrument tilts and the standard deviations (SD) of all the gravity measurements were recorded to ensure that only good quality data were accepted. The gravity data were both recorded manually and stored in the equipment’s system memory. The data were then dumped to a laptop for validation and verification before further processing.

DATA REDUCTION AND PROCESSING

The raw microgravity data (tide and drift corrected) were validated for errors before inputting into an MS Excel spreadsheet and reduced to bouguer anomalies using standard reduction gravity formulae. To facilitate data reduction, the local coordinates of each station were also converted to WGS84 (longitude and latitude) coordinate system. Bouguer anomaly map was generated after all the data were reduced. This was the primary map used for interpretation and to identify anomalies.

Latitude corrections are usually made by subtracting the normal gravity, calculated from the International Gravity Formula, from the observed or absolute gravity

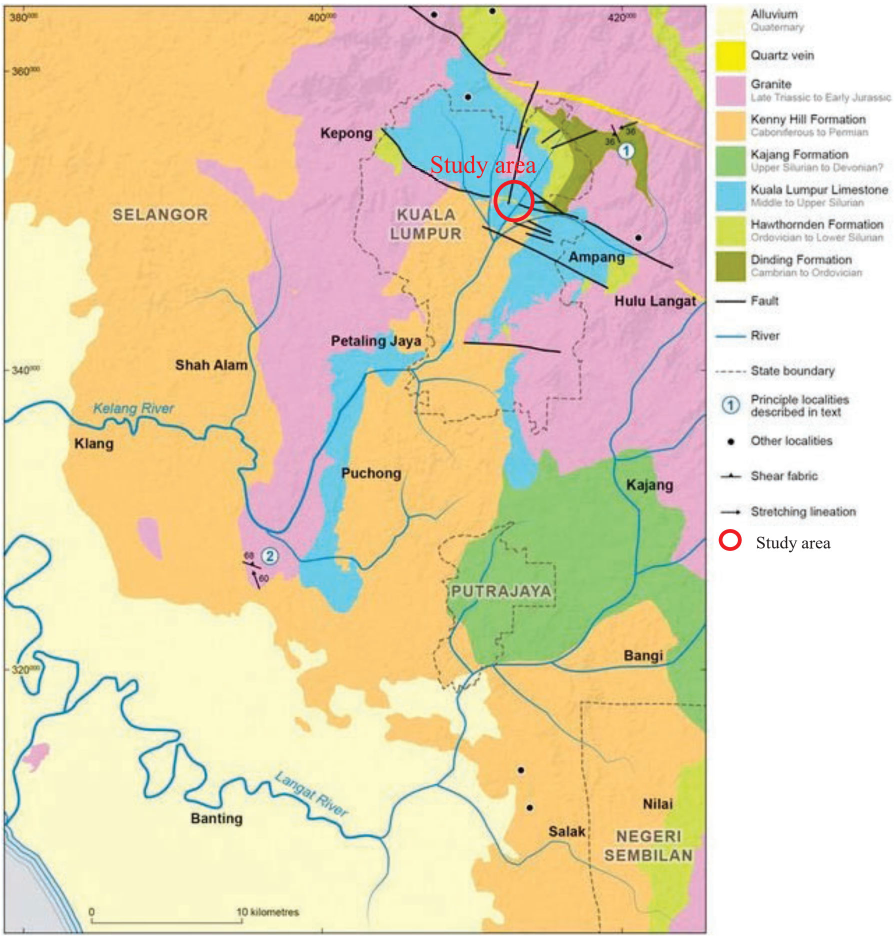

FIGURE 1. General geology map of Kuala Lumpur (Jabatan Mineral dan Geosains Malaysia 2011)

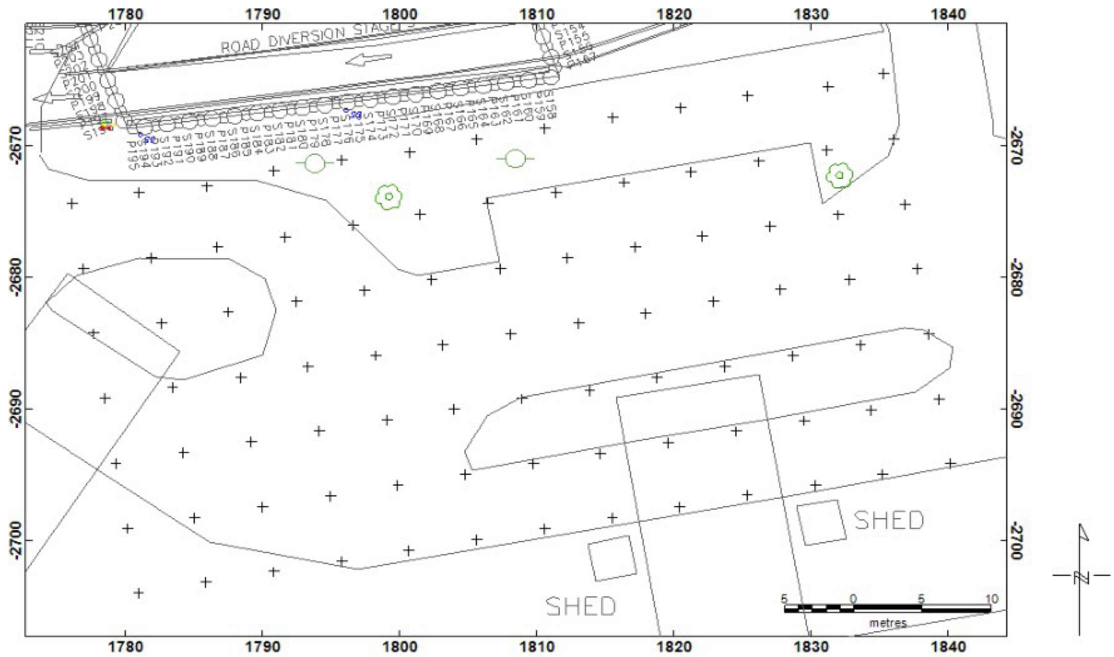

FIGURE 2. Distribution of microgravity stations

(Telford, Geldart & Sheriff 1990). But due to the small scale of this survey, Equation (1) that was devised for local latitude correction will be used:

$$LatCor = 0.811\ sin2\emptyset\ mGal/km \quad (1)$$

In which $\emptyset$ is the latitude, then we either add the correction if the points move toward the equator or subtract if they move away from it (Telford, Geldart & Sheriff 1990).

Free air correction reduces all stations to the datum or geoid without accounting for the mass of the rocks between the datum and the actual measurement elevation because the earth is not perfectly flat by using Equation (2):

$$FACor = h \times 0.3086\ mGal/m \quad (2)$$

where h is the elevation, the resultant would be added to the observed readings if the station is above the datum and subtracted if the station is below the datum (Telford, Geldart & Sheriff 1990).

The Bouguer correction accounts for the mass that was ignored in the free-Air Correction as that mass has attraction force that can affect the readings significantly, and it can be calculated through the following Equation (3):

$$BCor = h \times \rho \times 0.04192\ mGal/m \quad (3)$$

where ρ is the density of crustal rocks and usually it assumed to be 2.67 m/cm^3, also the Bouguer correction is applied in opposition to the free-air correction, therefore, if the station is above the datum, the resultant value would be subtracted from the observed readings and if it is below, it would be added (Telford, Geldart & Sheriff 1990).

The bouguer anomaly map was further subjected to regional trend removal to produce residual map. A second-degree polynomial fit was generated to represent the regional trend which was then subtracted from the bouguer anomalies. The resultant values were then plotted as residual anomaly map. A 90° (counter-clockwise from x-axis) directional horizontal gradient filter was also applied to the bouguer anomaly map to generate the bouguer anomaly horizontal gradient map. This map is another form of a residual map meant to determine the edges of the causative (source) bodies more accurately.

The reduced bouguer and residual anomalies were then contoured and plotted using the GEOSOFT Oasis Montaj Mapping and Processing system. 2-D gravity modelling was carried out on anomalies of interest identified by the survey to determine the dimensions (shape, depth, thickness & dip) of the causative (source) bodies. The modelling was done using the PotentQ software, which is available as an extension to the GEOSOFT Oasis Montaj Mapping and Processing system.

RESULTS AND DISCUSSIONS

MICROGRAVITY ANOMALY MAP

The results of the survey are presented as bouguer, residual and horizontal gradient maps (Figure 3(a), 3(b) and 3(c)). The bouguer anomaly map is the primary basic map produced as output in any gravity survey. It indicates gravity variations due to both shallow and deep geological features. The residual map is a derivative map (generated from the bouguer anomaly map) which focuses on shallower geological features of interest which are relevant to this investigation. A residual map enhances and better defines subtle anomalies which are sometimes hardly recognizable on the bouguer anomaly map.

Like the residual anomaly map, the horizontal gradient map is a filtered map similarly derived from the bouguer anomaly map by applying a directional horizontal gradient filter. This map is targeted at defining the edge (which will be observed as peaks on the map) of the source attributed to the anomaly more accurately. Figure 3(a) shows the bouguer anomaly map of the survey site. The small range of gravity values from -9.24 to -9.10 mGal (maximum difference of only 0.14 mGal) is indication that the variations in limestone bedrock topography is not large. Extreme limestone bedrock topography is not to be expected.

An east-west trending gravity highs (> -9.15 mGal) dominate the bouguer anomaly map covering about 50% of the survey site. These gravity highs are typically associated with shallow limestone bedrock. Gravity lows ranging from -9.23 to -9.21 mGal are mainly observed south of the gravity highs. Isolated gravity low is observed to the north and north-west of the gravity highs. The limestone bedrock is generally deeper towards the southern end of the survey site. It is very likely that the isolated gravity low would be attributed to the presence of cavity (Eslam, Ahmed & Keisuke 2001). The residual anomaly map is shown in Figure 3(b). Removing the regional trend which constitutes deeper sources has the effect of enhancing shallower features of interest to the present investigation.

Gravity highs (> 0.01 mGal) cover roughly 50% of the site, mainly covering the northern section, whereas gravity lows dominate the southern section. Significant isolated gravity lows, including small low amplitude (KK-A and KK-B), are also observed within the region of gravity highs. All these isolated gravity lows are better defined on the residual anomaly map as compared to the bouguer anomaly map. The gravity highs (> 0.01 mGal) are interpreted as shallow limestone bedrock as opposed to gravity lows (-0.04 to -0.01 mGal) (attributed to deeper bedrock). However, the small difference in gravity values observed suggests that the variation in bedrock depths is small. The east-west trending gravity lows form a shallow (deduced from the small gravity difference) channel-like feature, deepening towards the east. Isolated gravity lows are commonly associated with cavity within the limestone. Branston and Styles (2003) state that the cavity is associated with negative gravity anomaly, after interpreted to be a region of migrating lower density.

The horizontal gradient map is presented in Figure 3(c). Although both the residual anomaly and horizontal gradient maps were derived from the same bouguer anomaly map, both the maps were generated for different purpose. Unlike the residual anomaly map, the horizontal gradient map serves to map the edges of the source (causing the anomaly) more accurately. Although both the bouguer and residual maps are able to identify anomalies, they are not able to resolve the edges of the source effectively. On the horizontal gradient map, edges of the source (causing anomaly) appear as peaks. Several peaks are identified and marked on the map as shown in Figure 3(c). Peaks close to the isolated gravity lows represented the edges of the interpreted cavity. Several other peaks observed are likely edges of the channel-like feature and/or edges of the shallow bedrock.

2-D GRAVITY MODELLING

Four profiles (AA', BB', CC' and DD' in Figure 4) were extracted for 2-D gravity modeling. All the modeling were carried out assigning a density of 2.30 gm/cc for the limestone bedrock and 1.80 gm/cc for sediment (Telford, Geldart & Sheriff 1990). Profiles AA' and BB' were modeled as the deepest part of the channel. Profiles CC' and DD' were modeled as air-filled and sediment filled cavity respectively. The 2-D gravity models were developed based on the signature and trend of the anomaly and guided by boreholes data.

2-D gravity models of Profiles AA' and BB' are shown in Figures 4 and 5. Both these profiles were selected to cross the deepest part of the channel. The deepest part of the channel across Profile AA' is about 3.5m with a width opening reaching to about 16 m. It is a little shallower (2 m) across Profile BB' however, with similar width opening. Figures 6 and 7 show the results of 2-D gravity modeling for Profiles CC' and DD'. Profile CC' was modeled as an air-filled cavity whereas Profile DD' as sediment-filled. The air-filled cavity (Figure 6) indicates a thickness of only 0.5 m located at 0.5 m depth from the limestone bedrock level. The width extent is about 13 m. Figure 7 shows a sediment-filled cavity with a thickness reaching up to 7 m and a width extent of about 15 m. The depth from the limestone bedrock is between 0.5 m and 1 m.

Isolated gravity lows KK-A and KK-B were not modeled as they were small with very low amplitude. If these are due to cavities, they would have very small thickness and width extent. It should be noted that the isolated gravity low where Profile DD' was extracted is an open- ended anomaly to the north. As such, the anomaly is not well defined. Unlike the other profiles, which was extracted in an almost north-south direction, Profile DD' is in an almost east-west direction as this was the best profile where there were microgravity measurements made along the profile.

CORRELATION WITH BOREHOLES

Four boreholes (NCBH-137, BH UG-48, KBH-2 and KBH-4) were previously drilled at the site (Figure 8). Out of the four boreholes only BH UG-48 falls within the site investigated. The other three boreholes were located just outside the site which unfortunately, was not covered by the microgravity survey. NCBH-137 was located to the north of the survey site whereas KBH-2 and KBH-4 were located to the south.

All the boreholes hit bedrock between 9.6 m and 12.3 m, except for KBH-4, which intersected limestone bedrock at 21 m. This is consistent with the microgravity findings which indicate the limestone bedrock is deeper

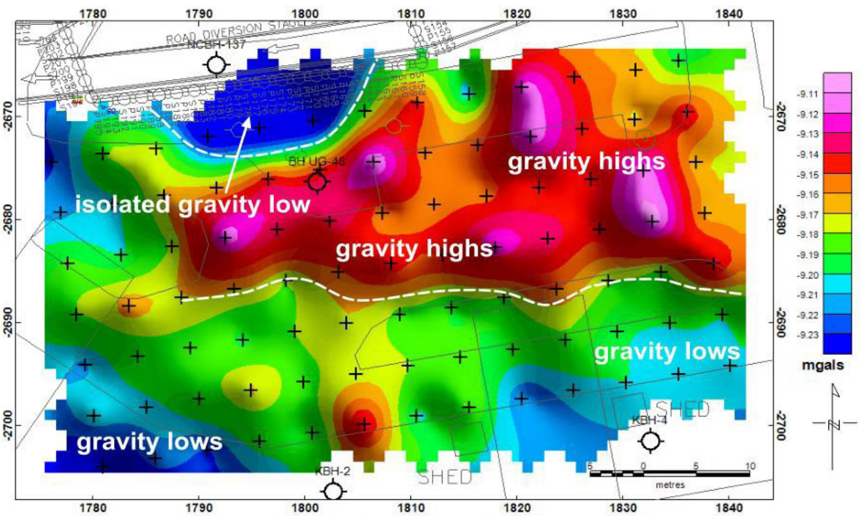

FIGURE 3(a). Bouguer anomaly map

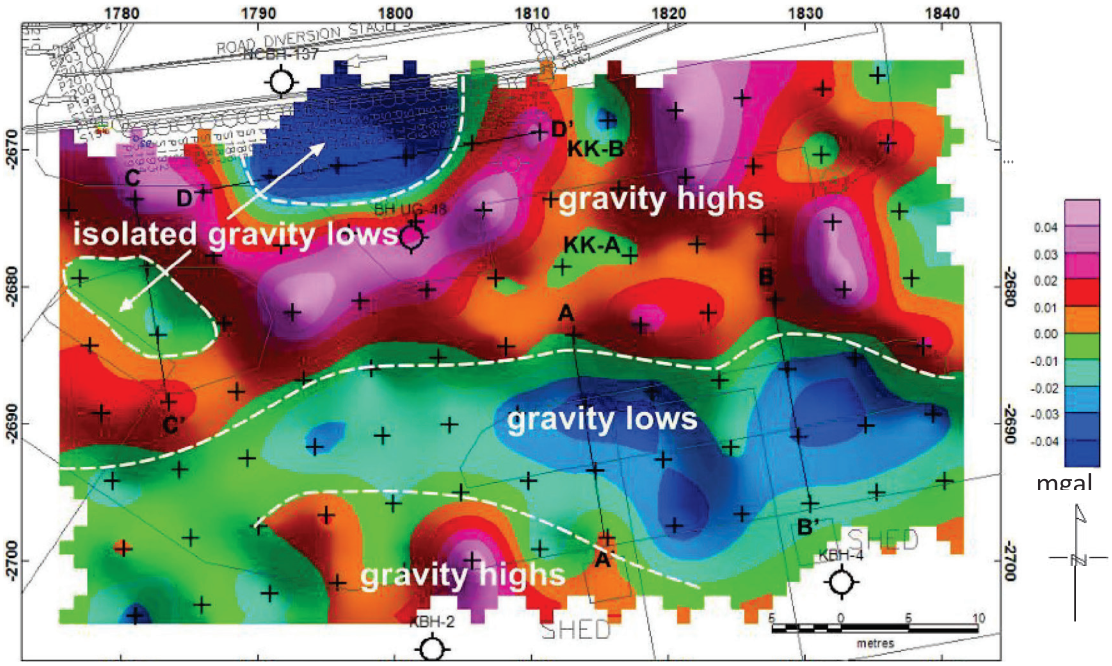

FIGURE 3(b). Residual anomaly map

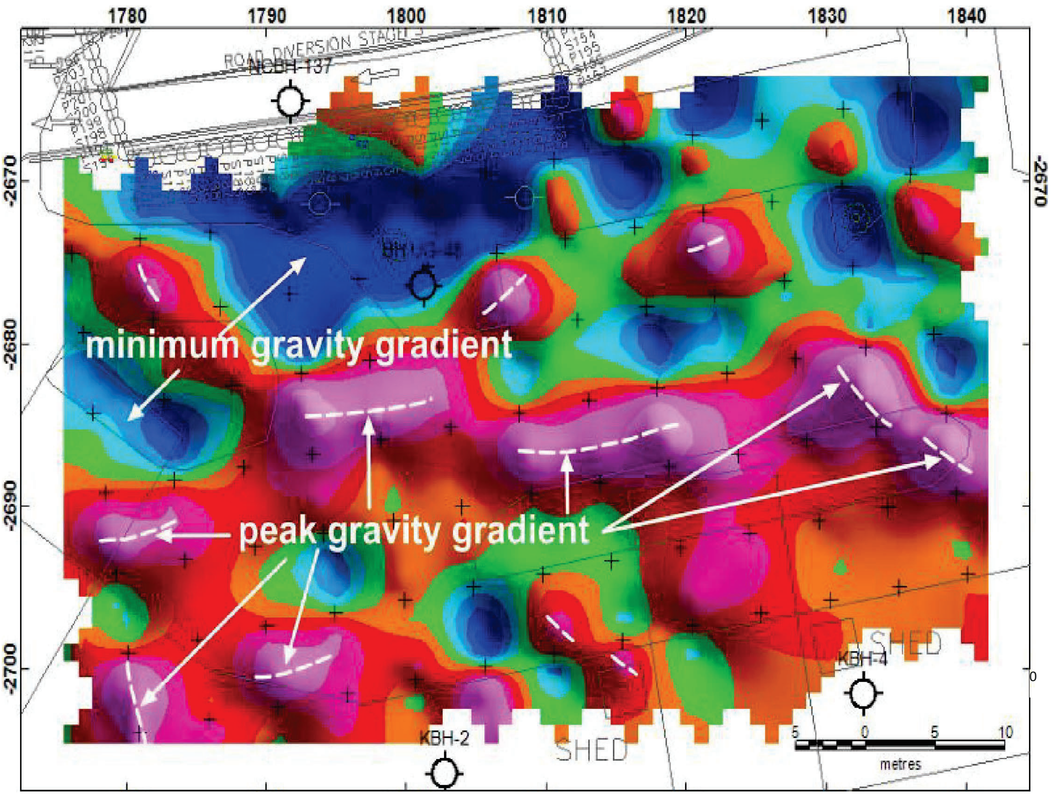

FIGURE 3(c). Horizontal gradient map

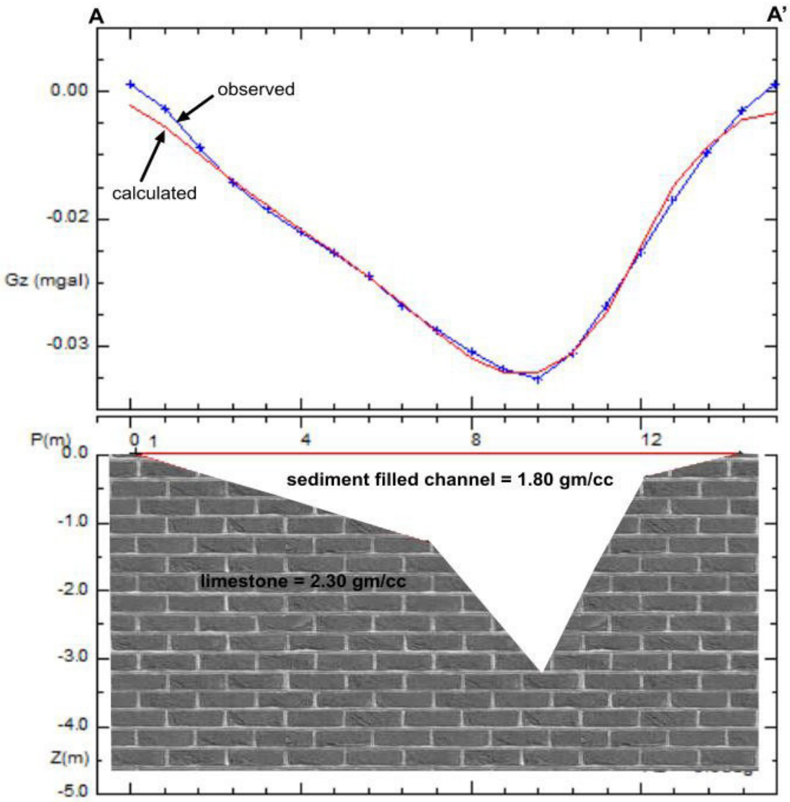

FIGURE 4 . 2-D gravity model of profile AA'

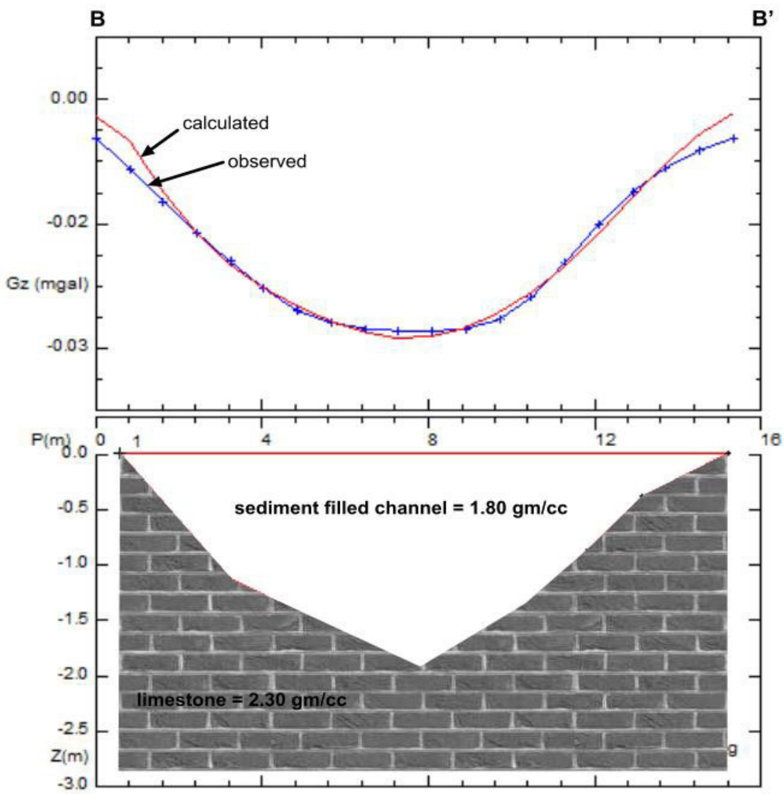

FIGURE 5 . 2-D gravity model of profile BB'

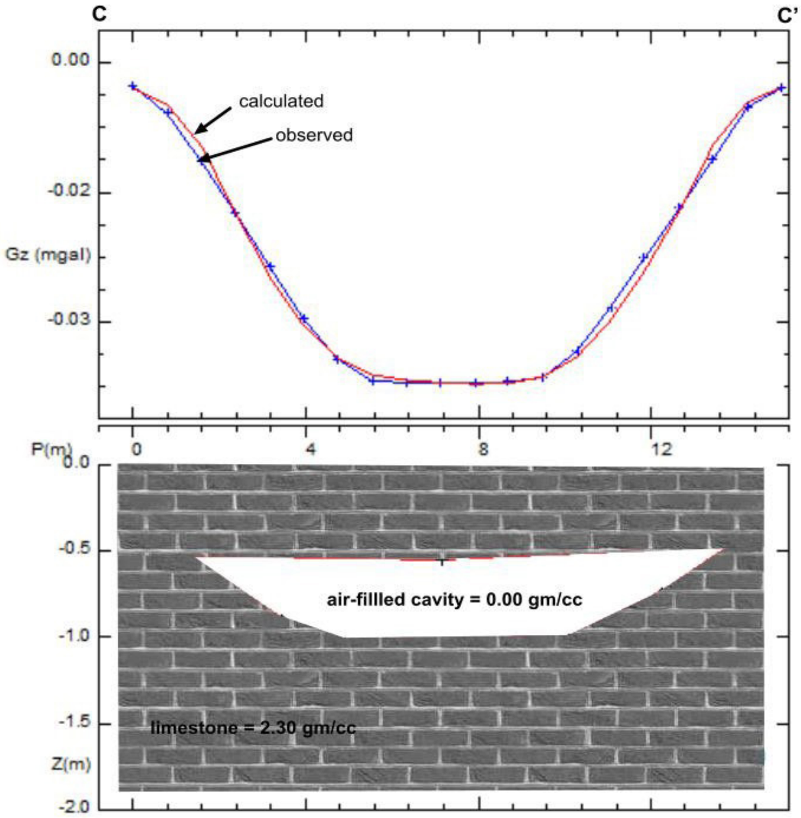

FIGURE 6 . 2-D gravity model of profile CC'

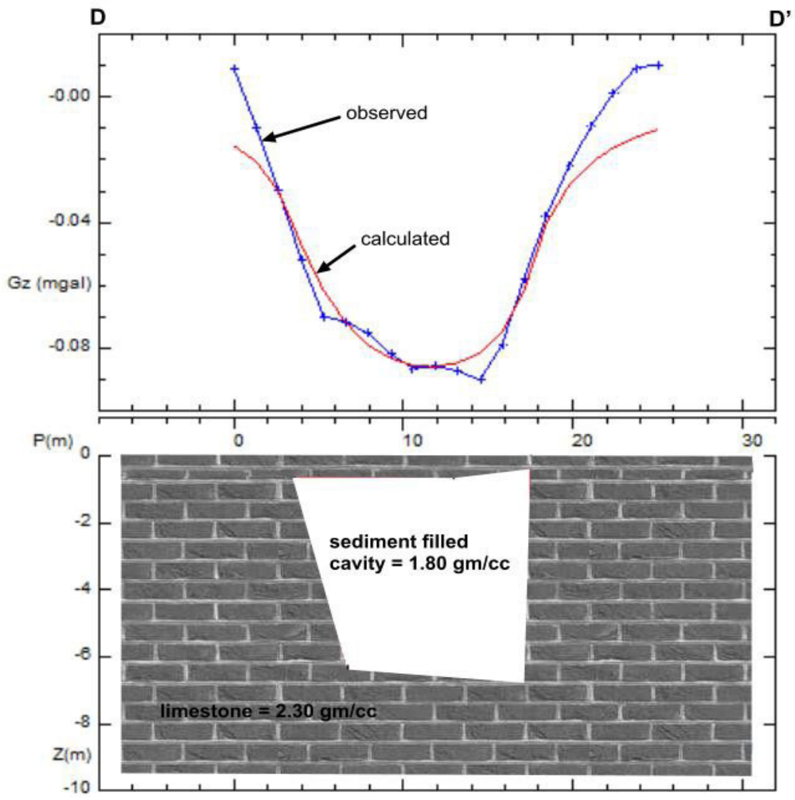

FIGURE 7 . 2-D gravity model of profile DD'

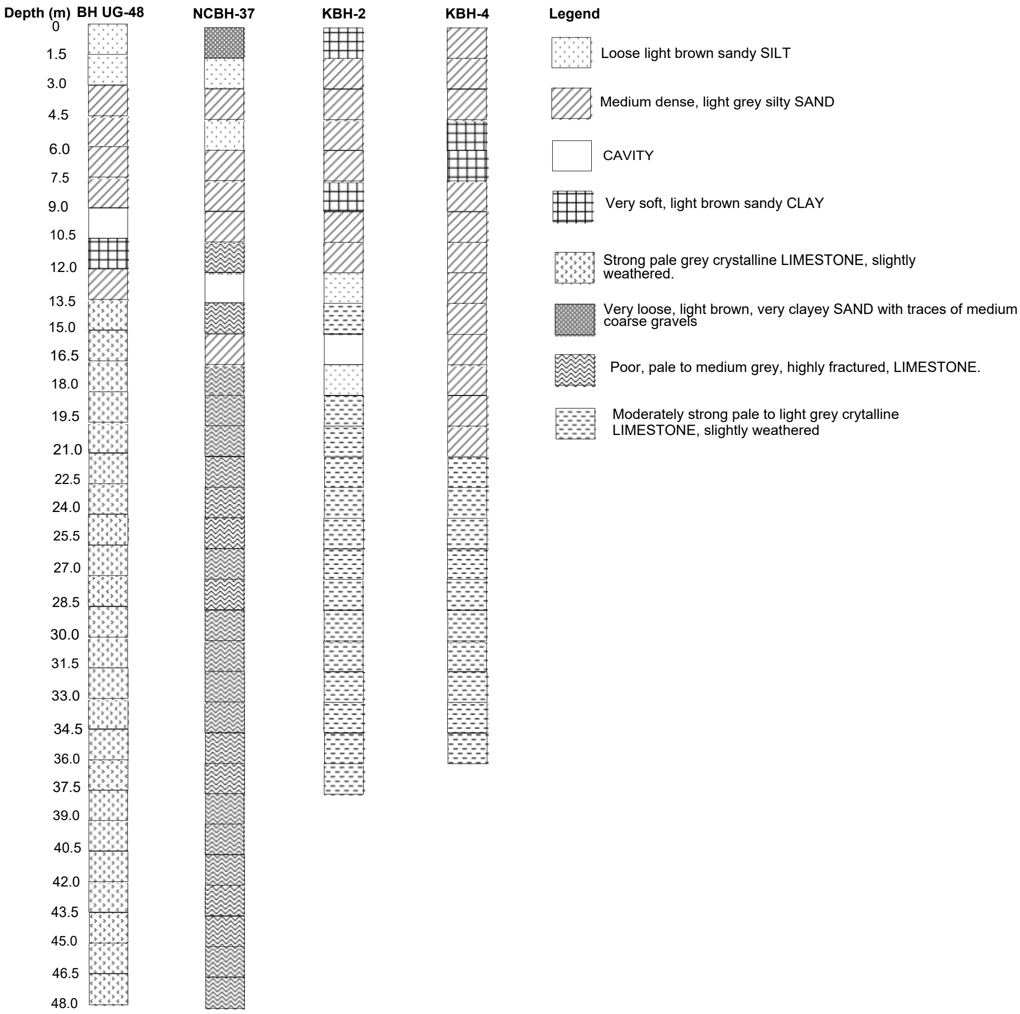

FIGURE 8. Summary of borehole records at the study area

towards the south of the survey site. However, KBH-2 indicated shallow limestone bedrock which was intersected at 12.3 m. This is again consistent with the microgravity findings (Figure 3(b)) where the gravity highs (indicating shallow limestone bedrock) observed are expected to extend further south towards KBH-2.

NCBH-137 and BH UG-48 intersected a 0.9 m and 3.3 m sediment-filled cavity, respectively. NCBH-137 hit cavity at 1.5 m whereas BH UG-48 intersected cavity at 0.3 m depth below the limestone bedrock. Profile DD' was modeled as a sediment-filled cavity with shallow depths of between 0.5 m and 1 m from the limestone bedrock level. The 2-D gravity modeling (Figure 7) indicate a sediment-filled cavity reaching-up to about 7 m in thickness with an almost east-west width extent about 15 m. The 2-D gravity modeling results is reasonably in good agreement with the boreholes.

CONCLUSIONS

This study demonstrates the effectiveness of gravity surveys in identifying subsurface features crucial for foundation planning. The microgravity survey showed a shallow limestone bedrock covering nearly 50% of the site in the north, while a deeper limestone bedrock was observed in the south, forming an east-west trending channel-like feature. 2-D gravity modeling along four profiles confirmed the deepest parts of the channel and identified potential cavities (both air-filled and sediment-filled). The findings align well with borehole data, confirming the subsurface characteristics. Boreholes generally intersected limestone bedrock between 9.6 m and 12.3 m, except for KBH-4, which encountered deeper bedrock at 21 m, consistent with the microgravity survey indicating a deeper bedrock trend towards the south. Additionally, KBH-2 confirmed a shallow limestone bedrock at 12.3 m, matching the gravity highs observed in the survey. Borehole data also validated the presence of sediment-filled cavities, with 2-D gravity modeling indicating a cavity thickness of up to 7 m and an east-west width of approximately 15 m. These results highlighting the reliability of microgravity surveys in assessing subsurface conditions for foundation planning.

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REFERENCES

Abdeitawab, S. 2013. Karst limestone foundation geotechnical problems, detection and treatment: Case studies from Egypt and Saudi Arabia. *International Journal of Scientific & Engineering Research* 4: 376-387.

Agus, S., Yoichi, F., Jun, N. & Takahito, K. 2015. Detecting land subsidence using gravity method in Jakarta and Bandung Area, Indonesia. *Procedia Environmental Sciences* 23: 17-26.

Ahmad, T.I. & Noorliza, C.L. 2004. Detecting subsurface voids using the microgravity method - A case study from Kuala Lipis, Pahang. *Geological Society of Malaysia Bulletin* 48: 31-35.

Arisona, A., Ishola, K.S., Muliddin, M., Hamimu, L.A. & Hasria, H. 2023. The potential of microgravity technique in subsurface cavities detection at Chan Sow Lin Site in Kuala Lumpur, Malaysia: A case study. *Modeling Earth Systems and Environment* 9: 771-782.

Beres, M., Luetscher, M. & Olivier, R. 2001. Integration of ground-penetrating radar and microgravimetric methods to map shallow caves. *Journal of Applied Geophysics* 46(4): 249-262.

Branston, M.W. & Styles, P. 2003. The application of time-lapse microgravity for the investigation and monitoring of subsidence at Northwich, Cheshire. *Quarterly Journal of Engineering Geology and Hydrogeology* 36(3): 231-244.

Eslam, E., Ahmed, S. & Keisuke, U. 2001. Detection of cavities and tunnels from gravity data using a neural network. *ASEG Extended Abstracts* 2001(1): 1-5. DOI: 10.1071/ASEG2001ab036

Gambetta, M., Armadillo, E., Carmisciano, C., Cocchi, L. & Tontini, F.C. 2011. Determining geophysical properties of a near-surface cave through integrated microgravity vertical gradient and electrical resistivity tomography measurements. *J. Cave Karst Stud.* 73: 11-15.

Gómez, O. & Martín, C. 2012. Assessing the risk of subsidence of a sinkhole collapse using ground penetrating radar and electrical resistivity tomography. *Engineering Geology* 149-150: 1-12.

Gyesoon, P., Samgyu, P., Myeong, J.Y., Hyoungrae, R., Seong, J.C. & Jung, H.K. 2010. Geostatistical integration using 2-D electrical resistivity and 3-D gravity methods for detecting cavities in a karst area. *Environ. Earth Sci.* 60: 965-974.

Hutchison, C.S. & Tan, N.K.D. 2009. *Geology of Peninsular Malaysia.* Geological Society of Malaysia, University of Malaya.

Jabatan Mineral dan Geosains Malaysia. 2011. *Geology and Mineral Resources of the Kuala Lumpur-Kelang Area*. MapReport. p. 22.

Kim, J.H., Yi, M.J., Hwang, S.H., Song, Y., Cho, S.J. & Lee, S.K. 2003. Application of integrated geophysical methods to investigate the cause of ground subsidence of a highly civilized area. *Journal of Geosystem Engineering* 6(3): 74-80.

Mohamad Ayob. 1970. Quaternary sediments at Sungai Besi, West Malaysia. *Geological Society of Malaysia Bulletin* 3: 53-61.

Muhamad Zaki, Z. 2019. Cavities detection by using microgravity and 2-D resistivity method in karst area. Master Dissertation, Universiti Sains Malaysia (Unpublished).

Neumann, R. 1967. Gravimetry of high precision application to cavities research. *Geophysical Prospecting*: 34-116.

Nouioua, I.A., Rouabhia, C., Fehdi, M.L., Boukelloul, L., Gadri, D., Chabou, R. & Mouici. 2013. The application of GPR and electrical resistivity tomography as useful tools in detection of sinkholes in the Cheria Basin (northeast of Algeria). *Environ. Earth Sci*. 68: 1661-1672.

Reynolds, J.M. 1997. *An Introduction to Applied and Environmental Geophysics*. Chichester: John Wiley & Sons.

Sobh, M. 2013. *Imaging Subsurface Cavities Using Geoelectric Tomograpgy, Ground-penetrating Radar and Microgravity*. Near Surface Geoscience 2013, 19th European Meeting of Environmental and Engineering Geophysics.

Telford, W.M., Geldart, L.P. & Sheriff, R.E. 1990. *Applied Geophysics*. Cambridge: Cambridge University Press.

Trepil Fouzie, M.A. 2021. Integrated geophysical survey in identifying ground subsidence-prone area. Master Dissertation, Universiti Sains Malaysia (Unpublished).

Youssef, A.M., Al-Harbi, H.M., Gutierrez, F., Zabramwi, Y.A., Bulkhi, A.B., Zahrani, S.A., Bahamil, A.M., Zahrani, A.J., Otaibi, Z.A. & El-Haddad, B.A. 2016. Natural and human-induced sinkhole hazards in Saudi Arabia: Distribution, investigation, causes and impacts. *Hydrogeol. J.* 24: 625-644.

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