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A microgravity survey over deep limestone bedrock

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Abstract: A microgravity survey had been carried out within a residential area. A total of 141 gravity values was obtained over an area of about 500 by 300 m^2. These data were obtained along the roads within the study site. The boreholes within the area indicate that the area is underlain mainly by fine grained material namely silty clay, silty sand, clayey silt and sandy clay. Near the bedrock coarser material such as pebble and gravel may be present. The density of this clayey material is 1.4 to 1.8 gc/m^3. The bedrock is limestone and has density of 2.64 to 2.75 gc/m^3. From the borehole data the limestone within the study area is at about 27 to 33 m deep.

A major problem within the study area is the presence of subsurface mass movement. This is indicated by the formation of large scale undulation on the ground both on the road and within the house areas and the cracks on the building structure including drains, walls and pillars. Both lateral and vertical movement occur on these structures indicating lateral and vertical mass movement. It has been suggested that collapsing of cavity roof within the limestone can be the cause. The microgravity survey was aimed at trying to determine the presence of the cavity. With the borehole data, the gravity modelling is very well constrained. The modelling indicates that the subsurface topography of the limestone is made up of a series of ridges and valleys. Possible occurrence of the cavity within the ridges has also been modelled.

Abstrak: Satu survey mikrograviti telah dijalankan di kawasan perumahan. Sejumlah 141 nilai gravity telah dikutip di kawasan seluas lebih kurang 500 x 300 meter^2. Data gravity ini dikutip di sepangang jalan yang terdapat di kawasan perumahan tersebut. Lubang gerudi di kawasan ini menunjukan kawasan ini dilapisi oleh bahan berbutir halus seperti lempong berlodak, pasir berlodak, lodak berlempong dan pasir berlempong. Berdekatan dengan batudasar bahan berbutir kasar seperti pebel dan gravel hadir. Ketumpatan bahan berlempung ini berjulat 1.4 hingga 1.8 g/cm^3. Batudasannya adalah batukapur dan mempunyi ketumpatan berjulat 2.64 hingga 2.75 g/cm^3. Dari lubang gerudi dalam kawasan ini kedalaman batukapur ini adalah di sekitar 27 hingga 33 meter.

Satu masalah besar dalam kawasan kajian adalah terdapatnya pergerakan jisim subpermukaan. Ini dikenalpasti dari pembentukan mukabumi yang beralun di jalan dan di kawasan rumah,dan retakan pada struktur bangunan termasuk parit, dinding dan tiang. Pergerakan tegak dan mendatar berlaku pada struktur struktur ini menandakan pergerakan jisim mendatar dan tegak telah berlaku. Ada cadangan mengatakan bahawa runtuhan bumbong lohong dalam batukapur adalah penyebabnya. Survei gravity adalah ditujukan untuk cuba menentukan kedapatan lohong dalam batukapur. Dengan adanya data lubanggerudi pemodalan gravity dapat di kawalan dengan baik. Ia membolehkan penentuan topografi batukapur yang terbentuk dari satu siri rabong dan lembah ditentukan. Kemungkinan adanya lohong dalam rabong batukapur tersebut juga telah di modelkan.

INTRODUCTION

A microgravity survey has been carried out in a residential area in Ipoh, Malaysia. Within this residential area the infrastructure such as the roads and houses sit on filled material. This filled material sits on clayey material of about 30 m thick. Underlying the clayey material is the limestone bedrock. Over the years the roads become undulating and some of the houses develops cracks. These have been associated to subsurface mass movements. Based on the surface movement on both the roads and the buildings there appear to be both lateral and vertical subsurface mass movement occurring. It is not obvious weather the movement is near surface or deep-seated. Based on this surface observations a number of theories can be formulated regarding the subsurface material movement. One of the possible causes of the movement is the presence of cavity within the limestone bedrock and the added weight of the surface structures causes collapse of the cavity roof and causes the subsurface material movement into the cavity. The main aim in carrying out the microgravity survey is to determine the possibility of the presence of this cavity and thus allowing follow up remedial work or further investigation to be planned.

AIM OF THE STUDY

The primary object in conducting a gravity survey is to measure the gravity field on the ground at various points. The changes in the measured value at these different points are correlated to changes in the densities of the subsurface materials. The different in densities can be correlated to different material types such as soil, rock and voids. The aim of carrying out the micro gravity survey at this site is thus to determine surface gravity field variation and to correlate these changes to the subsurface density changes.

These subsurface density changes can then be correlated to the subsurface structure present such as changes in the subsurface bedrock topography, changes in material above the bedrock and specifically at this site an attempt to detect possible presence of voids in the limestone.

THEORY OF GRAVITY METHOD

Newton's law of universal gravitation states that there is a force of attraction F between two particles with masses m_1 and m_2 separated by a distance r. These can be represented by the following relationship

$$F = G\ \frac{m_1 m_2}{r^2} \qquad (1)$$

where G is the universal gravitation constant. The value of G is 6.6732 x 10^{-11} N.m^2/Kg^2 (SI unit). Taking the mass of the earth as M, a mass on the earth surface m_1 and the distance between the centres of gravity of the two masses as R the relationship reduces to

$$F = G\ \frac{m_1 M}{R^2} \qquad (2)$$

Newton's second law of motion states that force F is a product of mass m and acceleration, g and given by

$$F = mg \qquad (3)$$

Taking mass m_1 in equation 2 and m in equation 3 to be the same the following relationship is obtained

$$F = G\ \frac{GM}{R^2} \qquad (4)$$

In the gravity method the measured parameter is this gravitational acceleration (e.g. Telford *et al.*, 1990). It is a result of the causative mass and the distance of the mass from the measuring point. In reality the measured value at each points on the earth surface will contain the g value from many masses including the earth mass. These masses can be of different densities and geometry, and have different distances from the measuring points. For homogenous subsurface conditions total g value from all the masses cause the same effect thus the measured g value everywhere on a plane surface will be the same. If the subsurface is inhomogenous such as, the presence of a void, the causative mass reduces because the void has a lower density than the surrounding. The measured g value on the surface above it thus reduces accordingly. Measurements on a series of point on the surface across the void location will produce a gravity low. Similarly if the location has material with significantly higher density than the surrounding material such as boulder in an alluvium, it will form gravity high. These are depicted in Figure 1.

The g value is expressed as m/s^2. In the gravity survey the unit is normally Gal, which is 1 cm/s^2. The variations in gravitational acceleration from changes due to near surface feature are small and the unit milliGal (1 mGal = .001 Gal) is used. For even smaller changes the microGal is used as in the case of this survey.

INSTRUMENTATION

The instrument used in the survey is the LaCoste & Romberg microgravity meter model D. It gives relative gravity value. The reading is in instrument unit and can be converted to microGal using the instrument calibration factor.

THE SURVEY AREA

The area under study is about 300 m by 500 m (see Fig. 2). It has double storey link houses. The areas around this residential site has been fully developed with double storey link houses except the areas to the southwest of this site. This area to the southwest is still being developed with both single and double storey link houses.

SUBSURFACE MASS MOVEMENT

Some of the roads within the study site become undulating with time. Some of the undulation is about 10 m wide. This is an indication of differential vertical movement. Around and in the houses the vertical movements are indicated by the cracks developing on the floor, drains and walls of the houses. Lateral movement are inferred from the presence of lateral displacement of the crack structures such as on the drains, walls and the movement of the pillars. Some of the houses experience slight tilting. The area to the southwest of the survey site has similar problem. The newly built houses developing cracks. However, as the development was at its initial stage when the problem was detected, the houses were demolished and redeveloped. One of the remedial steps currently taken at this site is by using different piling system. In the survey area the cause of the subsurface mass movement needs to be identified so that remedial work can be done. One possibility is the presence of the cavity, one of the method of detecting a cavity is by the microgravity method.

DATA ACQUISITION

A pre survey gravity measurements were carried to determine the possibility of observing gravity variation.

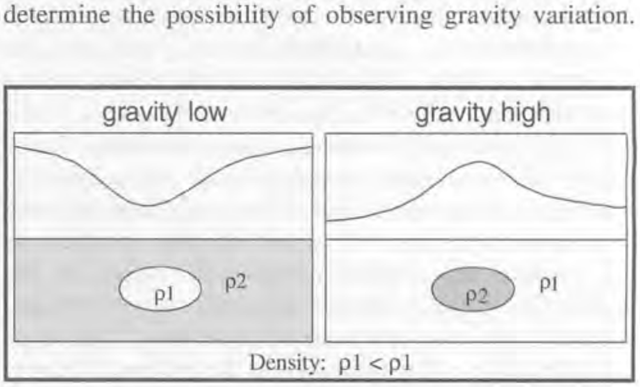

Figure 1. Examples of situation where gravity low and gravity high can be produce.

This is because the bedrock is quite deep and the lateral changes might be too small to be detected. It is also necessary to determine the frequency of the gravity points. A grid system was initially proposed, but access into the houses was a major problem. It was decided to do measurements only along the roads. The house areas are 20 ft. wide and 70 m long. To ease the positioning of the points both in the field and on the map it was decided to make measurements at two houses apart (40 feet) along the road. This gives a grid of about 40 by 80 feet square. A simulation modelling using a 10 m diameter cavity at 35 m depth indicates that it should produce a detectable anomaly using this grid spacing. These gravity data acquisition points were marked on the roads and named using numbers system. There are a total of 141 field data points (Fig. 2).

A base point or a reference point was selected. This reference point is used to obtain the daily gravity drift which can occur because of the earth tidal effect. To obtain the gravity drift or changes, measurement can be made constantly at the same point or the reference point. When using only one gravity meter, the reference point is reoccupied at regular interval. In this survey it is done at about one hour intervals. Variation within this one-hour period is assumed to be linear. The gravity meter itself does not produce significant drift because it is kept a constant temperature. But the base point drift measurements include both the tidal and instrument drift. The base point has been placed near a borehole (BH4) It is away from traffic and at a relatively open space.

During the data acquisition, the base point gravity value was first obtained. Gravity values at other points were then measured. The base point was then reoccupy after about an hour before proceeding to the other points. The last reading for each session is at the base point. The items recorded at each point are the point identification label, the time and the gravity meter reading.

DATA REDUCTION AND PROCESSING

When working in a large area and hilly terrain, the data needs correction for the terrain effect, different in heights, the excess mass effect, the latitude effect and the drift. However, the site is relatively small and flat, and the surrounding areas are flat, thus only the drift correction is applied to the raw data. This is carried out by assuming the base station has zero value and all others points has value relative to base point value. The rate of change of the gravity value with time needed for the correction is calculated from the hourly reoccupation of the base station. Using this rate the drift, correction at any time can be calculated. This is used to correct values taken at the other points. The corrected value can then be converted to microGal, otherwise it can be converted to microGal prior to the correction.

The data acquisition points are not surveyed because the locations of the points are known both in the site map and in the field. For mapping purposes the coordinates of the gravity data points are determined from the site map available. The map was first scanned producing a scanned map in screen pixels. This is calibrated to feet because the unit used in the map is in feet. The origin of the coordinate system is placed where the map is clear and calibration is easy. The software DIDGER (GSI, 2000) was used to carry out the scaling and digitising.

THE GRAVITY ANOMALY

The corrected gravity values are contoured using the program SURFER (GSI, 1993). The contoured gravity anomaly is shown in Figure 3.

The measured gravity value within the survey site gives a maximum difference of about 110 microGal. The lowest value occurs at the southern eastern part of the site

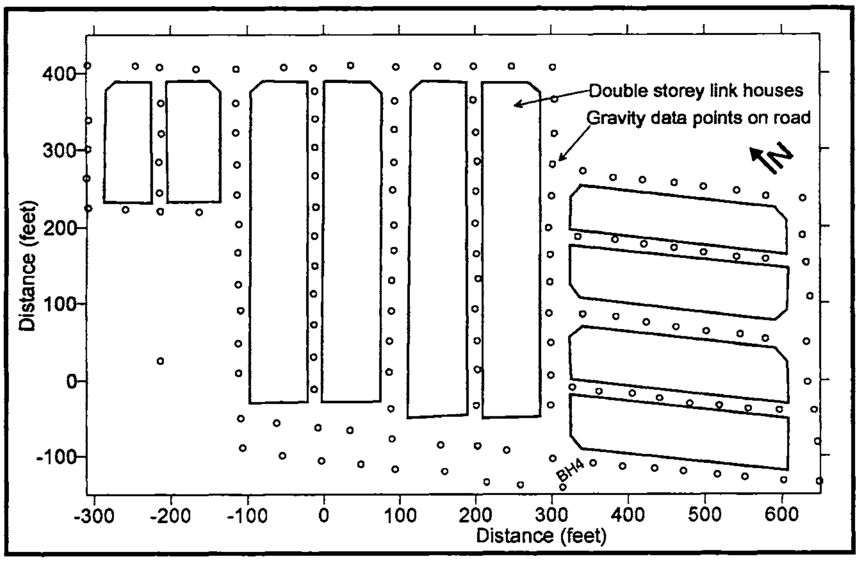

Figure 2. The survey site showing the infrastructure and the microgravity measuring points.

(dark colour). It has a northeast-southwest trend. It gradually increases to the north reaching the highest value at the central and north eastern part of the site (light colour) forming distinct peaks. The gravity peaks form two distinct elongated gravity high trends aligned almost northeast southwest (A-A' and C-C', Fig. 3). These two are separated by an elongated gravity low (B-B').

QUANTITATIVE INTERPRETATION

Based on the relationship given earlier the gravity highs can be due to excess mass while the gravity low can be due to deficient source mass. Although these can occur in different settings the former can only occur when a higher density material with a considerable volume is within a lower density material and the latter, the gravity low can occur only when a lower density material with a considerable volume is in a higher density material. Among the structure that can cause a gravity high is a subsurface topographic high and the gravity low is the existence of a subsurface topographic low or cavity. The elongated trend indicates that a topographic high is more likely to be the source of the gravity high (A-A' and C-C' Fig. 3). Therefore, in the north western part of the site a series of subsurface ridges and valley are present. The gravity low at the southern part of the area indicates a deepening of the limestone body and probably defines a basin feature.

Within the gravity high region the contour lines are sometime irregular. This indicates lateral variation in the subsurface material caused by smaller feature. Some indicate mass deficiency while others indicate excess mass. In the case of mass deficiency it may be caused by presence the of smaller features such as a cavity or smaller topographic low. The excess mass indicates small topographic high as an undulation on the top of the limestone.

MODELLING

The elongated feature allows a two dimensional modelling to be carried out. Modelling of the gravity anomaly is essentially an attempt to determine the source of the anomaly. As seen earlier, modelling of the source involves three parameters. There are (1) the density or different in density of the source to the surrounding material (2) the shape or geometry and size of the source and (3) the distance of the source from the measuring point. If none of these parameters are known then ambiguity sets in the model obtained. In order to obtain exact model, these parameters must be known otherwise ambiguity will set in.

The modelling has been carried out along profile D-D' (Fig. 3). The profile cuts across the series of ridges and valleys and the basin. The program GMODEL (LRGI, 1992) has been used for the modelling. Gravity profile D-D' satisfies the requirement of a two-dimensional modelling by GMODEL. The main condition is that the source is elongated and can be assumed to extend to infinity. The gravity anomaly along D-D' is given in Figure 4. The gravity highs due to the possible ridge feature are obvious. The parameters for the modelling are obtained from the borehole data in the area.

Parameters for the modelling

In the survey area and the surrounding areas there are numerous boreholes (Fig. 5), most reaching the bedrock. A summary of the result is given in Table 1. The bedrock is limestone and the depths of the bedrock encountered in the boreholes within the site are generally between 24 to 34 m. 6 m cores have been made in three of the boreholes. The limestone encountered at BH2 (S1) at 6.3 m may not be the bedrock. The neighbouring borehole (west of site) gives a slightly shallow depth of 17.23 and 20.4 m to the bedrock while borehole to the south of the site gave depth

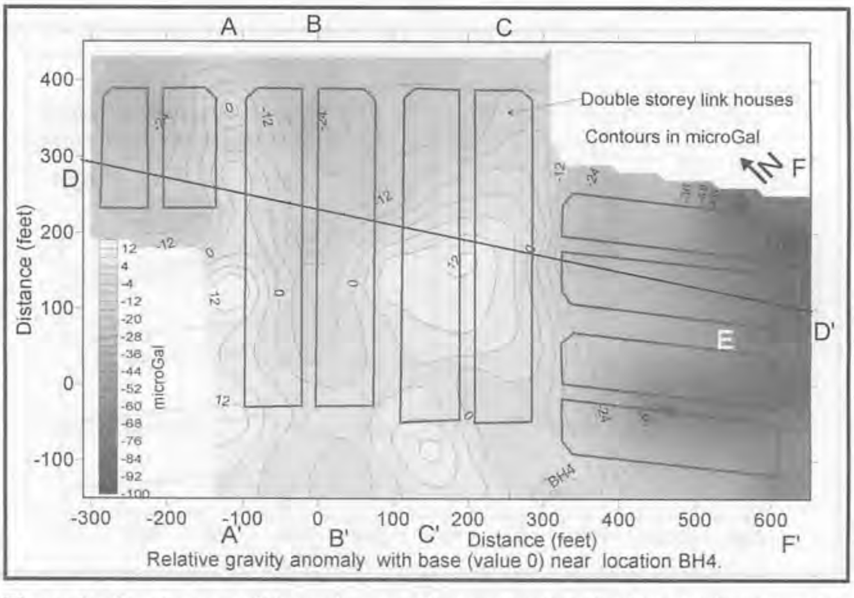

Figure 3. Gravity map of the study area. Contours are in microGal. Light coloured is high value and dark coloured is low values.

of 39.9 and 45 m without encountering bedrock.

The residual soil above the limestone bedrock is mainly loose fine-grained materials. They are described and named according to the fine-grained naming method such as silty clay, clayey silt, silty sand and sandy clay. Some are identified as fill and slime materials. They are essentially loose and soft material and are probably transported materials. The N-value of standard penetration test (SPT) are low also indicating loose and soft material. The N values are mainly less than 10 from the surface until the bedrock. When the N value is relatively high, the material generally contains gravels.

Density measurements on the soil samples from some of these boreholes give densities that vary from 1.4 to 1.8 g/cm^3. Most of the samples give density of about 1.6 g/cm^3. The density of the limestone from the cores obtained from the boring ranges from 2.64 to 2.75 g/cm^3.

Modelling Procedure

The procedure used to model the source of gravity anomaly is a trial and error method (Fig. 6). It requires a field anomaly which is the gravity profile D-D'. The first step is to assume a starting model or source from the known parameters for this field anomaly. In this case the profile D-D' passes boreholes BH1 and BH2. The depth to the limestone is known as 27 and 30 m. These have been used as the depth at the respective points. Starting depths of the limestone at the other points are assumed to follow

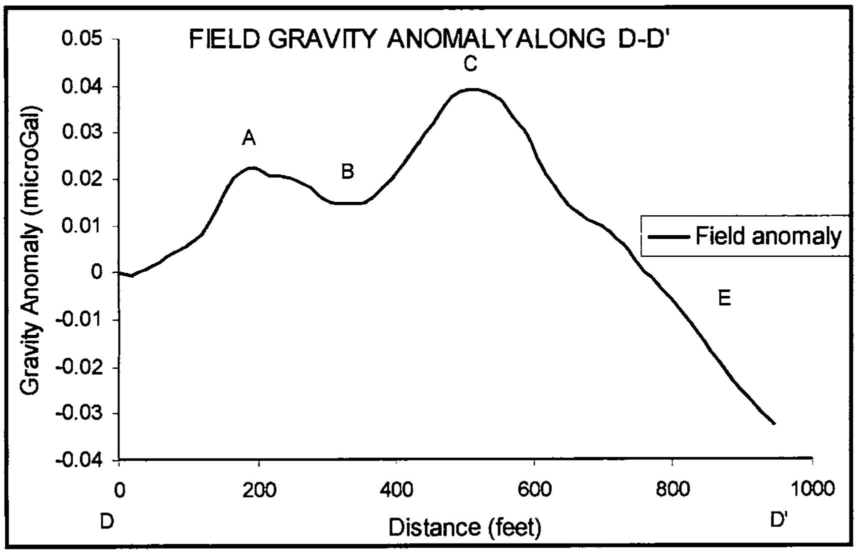

Figure 4. The gravity anomaly along profile D-D' used in the modeling. There are two distinct gravity high (A and C) separated by a gravity low (B) and a steep slope towards D'.

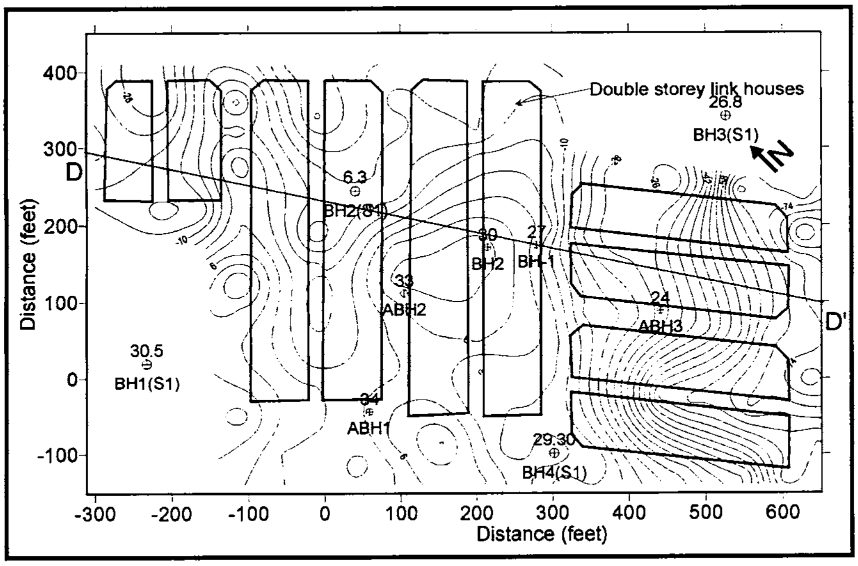

Figure 5. Location of the boreholes are marked by the cross symbol. The values above are depth to the bedrock in meters. The labels below are names of the borehole. There are three boreholes along the profile D-D'.

the anomaly pattern constrained by these two points. The density of the limestone is taken to be 2.65 g/cm^3, and the density of the loose material above the limestone to be 1.6 g/cm^3. The remaining parameter to be determined is the shape or geometry of the bedrock.

Based on the above assumed geometry of the bedrock the anomaly of the model is calculated. This anomaly is compared to the field anomaly. When differences exist between the field and calculated anomaly, the geometry of the source is modified. The anomaly is again recalculated and compared to the field anomaly. This routine is carried out until the two anomalies fits well. When this occurs the model is taken to be the source model for the field anomaly.

GMODEL allows the input of the above parameter and correction or modification of the model interactively. As the density and depth are well constrained, the model obtain is also well constrained. The final model, the calculated anomaly for the model and the field anomaly along D-D' are given in Figure 7.

The source

The modelled limestone subsurface topography along D-D' indicates the presence of three topographic high (RA, RC and R, Fig 7) separated by two valleys (VB and V). These are major structures or features. Minor features can occur within the ridge. An example of such feature is narrow valleys at the ridge (A1, Fig. 8). Such a model will also give a good fit between the field and calculated anomaly. Similarly a cavity (A2, Fig 8) within the ridges can also give good fit between the field and the calculated anomaly.

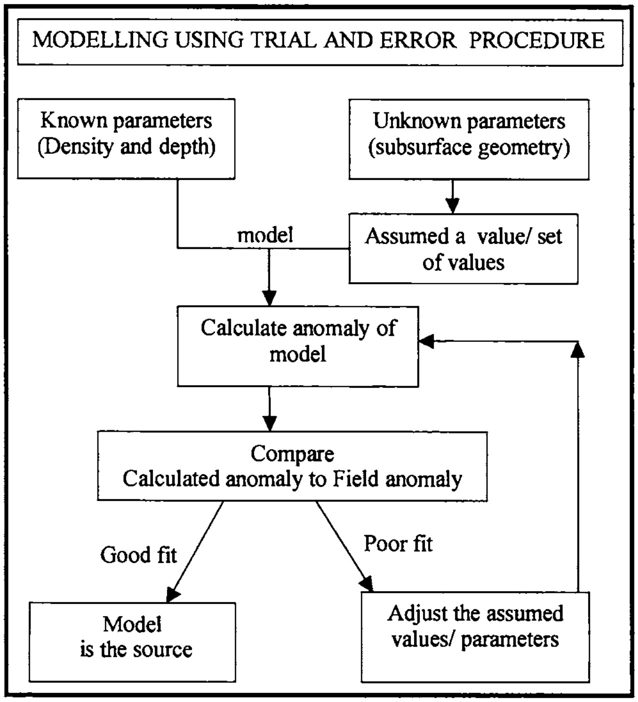

Figure 6. The trial and error procedure used for the modeling.

Discussion of the source

Anomaly along profile D-D' has two distinct linear gravity high at A-A' and C-C' (Figs. 3 and 4), a linear gravity low (B-B') and a distinctly very low gravity region (E). The gravity highs have been modelled as topographic high (RA and RC Fig. 7) and the gravity low as a topographic low (VB). The location of these two topographic highs and the low correspond to the two linear anomalies high and the gravity low trending northeast southwest on the gravity map. They define subsurface ridges roughly along A-A' and C-C' respectively separated by a valley or channel like feature (VB).

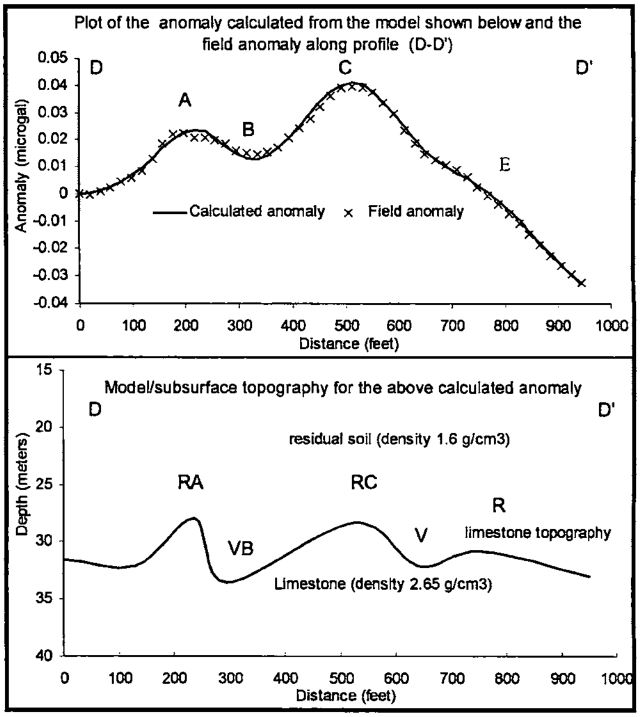

Figure 7. The top figure shows the good fit between the field gravity anomaly and the calculated anomaly from the model in the bottom figure. The occurrence of subsurface topographic high is obvious in the model (RA, RC and R). These alternate with the topographic low (VB and V).

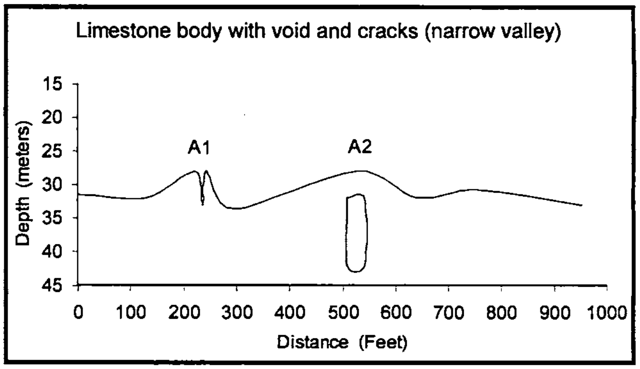

Figure 8. Subsurface limestone ridges with narrow valleys and limestone body with cavity. The cavity is about 10 m by 10 m square.

The modelling also indicated that at location E on the gravity profile (Fig. 7 top) there is also a topographic high R (Fig. 7 bottom). It is separated from ridge RC by a valley V. This feature is not obvious in the gravity anomaly map as the anomaly shows a gradual decrease to a minimum value for the site. This is probably a localized topographic high (see gravity map Fig. 3) because the anomaly pattern show a constant decrease to the west while to the east the contour forms an almost circular pattern which defines this topographic high.

Narrow deep valleys may cut the subsurface limestone topography as modelled above. This smaller feature is typical in the limestone topography. Similarly modelling with a cavity within the ridge can also explain the anomaly along (D-D') particularly at the ridge. Thus the presence of cavity is a possibility within the study area occurring where there is topographic high.

Table 1. Summary of the bedrock depth from the boreholes logging.

Borehole within the site			Borehole near the site	
Name	Depth (bedrock) (m)	Core in bedrock (m)	Name	Depth (m)
BH1(S1)	30.5		BH-2A	20.4
BH2(S1)	6.3		BH3	17.23
BH3(S1)	26.8			
BH4(S1)	29.3		BH3	45
ABH1	34	6	BH4	39.9
ABH2	33.3	6		
ABH3	24	6		
BH-1	27			
BH-2	30			

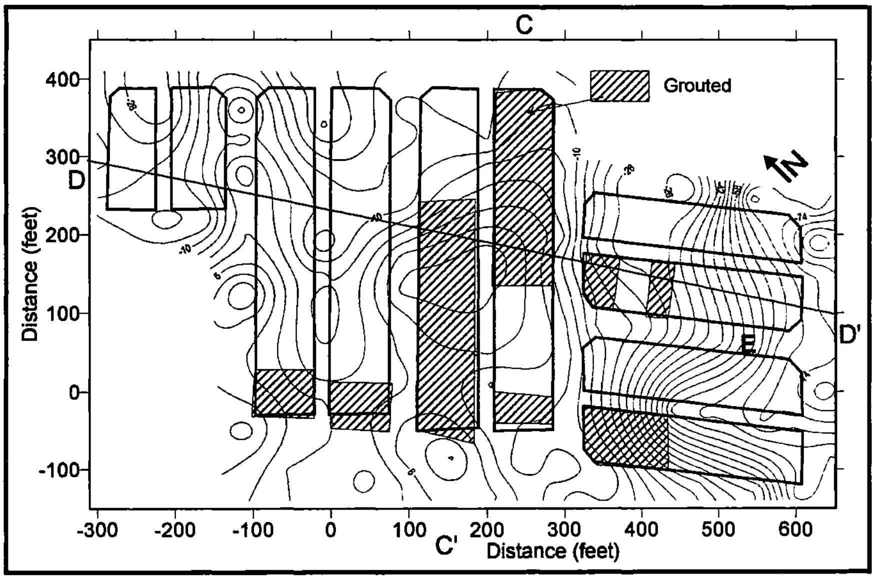

Figure 9. Map showing the grouted areas superimposed on the gravity map. Most of the grouting are at the gravity high C-C'. E is region where the gravity anomaly slopes to minimum.

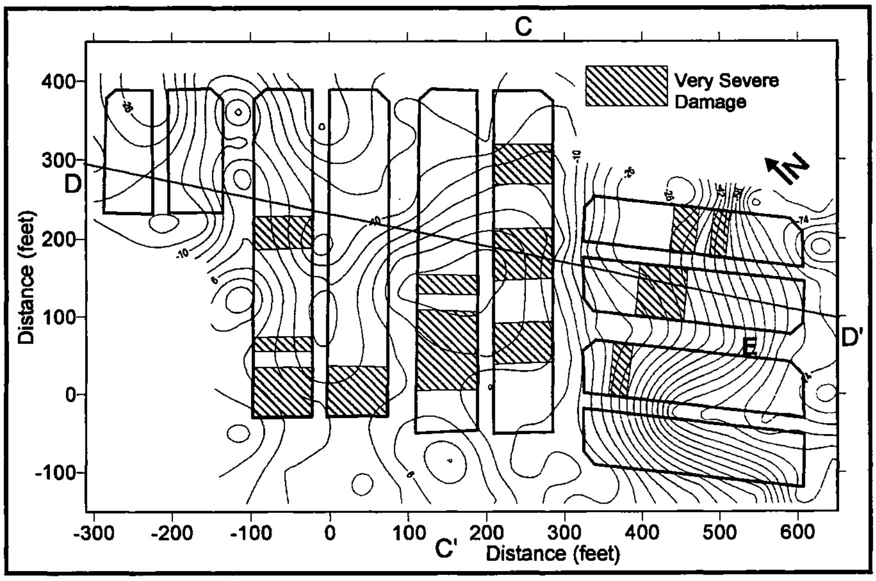

Figure 10. Map of the severely damaged area superimposed on the gravity map. The severely damage area are mostly at the ridges especially C-C' and where the gravity anomaly slopes to minimum.

MICROGRAVITY AS A TOOL IN THE STUDY OF SUBSURFACE MASS MOVEMENT PROBLEM

There are indications that the site is experiencing subsurface mass movement. As indicated by the surface evidence it can be either a vertical movement or a lateral movement. The undulations on the roads and the structures related to the buildings indicate vertical movements. The displacement of the house structure such as drains and walls and tilting of pillars indicates lateral movement. Tilting of some of the houses suggest that the movements are not restricted only to near surface movement but also deeper mass movement. In limestone areas one of the possible causes of subsurface mass movement is the movement of the unconsolidated material into the cavity. This can occur in case of cavity roof collapsing and material move into the cavity.

Comparison Of The Gravity Anomaly To The Grouted Area

Grouting is a process of injecting cement under buildings to stabilized or stop the building from mainly vertical movement. The houses which develop damage have been grouted. Some have more grouting material injected than others. The gravity map is compared to the grouted region. These grouted region are based on the injected points and area, however, the actual subsurface distribution of the grouting material is not exactly known.

Comparison of the grouted area to the gravity anomaly suggest that the area grouted is mainly on (a) the central gravity high (C-C', see Fig. 9) and (b) on a down sloping section (E) of the gravity anomaly (southern part).

Comparison Of The Gravity Anomaly To The Severely Damaged Areas

The severely affected area refers to area where a lot of cracks and movements occurred on the building structure. Comparison of the severely damaged areas to the gravity map indicates similar trend as the grouted area (Fig. 10). The affected area is mainly (a) on the ridge and (b) on the sloping section of the gravity anomaly. The damage areas may be more than shown, because this assessment is based mainly from the exterior of the building.

CONCLUSION

The gravity mapping produces a gravity map which defines the general subsurface topography of the limestone bedrock. The linear gravity highs and lows define a series of two ridges and valley feature on the limestone bedrock topography.

The modelling has been well constrained because the parameters required to obtained the bedrock topography is well defined from the borehole data. The modelling enable the determination of the presence of another ridge and valley feature. The modelling indicates that there can be smaller features such as cracks or narrow steep valleys within the ridges. This can explain differences in the limestone depth in nearby boreholes

The presence of the limestone ridge/hill allow the formation of a cavity before subsidence occur and the residual soil covers the topography. The modelling indicates the cavity can be present. Its presence can be indicated by the small change in the gravity contour where small mass deficiency exist within the gravity high region.

Areas of subsurface mass movement are indicated by the grouted area and the damaged structure. Comparison of the anomaly to the severely damaged structure and the grouted areas indicates that these areas occur where the gravity anomaly is relatively high or mainly at limestone ridges. The close relationship between the gravity high region to grouted and damage area suggest that subsurface mass movement occur within this region. Movement of mass into cavity is thus a likely cause.

The cavity theory needs to be further proven. The main object is to locate the possible location of the cavity. A borehole penetrating the limestone can be made to confirm the cavity. Further study is underway to determine this. One is to use the various filtering procedure to obtain the short wavelength anomaly which can be associated to the cavity. A more close spacing data may be necessary to do this. Measurement of vertical and horizontal surface mass movement may be necessary to assist locating the maximum vertical movement points and comparing to the filtered gravity data. Finally boring through the limestone will be necessary to confirm any existence of the cavity.

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