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Detecting subsurface voids using the microgravity method – A case study from Kuala Lipis, Pahang

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Abstract: The gravity method is one of the more popular geophysical methods to detect subsurface voids. The voids, whether they are filled with air or water, will give anomalous gravity lows above their localities. The gravity pattern is also related to subsurface topography of the bedrock. A borehole drilled earlier indicated a possibility of a cavity. This study was conducted to see if the suspected cavity could also be detected by gravity method. Based on the borehole information, the lithology of the area comprises sandy clayey silt with limestone bedrock. A total of 42 observations were made in four profiles bearing east-west and north-south along the bunds (*batas*) of a paddy field. The survey area measured 50 m by 40 m. Readings were made at 5 m spacing, using a LaCoste-Romberg Model D gravimeter. This instrument was chosen because of its capability for detecting minute changes in the earth gravity field caused by local anomaly. The results indicate the possibility of cavities at four locations at depths varying from 3.77 to 6.50 m. The depth to the center of each anomalous body was calculated using the half-width method. The depth of the cavity interpreted from the borehole turned out to be shallower when the field gravity data is inverted using that method. The cavities were probably filled with wet sediments of densities between 1.85 to 2.05 g/cm^3.

Abstrak: Kaedah graviti merupakan salah satu kaedah geofizik yang popular untuk mengesan lohong bawah tanah. Lohong, samada diisi oleh udara atau air, akan memberikan bacaan rendah berbanding sekeliling sekiranya ketumpatan lohong kurang dari batuan sekeliling. Corak anomali juga boleh dikaitkan dengan topografi subpermukaan. Penggerudian yang dibuat terdahulu menunjukkan kemungkinan wujudnya lohong. Kajian ini dijalankan untuk menentukan samada lohong ini boleh dikesan dengan menggunakan kaedah graviti. Maklumat lubang gerudi menunjukkan geologi kawasan ini terdiri daripada lodak berpasir dan berlempung dengan batukapur sebagai batuan dasar. Sebanyak 42 bacaan dicerap sepanjang beberapa garis timur-barat dan utara-selatan mengikut batas yang ada. Luas kawasan adalah 50 m x 40 m. Cerapan dibuat menggunakan gravimeter LaCoste-Romberg Model D. Peralatan ini dipilih kerana keupayaannya mengukur perubahan mikro dalam medan graviti bumi yang disebabkan oleh anomali setempat. Keputusan yang diperolehi menunjukkan kemungkinan wujudnya lohong di empat lokasi, pada julat kedalaman antara 3.77 hingga 6.50 meter. Kedalaman ke titik pusat anomali dikira menggunakan kaedah separa lebar (half-width). Kedalaman lohong pada lokasi penggerudian didapati adalah lebih cetek daripada kedalaman yang ditafsirkan daripada data graviti. Lohong ini berkemungkinan dipenuhi oleh sedimen basah yang berketumpatan antara 1.85 ke 2.05 g/sm^3.

INTRODUCTION

The objective of this project was to delineate subsurface cavity in an area where a borehole was drilled and a cavity interpreted. A cavity would create an anomaly due to the density contrast between the cavity and the host rock. The microgravity method was chosen. The microgravity method is widely used in locating cavities (Samsudin, 2003). The location of the survey area is shown in Figure 1. From the borehole information, the lithology of the area was determined to consists of sandy clayey silt on top and limestone as the bedrock. Limestone areas are normally associated with karst topography, which includes pinnacles, subterranean voids or caves that are filled with air, water or debris. No other borehole data is available in this area except for the one mentioned above.

GEOLOGY

The area is underlain by limestone of Upper Permian age (Lim, 1994). In the low lying areas they consist of dolomitic wackestone and grey-coloured oolitic packestone-grainstone. The lithology makeup of the survey area was shown in the borehole report as being sandy, clayey silt on top of limestone bedrock (Figure 2). The silt layer in the borehole occupied the first 6 meters from ground surface, followed by a cavity from 6 m to 10.4 m. Limestone bedrock is found from depths of 10.4 m onwards. There is no subsidence or sinkholes observed in this area.

THE GRAVITY METHOD

The method chosen is microgravity, which was found in various studies as one of the best ways to detect subsurface cavities (Samsudin, 2003). The gravity survey is a method in which a gravimeter is used to measure the strength of the earth's gravity field. Microgravity survey is the term used when the area of the survey is small and when the objective of the survey is to locate local anomalies. The gravimeter used for this study was the La Coste – Romberg Model D. The gravimeter is capable of detecting minute changes, as small as 1 per one millionth of the earth's gravity field, which is caused by variations in the macro (regional) scale and micro (local) scale.

The gravity method detects the variation in densities. A cavity in limestone can either be filled with air or water or debris (Samsudin, 2003). Table 1 gives the densities of limestone, air, water and other materials that might be present here. If there is sufficient change in density, the gravimeter would then record a gravity low on top of the cavity. The best response would be from an unfilled (or air-filled) cavity because of the high contrast in density between air and the host rock. A gravity high is produced if the subsurface density contrast is positive (target is denser than host rock) such as the presence of pinnacles or subsurface topographic highs.

The gravity data has to be reduced to remove external factors affecting the reading, other than the local gravity anomaly. Among the corrections that need to be applied to raw gravity data are the drift correction (to remove the effects from instrumental drift and natural tide), elevation correction (to remove the effects of varying heights between stations) and latitude correction (to remove the varying density due to locations on earth). The data also has to be separated from the regional anomaly caused by the gravity effects in the macro scale, before any interpretation can be done to ensure the anomaly analyzed is truly from a local source.

Other important considerations that have to be made were altitude determination and the location of the base station. Altitude correction is only necessary if there is significant difference in height between stations, which is not the case here. The base station's reading will be used in the calculation for drift and other corrections. The base station should be located at a stable place, with known station location and the least amount of anticipated error or noise.

Table 1. Densities of rocks and materials found in the study area. Modified from Telford *et al.* (1990) and Samsuddin (2003)(*).

Material	Density (g/cm^3)	
	Range	Average
Limestone (wet)	1.93 -2.90	2.55
Limestone (dry)	1.74 – 2.76	2.11
Limestone bedrock *	2.64 – 2.75	2.65
Water	0.9 – 1.1	1.0
Air	0	0
Loose sediment (wet)	1.7 – 2.4	2.1
Loose sediment (dry)	1.4 – 2.2	1.6
Clayey, Sandy Silt *	1.4 – 1.8	1.6

Figure 1. Location map.

One should also be aware of the noise and error that might occur in the gravity survey area so that the readings made truly represents the anomaly. Error and noise will lower the accuracy of the results.

FIELDWORK AND DATA COLLECTION

The fieldwork for the gravity survey was carried out for two days. The site of the borehole was in the middle of a paddy field. The selection of station locations was limited to the availability of "batas" or bunds. These raised soil boundaries, separating the individual compartments in a paddy field, were the only dry area suitable to put the gravimeter on. It would have been better to put the gravimeter in the compartments but those were soggy from a recent downpour. The bund has to be wide enough for the instrument to stand on and stay stable throughout the survey. There was also an unexpected obstacle in the form of water buffaloes protecting their territories and their young.

Given the area that had to be covered in this survey and the size of the anomaly expected, the distance between stations was set at 5 meters. The distance was considered sufficient for this reconnaissance site investigation.

One of the crucial field decisions was choosing the base station. The base station would be used for drift correction. In this area, the location of the base station was selected at the borehole location because its exact location was already established. Furthermore, it was the best (stable) location to place the gravimeter, with the widest bund. The base station was located (using a GPS receiver) at coordinates 4°11.12' N and 101°58.37' E and at an elevation of 105 meters above sea level.

The bunds in this particular paddy field are arranged in a non-uniform rectangular grid with the north-south bunds at a bearing of about 030° while the east-west bunds are roughly orthogonal to the north-south ones.

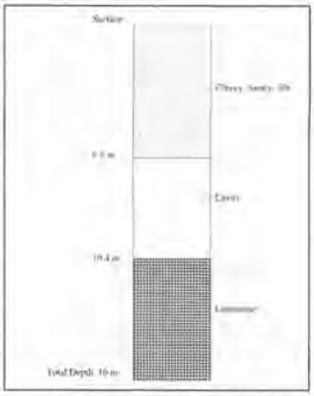


Figure 2. Borehole log at the Base Station.

A total of 42 readings were taken, mostly along four profiles while others served as fill-in points. The readings taken were converted to miligals, a common unit used in microgravity survey. No altitude readings were taken because the area was quite small and flat. The stations were located at regular spacing along a series of straight lines whenever possible. However, due to the lack of flat and stable surface to put the gravimeter on at some places, the resulting grid was somewhat irregular and incomplete. This would later affect the appearance of the gravity contour map.

Among the noises expected in this area are the presence of natural noise (e.g. fauna and flora activities) and man-made noise (e.g. traffic and discarded metal objects). Repeating the readings at least twice minimized the error, ensuring that the readings did not differ by more than 0.01 mgal.

DATA PROCESSING AND INTERPRETATION

Data Correction

For this particular set of data, the only correction done was the drift correction. No elevation correction was necessary because of the flat topography. The latitude correction was also not necessary because all stations were located within the same latitude. Drift correction was done to correct the data for the drift in the readings caused by the instrument and the earth's tidal effects. Readings were taken in a looping sequence, starting and ending at the base station. Repeat readings were done at the base every hour. These readings taken at the base were plotted against time. Drift correction was calculated from the slope (in terms of miligals per minute) and applied to every reading taken according to the time lapse between readings. After correction, the first and last base readings should be equal.

Regional Data Reduction

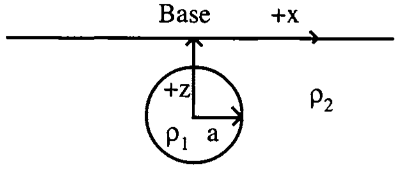
The readings were then plotted against distance for every profile. These readings represent the total gravitational field of the area, the sum of local and regional gravity. Before any interpretation could be done, the regional effect has to be removed. In this study, however, the regional effect was found to be little to none, and was ignored. The gravity values plotted are taken as the residual gravity anomaly.

Interpretation

When it comes to interpretation in geophysics, each interpretation is not unique, with more than one way to interpret the data. Different conclusion can be drawn based on the same data. In this interpretation, the main assumption is that the gravity lows are caused by cavities only. The readings are normalized relative to base, meaning that the base reading was subtracted from all of the readings. The resulting base reading was zero. The borehole data was used as a constraint for the determination of other anomalies in this area.

Table 2. Calculations to the center of the anomaly using the Half-Width Method.

Coordinates	Max. Amplitude g_{max} (mgal)	Depth to center of anomaly (m)
0,0	-0.25	6.50
-7,-8	-0.11	3.90
-14,-8	-0.44	3.77
-4,-18	-0.20	4.55



$$g = k\rho a^3 z / (x^2 + z^2)^{3/2}$$

where $k = 27.9 \times 10^{-3}$
a = radius of the sphere
z = depth to the center of the sphere
x = distance from the center of the sphere
ρ = difference in density = $\rho_1 - \rho_2$

Figure 3. Effect of a spherical body on gravity, with units in meters and g/cm^3 (modified from Telford *et al.*, 1990).

Qualitative Interpretations

Comparison to simple shapes

According the borehole information, a cavity was found between the depths of 6 to 10.4 meters. The effect of a spherical body can be calculated using the equation in Figure 3.

Information from the borehole log was used for this calculation. The radius of the anomaly, 'a' is assumed to be 2.2 m, the density deficit, r, varies from -2.6 for air-filled to -1.6 for water-filled to –1.0 debris-filled. The depth to the center of the anomaly, 'z' is set to 8.2 m. The resulting curves are illustrated in Figure 4. None of the curves fit the one from the field data; the profile across the borehole gives maximum amplitude of –0.25 mgal. Assuming the radius and depth of the cavity remain constant, the density deficit that produces the curve to match that of the field is -0.55, giving the average density of the anomaly as 2.05 g/cm^3 (curve labeled as "simulated"). That density is consistent to that of wet sediments (Table 1). This implies that the cavity is not empty, but filled with water-saturated sediments.

Profile Lines

A total of 42 gravity readings were taken along several profiles. The main two profiles, Line 1 (north-south) and Line 2 (east-west), ran through the base station. Lines 3 to 7 were taken in the east-west orientation at various offsets roughly parallel to Line 2. The locations of the stations were superimposed on the gravity contour map (Figure 5). Line 1 had to be offset at some points to follow the bunds available.

Of all the lines, only four (Line 1, 2, 3 and 5) have enough points to create profiles showing significant change in gravity needed for interpretation. Line 4, 6 and 7 are too short to be evaluated individually.

Line 1 (Figure 6) shows a negative anomaly at the base, consistent with the borehole information. There are other undulations on the curve. These may be due to smaller structures or noise. For this paper, only anomalies larger than 0.1 miligals are considered.

Line 2 is located perpendicular to Line 1, with the crossing at the base. Like Line 1, Line 2 (Figure 7) also shows a negative anomaly at the base as expected. There is also a peak at +15 meters. In a limestone area, either a pinnacle or a topographical high can cause a positive gravity anomaly. In this case, however, the source of the anomaly may be nearer to the surface. The station was located at the base of a big tree. The increase in density might be caused by the dense root system of the tree.

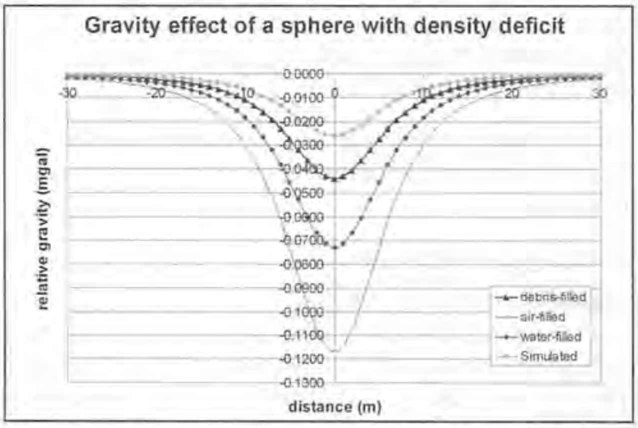


Figure 4. Theoretical gravity curves for a buried sphere of varying densities. The different curves correspond to different materials that may fill the cavity.

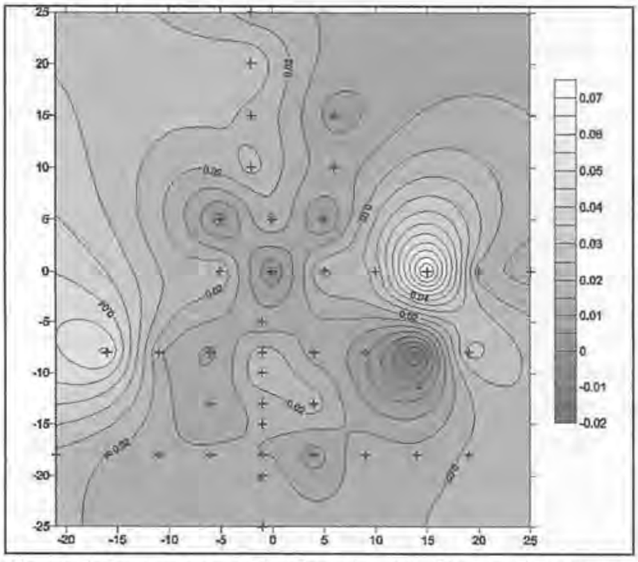


Figure 5. Contour map of field gravity data. Distance is in meters and gravity in mgal. Stations are marked with '+'s.

Line 3 is located 8 meters south of Line 2. The profile (Figure 8) shows two lows, one at –7 m and another at +14 m. The first anomaly has an amplitude of -0.11 mgal, implying the source could be smaller that the one at the base. The second anomaly's amplitude is –0.42 mgal, almost twice as much as the one at the base. The increase implies that the source is larger than the one at the base. There is also an anomalously high reading at –15 m. This gravity high is caused by a denser object, for example limestone pinnacles or buried metal / high-density objects.

Line 5 is located 18 m south of the east-west baseline. The profile (Figure 9) shows a gravity low at +4m. The amplitude, 0.2 mgal, which is smaller than the one at the base, implies that the source is smaller than the one at the base.

Contour map

All the readings are combined to produce a contour map of the area using the SURFER software. The contours are based on the point of observations that do not fall on regular grid. The unevenness in data collection makes the map incomplete, lacking information in some areas and causing anomalies to fall directly on coordinate crossings.

The map (Figure 5) shows four distinct gravity lows (dark color) – at x-y coordinates of (0,0), (-7,-8), (14,-8) and (4,-18), and two gravity highs (light color) – at coordinates of (0,-15) and (-15,-8). Assuming the lows are caused by cavities, the map suggests possible cavities at the four locations mentioned above. Different magnitudes suggest differences in size and/or depth of burial.

Quantitative Interpretation

Half-Width Method

One of the ways to estimate the depth to the center of the anomaly is using the half-width method (Telford *et al.*, 1990). According to this method, the depth of the anomaly is proportional to the width at half the maximum amplitude, given in the equation:

When $g = g_{max} / 2, \quad z \sim 1.3\, x$.

The assumption made is that a sphere causes the anomaly. The resulting curve should be symmetrical. Any non-symmetricalness in the anomalies would contribute to the inaccuracy of the interpretation.

The results for the calculations are tabulated in Table 2. The anomaly at the base, coordinate (0,0), is located at a depth of 6.5 m. This is shallower than the depth of cavity interpreted from the borehole information (8.2 m). One explanation is that the surface height has been reduced in the time between when the borehole was logged and the present height. If this depth is used in the calculation of a buried sphere, this would correspond to a density deficit of 0.75, implying a material with a density of 1.85 g/cm^3. Even though this is lower than the density mentioned before, it still falls within the category of wet sediments, probably with more air. The other three anomalies are located at shallower depths of 3.77 to 4.55 m.

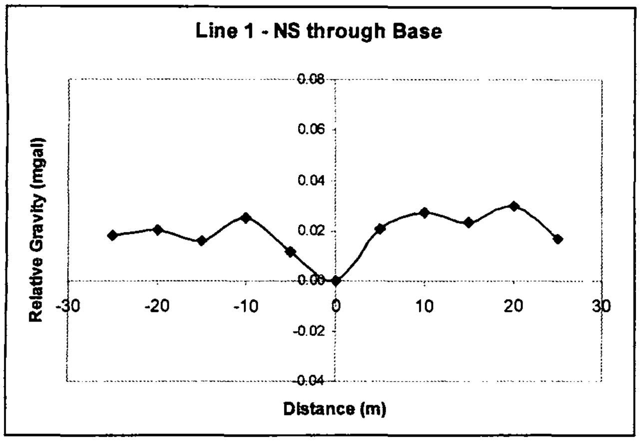


Figure 6. Gravity profile of Line 1. Base Station is located at (0,0).

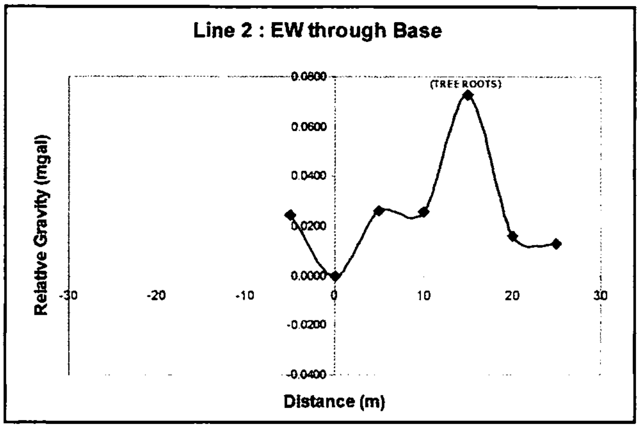


Figure 7. Gravity profile of Line 2. Base Station is located at (0,0).

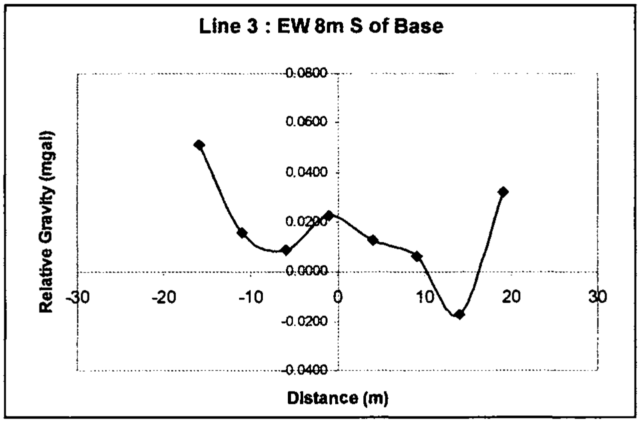


Figure 8. Gravity profile of Line 3, located 8 meters south of Line 2 (Baseline).

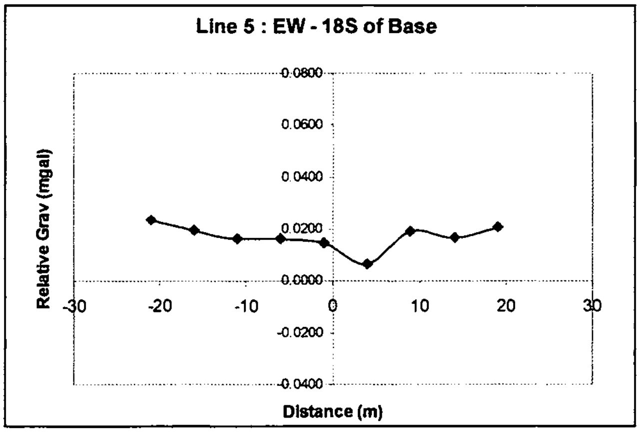


Figure 9. Gravity profile of Line 5, located 18 meters south of Line 2 (Baseline).

DISCUSSION AND CONCLUSION

The study was designed as a reconnaissance survey of the area. The 50 m by 40 m area was surveyed using 5-m spacing. Readings were only taken at 42 selected points, limited by the availability of the bunds. Four profiles and a contour map were made. From these, four locations of gravity lows and two locations of gravity highs were identified. Using calculations for response of a simple geometric shape, the anomaly was suggested to be caused by cavities filled by wet sediments. The half-width method puts the depths to the center of the anomalies at 3.77 to 6.50 meters.

A more detailed study, with closer spacing and covering a larger area, is recommended in this area to delineate the subsurface with better accuracy on the size and location of the cavities. At least one borehole should be drilled to physically confirm the existence of a probable cavity and to verify the filling material. Modeling, using modeling software such as GMODEL, should be done to model the subsurface with better accuracy and in greater detail.

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