Geotechnical Engineering Journal of the SEAGS & AGSSEA Vol. 48 No. 2 June 2017 ISSN 0046-5828

Application of Gravity Survey in Urbanized City Environment

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ABSTRACT: Subsurface information and geotechnical data are required during the planning, development and design stages of all construction projects particularly where major components are supported on or in the earth and underlying rock. An understanding of the basic site geology is also necessary for the proper planning of the ground investigation works. Consequently, the geological features that will affect the design and construction of the project must be investigated and evaluated as much as possible within the allowable project timeframe to ensure successful implementation of the project. This paper presents an overview of the authors' experiences in using Gravity Survey, as a reconnaissance ground investigation method to identify areas of enhanced ground risks, in the complex variable and unpredictable Kuala Lumpur Karstic Limestone formation during the underground reference design stage of the Klang Valley Mass Rapid Transit Line 2 (SSP Line) in Kuala Lumpur, Malaysia. This paper also presents some lessons learnt of the past in the region, and what were the specific measures that had been strictly implemented on this occasion to ensure quality results can be derived from the Gravity Survey within the urbanized city environment and meet the objectives of the survey.

KEYWORDS: Ground Investigation, Urbanized City Environment, Geophysical Survey, Gravity Survey, Karstic Limestone.

1. INTRODUCTION

The proposed KVMRT SSP Line 2 alignment comprises a new 14.3km underground Mass Rapid Transit system with eleven (11) underground stations positioned along the alignment, namely Sentul West Station, Titiwangsa Station, Hospital Kuala Lumpur Station, Kampung Baru North Station, Ampang Park Station, KLCC East Station, Conlay Station, Tun Razak Exchange (TRX) Station, Chan Sow Lin Station, Bandar Malaysia North Station and Bandar Malaysia South Station. The KVMRT SSP Line 2 underground alignment is illustrated in Figure 1 below.

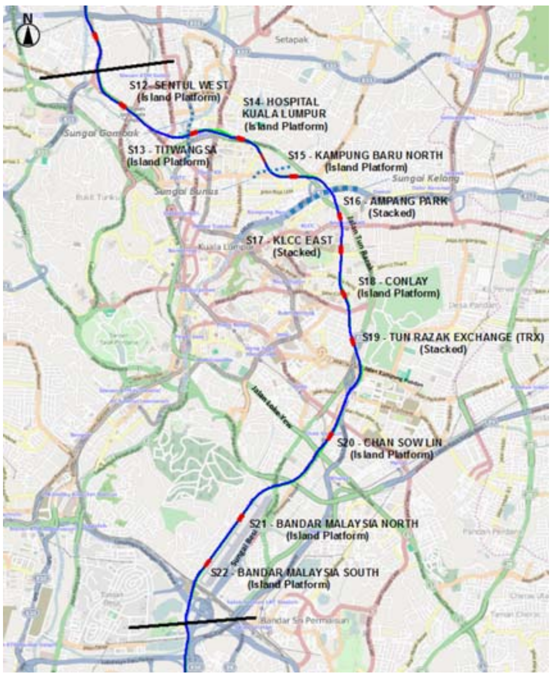


Figure 1 KVMRT Line 2 Underground Alignment

The contract arrangements were for a reference design to be developed for the underground section of the alignment and subsequently to let a design and construction contract to deliver the works.

During the underground reference design stage of the KVMRT SSP Line 2, a ground investigation programme including intrusive and non-intrusive ground investigations was developed to establish adequately the ground characteristics and condition along the entire underground alignment. This was done to identify and mitigate the potential construction risks to facilitate the reference design works. Particular attention has been paid to investigate the complex Kuala Lumpur (KL) Limestone formation and this is the main focus of this paper.

2. SITE CONDITION AND GEOLOGY

2.1 Existing Condition and Topography

Along the proposed SSP Line 2 underground alignment, the existing ground level is generally between approximately 35mRL and 44mRL, except a small portion of the southern section of the proposed underground alignment which is more undulating with ground levels up to 79mRL. Essentially the proposed alignment passes through the urban area of Kuala Lumpur city with high-rise buildings in the central portion as well as under rivers such as sungai Gombak, Sungai Bunus and Sungai Kelang.

2.2 Headings

Based on available borehole information along the alignment and the published geological maps of Kuala Lumpur, the geology along the alignment is expected to be quite variable as it traverses not only the bedrock of Kuala Lumpur Limestone, Kenny Hill Formation, and granitic, but also in some sections, the alluvium and potentially some mine tailing materials. It is of note that more than half of the underground alignment is within the limestone, which is shown by the Geological Map with the KVMRT SSP Line 2 underground alignment overlaid in Figure 2.

Much of the Kuala Lumpur area had probably been uplifted which resulted in active sub aerial erosion and the accumulation of the thick coastal and inland alluvial deposits. Accumulation of tin ore in these loosely consolidated superficial formations once supported an important tin mining industry in Kuala Lumpur. Deep depressions developed in karstic limestone surfaces, Figure 3, are natural traps of alluvial tin ore transported as sediments and this explains why tin mining was concentrated in alluvial areas underlain by the limestone bedrock in the Kuala Lumpur area.

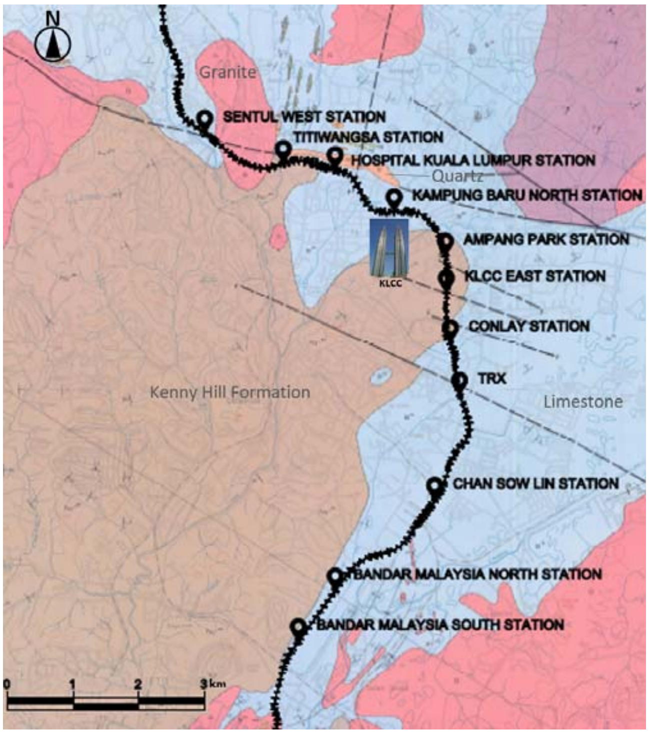


Figure 2 Alignment overlaying Geological Map of KL

Figure 3 KL Limestone karstic features

All tin mining lands are covered with remnants of highly heterogeneous material nature from slime to sands and gravels, and this correlates well with observations from many of the existing boreholes showing the sandy and cohesive materials above limestone bedrock in Kuala Lumpur which are loose and soft respectively. The precise tin mining locations and their extents are very difficult if not impossible to trace back nowadays. If the underlying karstic limestone features are overlooked during the planning and design stage, it may pose uncertainty and difficulty during underground construction.

3. GROUND INVESTIGATION PROPOSAL

Most ground investigations have constraints in achieving the ultimate objectives with the final scope of works being a compromise between satisfying the constraints and carrying forward an acceptable level of ground risks to the tunnel and station construction works. Limited existing GI information to aid our GI planning and very tight programme were the challenges in the execution of the Underground Reference Design.

In view of the highly erratic karstic features within the Kuala Lumpur limestone formation, conventional borehole GI and geophysical survey techniques were included as part of the GI programme. A combination of both in a controlled sequence can maximize the findings in terms of the investigation.

3.1 Objective of geophysical Survey

The objective of a geophysical survey is to complement borehole GI in areas of difficult ground such as the karstic limestone formation, by providing additional detail between boreholes and locally in places where boreholes may not be practically feasible. To achieve that objective the geophysical survey attempts to:

- Define and map the variable rockhead topography, which can be extremely irregular within the limestone formation;
- Recognize and identify karstic zones such as potential cavities or solution channels
- Expand existing geological information where detailed ground conditions have already been identified in point locations by borehole GI.

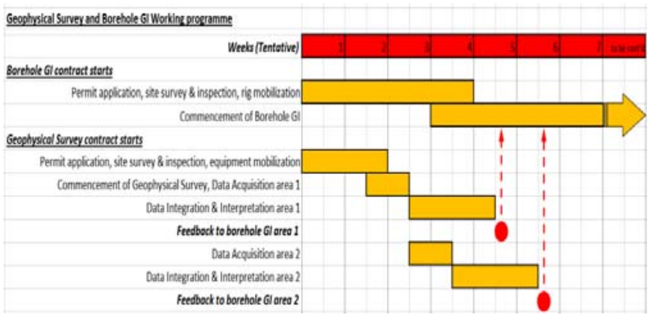
From an operational perspective, the purpose of the geophysical survey is to provide a reconnaissance ground investigation with a view to identify areas of enhanced ground risk that may be present and hence to plan an efficient and objective borehole GI programme. However, one must remember that geophysical investigations cannot be a substitute for boreholes but applied correctly and by observing the many ground constraints of an urban environment, useful support information can be obtained.

Each geophysical technique requires sufficient contrast in measurable physical properties and has different limitations and resolution, depending on the equipment used. It is necessary to recognize those limitations and resolutions since selection of an appropriate geophysical method is a key factor for making applied geophysical techniques successful.

3.2 Sequence of Borehole GI and Geophysical Survey

The geophysical survey should planned as an integral part within the sequence of the GI programme to derive maximum benefit from the feedback. By this sequence, boreholes can be focused upon geophysically identified locations to maximize the chances of revealing specific geotechnical risks within the limited project timeframe. A recommended sequence is presented as follows (see Table 1 below):

Table 1 Combined Sequence of Borehole GI & Geophysical Survey



3.3 Why Gravity Survey?

All geophysical methods are inevitably subject to various sources of natural and induced error and consequent uncertainties in the output geological results. Gravity Survey is currently one of the very few methods that realistically is capable of generating a map of rock head distribution in karstic terrain in an urban environment, albeit subject to limitations. Multichannel analysis of surface waves (MASW) which is a seismic surface wave method for shear wave velocity, and Electrical Resistivity (EI) which measures a material's ability to conduct electric currents are the more commonly available methods in the region. These two tests have been conducted previously in the Kuala Lumpur urban areas. Technically, the results from MASW and EI are subject to influence from the near surface ground conditions and utilities, and the geotechnical conclusions may be adversely affected accordingly. To carry out MASW and EI along the proposed underground alignment in the Kuala Lumpur urban areas is a relatively complicated process as a long stretch of made road surface often needs to be temporarily closed and therefore official road closure permits are required. And some areas of geotechnical concern are beneath existing structures which would present further obstacle, effectively rendering MASW and EI practically impossible. Both methods are significantly susceptible to induced noise, seismic and electrical, which are pervasive in densely built-up and active urban areas, see Figure 4.

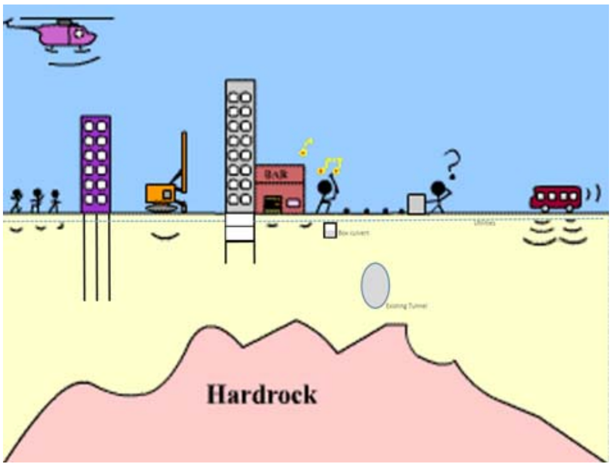


Figure 4 Typical constraints in urban environment

The gravity geophysical method is totally passive. It relies on no controlled energy sources but measures naturally occurring variations of the earth's gravity field. Errors arising from variable source signal generation and reception, as observed with seismic signals or electrode contact resistance in urban environments, are therefore wholly avoided. Measurement of the variation of the gravity field provides information about the local variations of the rock densities. The strength of the local variations of the gravitational field is directly proportional to the rock mass excess or deficiency, and therefore also to the density of the subsurface materials.

Although the gravity survey method could not exactly define the underlying geology, it is largely unaffected by made surfaces, utilities and normal traffic and, if executed with sufficient care, is capable of providing a suitable reconnaissance map of the underlying rock head surface to guide subsequent selective borehole GI, regardless of the rock head irregularity and provided the density contrast is appropriate. Within the limestone karstic formation, the density contrast between the limestone and the overlying loose and soft soil is large, approximately 600 kg.m-3 or higher, and therefore it is entirely appropriate for application of the gravity method. On the contrary, a low density contrast between these lithological units would have resulted in unacceptably large errors of depth determination.

Operationally the gravity method is a non-intrusive passive technique requiring only a small footprint for setting up, fast in data collection with minimum logistics preparation and usually demands no special provisions for execution in the urban environment. It may also be conducted within buildings at ground or basement level if necessary and not being confined to profile operations, enables lateral definition. Figures 5a to 5e illustrate operation within the urban environment. Lateral definition is regarded as an important criterion for the definition of limestone pinnacles.

Figure 5a Typical gravity meter (CG-5), 5b Operation along car parking bay, 5c Operation within the office, 5d Operation at the building basement, 5e Operation within a food market

The gravity method was therefore considered to be appropriate and was adopted to develop a map of the rock head surfaces.

3.4 Understand the Limitation of Gravity Survey

Inevitably the method is subject to limitations, which are mainly in the interpretation phase rather than the data acquisition, if performed correctly and accurately. Those limitations include the requirement for interpretation control, usually from some initial existing boreholes or outcrop, the limited information on density distribution of rock and all overlying deposits, and significantly in this case the necessary assumption that rockhead is a sharply defined horizon between rock and the overlying low density materials.

In karstic limestone conditions, individual voids cannot be resolved and an area of multiple voids would be interpreted as an effective depression of rockhead. Figure 6 illustrates the point. However in those karstic limestone cases, where the gravity defined rockhead is significantly below the point definition of borehole rockhead, the increased probability of further cavities or voids can be realized.

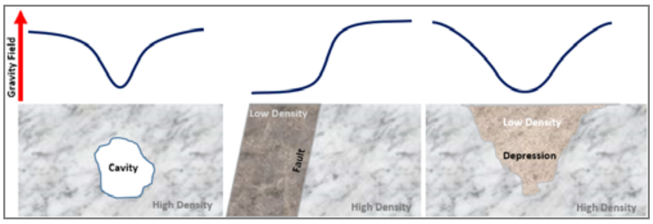


Figure 6 Illustration showing the relative gravity field over different geological structures

4. PLANNING OF GRAVITY SURVEY

4.1 Lessons Learnt of the Past

Gravity data acquisition is being seen as a relatively simple task that can be performed by one person, however, it requires significant care by the instrument observer/operator.

Based on our past experiences in the region, the commonly observed technical deficiencies were mainly relating to,

a) instrument setting deficiencies and b) procedural deficiencies. They are summarized as follows:

a) Instrument Setting Deficiencies:

Parameter settings of gravity meters have been grossly incorrect on some surveys observed in the past. In general the data quality was not examined by the operators and was not verified by the supervisors. Defects in the data included:

- Instrument survey date not set (incorrect earth gravity tidal correction).
- Instrument location not set (incorrect tidal correction).
- Difference to GMT not set / incorrect (incorrect tidal correction).
- Standard deviations of readings, which indicate noise levels, have been ignored.
- Noisy data have not been repeated.
- Extremely large standard deviations due to earth tremor conditions have been completely ignored, resulting in grossly incorrect drift corrections.
- In general the data quality was not examined by the operators and was not verified by the supervisors.

b) Procedural Deficiencies:

There has been a lack of QA/QC in general, and correct procedures have not been adopted and or verified. Those shortcomings included:

- Measurement stations have not been accurately surveyed for elevation, which is a critical factor to correct results
- Data station identities have been confused between topographic and gravity survey teams
- Lack of awareness/understanding by survey operators of the data quality requirements.
- Data have not been subjected to Quality Control procedures, internally or externally.
- Variable terrain and surrounding artefacts such as buildings, basements, etc. which have a significant influence upon the measured gravity data locally, have been generally ignored.
- Data review at time of measurement has not been conducted.
- Data specifications have not been prepared or have been ignored.
- Instrument auto-tilt levels exceeded the permitted limit on several readings but data were not rejected or repeated.
- Data have not been retained as ascii files for subsequent data checking/repair and equipment digital data files have sometime been erased or not recorded.
- Base station reading stability (instrument drift) has not been monitored.
- Base station readings have not been routinely repeated.
- Incorrect manual transcriptions of data to field data sheets have not been checked.
- Pre-survey stability and calibration checks were not conducted.

4.2 Specific Project Requirement to enhance the accuracy of gravity measurement

To ensure high quality data can be obtained, some specific process and requirements have been established to avoid the noted deficiencies:

- A formal inception meeting between Engineer and Contractor /contractor's operators will establish unequivocally contractor's responsibilities, reviewing and clarifying each item of the specifications.
- Specifications will be strictly observed and data or procedural departures will be repeated.
- Strict internal and external QC monitoring procedures will ensure compliance for which an onsite monitor(s) should be appointed.
- Operators should also monitor their own data, to be verified onsite by Engineer's QC monitor.
- The Gravity meter should be checked by QC monitor at commencement of each day's survey to verify correct parameter settings.
- Gravity meter stability and calibration checks should be carried out at commencement of survey.
- Where more than one gravity meter is deployed, ideally they should not be inter-mixed on a single survey site but should be calibrated together to ensure mutually consistent performance.

5. IMPLEMENTATION

5.1 Inception Meeting

Prior to survey commencement, an inception meeting was held between the contractor and consultants. The meeting was held in Ipoh at the time of the pre-survey calibration of the gravity meters The purpose of the inception meeting was to ensure that all individual responsibilities were recognized and understood clearly to ensure smooth progress of the survey, that the requirements of the specifications were understood by the contractor's operators as well as to confirm that adequate HSE provisions were in place.

5.2 During the Inception Meeting

The gravity meters required a calibration check to confirm suitable performance for the planned work and to verify their mutual compatibility before gravity measurements on site in Kuala Lumpur commenced. Two (2) Scintrex CG5 gravity meters were subjected to the check between three (3) different locations with known values of absolute gravity with a total calibration range of 212.20mGal, see Figure 7.

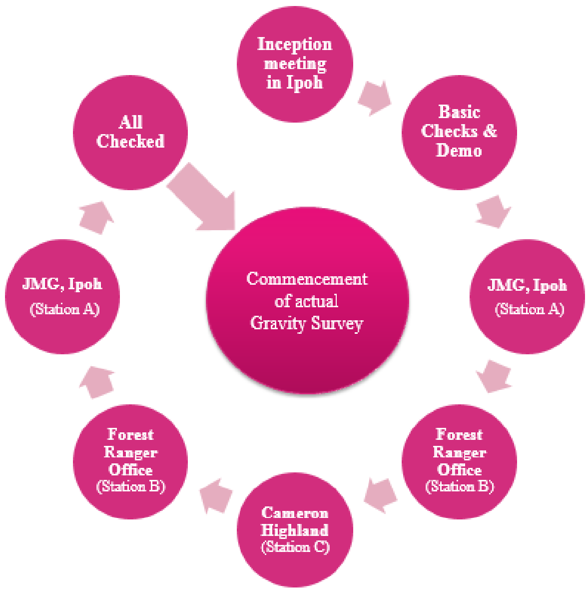


Figure 7 Equipment calibration check

The checks were conducted successfully and the results showed that the discrepancy of the meter readings over the range of true absolute gravity values, applied to the individual Kuala Lumpur sites, would result in a discrepancy between the meters of less than 2 microGal. For the current application this discrepancy would be negligible.

The calibration and drift check complied with the requirements of the project specifications. Gravity meters are extremely sensitive systems and they drift naturally and their characteristics change over long periods of time. Calibration and drift checks with meter fine adjustments were therefore conducted as a routine prior to the surveys to ensure correct performance and conformance with the specifications. This rigorous procedure supersedes a calibration certificate, which typically is issued upon manufacture, and which thereafter advises a similar procedure to be repeated only once every 'several years as per the Scintrex CG5 manual.

5.3 Commencement of Gravity Survey in Kuala Lumpur

Following the Inception meeting and equipment calibration, a base station was set up in each of the survey areas in Kuala Lumpur prior to commencement of the actual survey. The specifications required that the base station should be stable, easily accessible and not subject to vibration or disturbance from the traffic. Once a suitable location for a base station had been identified, the gravity meter(s) was placed on the tripod and levelled within the acceptable range, which is within 10 arc seconds for auto-tilt control to be applied. The gravity measurements were taken over 60 seconds at 1 second intervals for 2 cycles. The site supervisor was required to check the consistency of the returned gravity values and also standard deviations of the 1 second readings obtained for both cycles. The gravity measurements was repeated if the gravity values and standard deviation values were not consistent or were outside the specified acceptable range.

5.4 Weather / Noise / Traffic Avoidance

The gravity meters used for the survey were Scintrex CG-5 type. The equipment is sensitive to heavy traffic and weather conditions. To avoid detrimental influence of adverse weather conditions, the operators were instructed to suspend measurements and standby in heavy rainfall and to use an umbrella to reduce the impact of strong wind and sunlight, see Figure 8. Strong wind tends to increase the standard deviation of the gravity readings due to turbulence on the meter and also due to long period ground vibrations from adjacent buildings.

Survey points in locations adjacent to heavy traffic were repeated at a cycle period of 120 seconds (120 readings at 1 second intervals) where the standard deviation obtained over a 60 seconds period exceeded the level allowed by the specification. Furthermore, survey points were repeated at night where the standard deviation of the readings failed to meet the specifications for cycle periods of 120 seconds.

Figure 8 Operation under strong wind

5.5 Gravity Survey (Daytime Operations)

Gravity measurements at survey points were commenced immediately after completion of the base station readings. Measurements were repeated at 60 seconds intervals or more if the traffic conditions were heavy. The site supervisors were required to check the standard deviations and tilt values obtained for all survey points and the gravity measurements were repeated if the values exceeded the specified acceptable tolerance. For this survey, the specifications required that standard deviations of the 1 second readings over a period of 60 seconds should not normally exceed 0.07mGal and that the levelled meter should not exceed 10 arc seconds of tilt. See Figure 9 for the routine QC checklist.

The height of the gravity meter above ground level was also recorded by the meter operators together with the obtained gravity values.

5.6 Gravity Survey (Night time Operations)

Part of the gravity survey was conducted at night in order to improve the accuracy of gravity meter readings for survey points that were otherwise detrimentally affected by heavy traffic and by earth vibration from nearby construction works. That loss of accuracy was gauged by observation of the increased standard deviations of the readings beyond the specified acceptable tolerance level.

QC daily check list

Survey location : QC : Date :

CG5 Meter Ser No. Operator : weather conditions

Set up (Y – tick N - cross)

- ☐ Heated min 48 hrs Y N (Incl heat ON overnight)
- ☐ Auto drift corrn ON Y N
- ☐ Survey date correct Y N
- ☐ Memory cleared at beginning of survey Y N
- ☐ Auto tide corrn set Y N
- ☐ Survey Lat, Long set Y N
- ☐ Tide corrn hrs to GMT (-8) set Y N
- ☐ Check meter parameters on display :
  - Tide corr YES
  - Cont tilt corr YES
  - Auto reject YES
  - Terrain Corr NO
  - Seismic filter YES
  - Save raw data NO

Survey

- ☐ Base stations minimum three (2) readings
- ☐ Std Dev less than 0.06 mGal for base stations
- ☐ If greater than 0.06 mGal base station repeated
- ☐ Overnight drift ....
- ☐ All gravity survey loops closed at base station – closure differences ....
- ☐ Meter levelling correctly set within 10 arcsec at all stations
- ☐ Differences on closed loops at base station less than 0.05 mGal

Daily drift on base reading ___ mGal

- ☐ Data ASCII file dump received for previous day.

Topographic survey

- ☐ All topo survey loops closed at topo base station (BM or TBM)
- ☐ Closure differences ....

Signed ....

Figure 9 Gravity Survey QC checklist

5.7 Reference to the ISGN'71 Network

For each of the sites, base stations were established to monitor the drift of the gravity meters. All of these base stations were tied and referenced to an absolute IGSN'71 (International Gravity Standardization Network) gravity station located at JUPEM (S401). Reference to absolute gravity basically allows comparison and linking of data and data interpretation from adjacent sites. Each individual survey and subsequent surveys can be readily integrated by reference to the ISGN'71 network. Reference to those absolute IGSN'71 values also facilitates expression of the survey data as anomalies on the normal gravity ellipsoid, part of the rigorous data reduction process.

5.8 Topographical Survey

In addition to obtaining a precise gravity reading, horizontal position and topographic elevation measurements are a critical part of the survey and may present the greatest difficulty to survey. The horizontal position may be expressed as either latitude and longitude or the x and y coordinates on a pre-determined grid projection. In this case the Cassinis projection for Kuala Lumpur was adopted, together with the Kuala Lumpur topographic elevation datum. Elevation measurements must be made with a precision of 1mm, at the place of gravity measurement. The final topographic elevation of each data point must be determined within an accuracy of +/- 50mm or better, directly at the place of gravity measurement. Figure 10 shows 377 survey points which were set out in a grid pattern at one of the proposed stations, namely Chan Sow Lin.

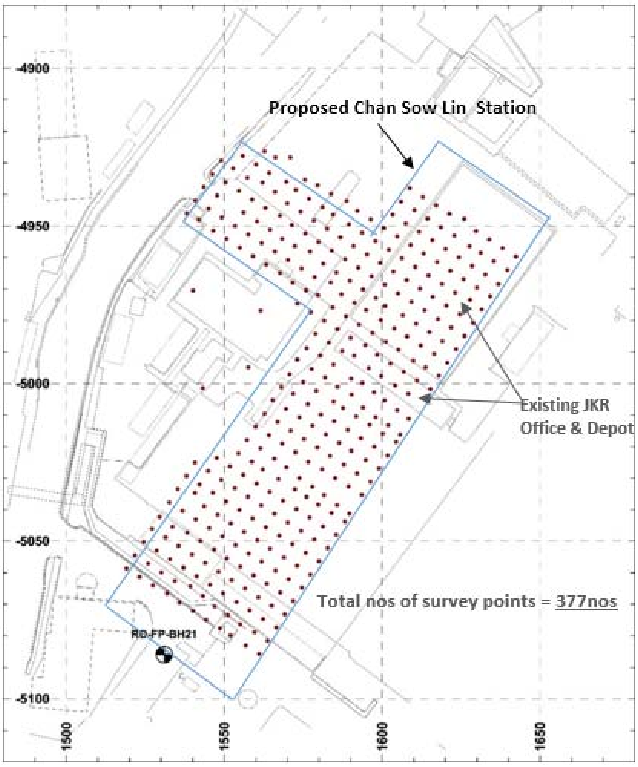


Figure 10 Gravity survey coverage

Ideally the actual surveyed location should be within a radius of 1 metres of the planned position, however a rigorous grid distribution is not critical and deviations may be necessary and are generally acceptable where access is difficult. In fact there is some advantage for an evenly spread random distribution but not all field operators can achieve that successfully within quantity specifications. Such accuracy for topographic data with reasonable speed and reliability usually requires electronic Total Station equipment.

5.9 Terrain and Artefacts Records

The last task of most fieldwork is to determine the local topographic variations and the locations, extents and heights and type of buildings, basements and structures such as elevated roadways, support columns, piles and pile caps, railway cuttings and tunnels in the near vicinity of the gravity stations. All of these artefacts will influence the data locally and their influence must be theoretically compensated. This may be achieved by reasonably accurate definition of the physical dimensions and construction of theoretical models from which the gravity effect at all data points may be computed and subtracted from the measured data. The density or density contrast of these artefacts must be estimated for this process, which for void conditions such as tunnels, basements and railway cuttings is straightforward but for buildings must take into account the type of structure. One way to do this is to adopt a range of densities and to determine which one yields a result in the final compensated data output that offers least correlation with the presence of the structure, For example, typical modern high rise steel and concrete buildings present an optimum density of approximately 300 kg.m-3 whereas older concrete low rise buildings with thick walls may require a slightly greater assigned density.

There are several methods by which regular and irregular structures may be geometrically defined as 3-D models for accurate gravitational computation, and that were deployed in this survey. One example for definition of regular buildings is provided in the reference list.

Local terrain changes, that is terrain changes of more than, say, two metres within the spread of data on each site, or larger terrain changes in the outer close vicinity, demand topographic terrain corrections to the data. This process is achieved through development of a digital terrain model, constructed from the data point elevations and all other sources of accurate digital or contour terrain definition in the area, and computation of the influence upon each gravity data point. The process of developing the digital terrain model may be tedious but necessary to obtain valid results in the final data interpretation of the rock head depths model, which otherwise would incur unsupported local depression of derived geophysical rock head levels.

6. DATA PROCESSING

6.1 Gravity Survey Reduction

Reduction of gravity data is a standard procedure, the purpose of which is to eliminate those large variations of the measured gravity field that are due to irregular ground elevations, artefacts, existing structures and to the variation of gravity with geographic latitude. The data are reduced to an appropriate topographic datum to support subsequent data interpretation. Data quality and procedural practice were continuously monitored on site and where data did not comply with the allowable tolerance; measurements were repeated or conducted at night in quieter conditions. Figure 11 shows the data reduction process.

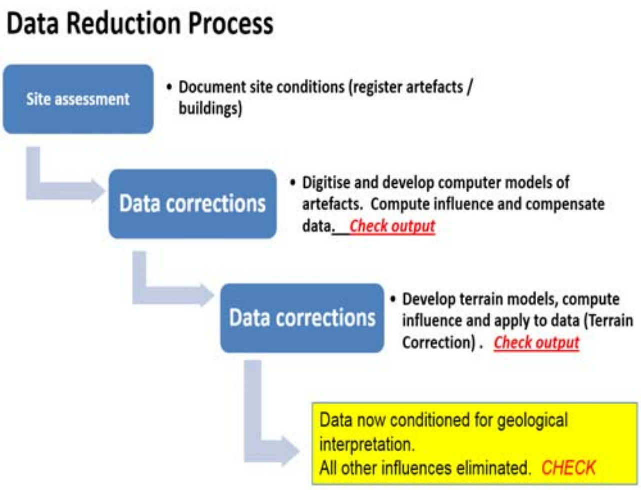


Figure 11 Data reduction process flow chart

6.2 Gravity Survey Data Interpretation

Data interpretation in all areas has adopted the following sequence:
The first process was to define the relatively negative component of the gravity field that can be attributed to the variable thickness of the mass deficient soil contrasted against the underlying Kuala Lumpur limestone. That component is referred to as the Residual Anomaly.
As discussed earlier, the density of the soil formation is significantly less than the density of the limestone and therefore the comparative mass deficiency will be manifested in the gravity data as a relatively negative influence that will vary across that area according to the formation thickness. Although it would be reasonable to expect density variation within the section overlying the limestone, there are insufficient or no control data from which those variations can be integrated by the interpretation processes. Nevertheless, in normal circumstance such variation is considered relatively smaller than the gravity field variations due to the limestone karstic irregularity. For each site, the control for this process was afforded by a few pre-existing boreholes that had penetrated limestone or that had defined a great thickness of soils and that ideally were located toward the ends of the data distribution. That selective borehole control is absolutely necessary to achieve interpretation of the gravity data in this urban environment where there is no visible outcrop of limestone. Figure 12 shows the geological modelling process.

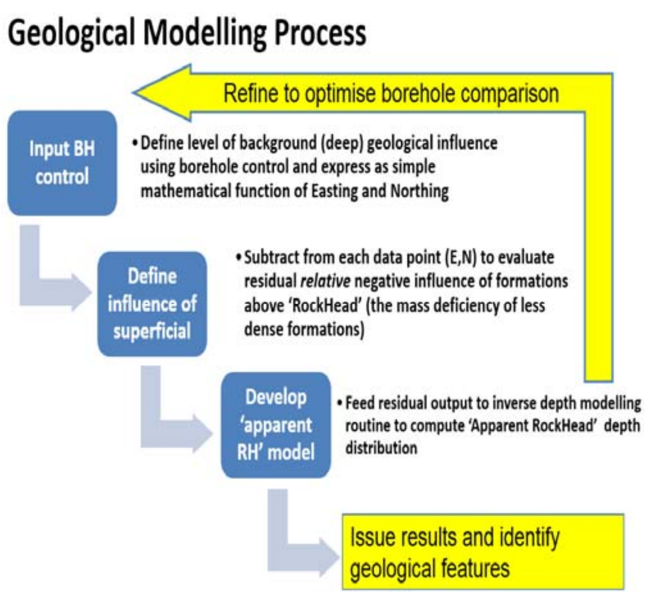


Figure 12 Geological modelling process flow chart

Having used the borehole data to determine control points, the relatively negative component of the gravity field attributable to the soil overlying the limestone (the residual anomaly) was determined for all data points by mathematical interpolation process and expressed on a regular rectangular grid. The theoretical thickness distribution of the soils that would be consistent with that determined gravity influence was computed iteratively as a grid model until the theoretical gravity response agreed closely with the derived residual anomaly. The thickness of that model expressed the depth to the apparent rock head below the datum selected for interpretation. The top of the rock was then subsequently expressed as elevations relative to the topographic datum.

The top of rock defined by the model is subject to several constraints that are discussed earlier and conceptually it may not coincide exactly with rock head defined by borehole results. The top of rock defined by the gravity models is therefore described as the Apparent Rock head, to make that distinction clear. Figure 13 shows the apparent rock head results from the Chan Sow Lin gravity survey.

7. APPLICATION OF THE GRAVITY SURVEY RESULTS

As part of the overall GI objective, the gravity survey results were then used to guide or refine the subsequent borehole location in order to verify and maximize the definition of abnormal or irregular ground conditions. The Chan Sow Lin gravity survey output interpretation model as shown in Figure 14, provides a good example of the application. The site is entirely covered by tarmac or concrete surface with relatively low rise buildings over much of the area. The model indicates that the limestone in the southern and northern parts of the data coverage is shallow, generally at a level of +37.5 metres which is within 3 metres of the ground surface and which by extrapolation is consistent with the two pre-existing boreholes immediately beyond each end of the gravity data coverage.

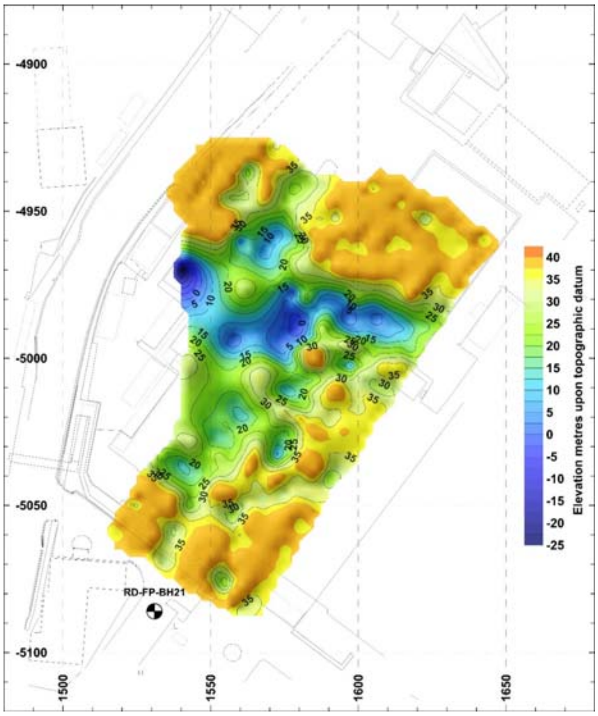


Figure 13 Apparent rock head at Chan Sow Lin gravity survey

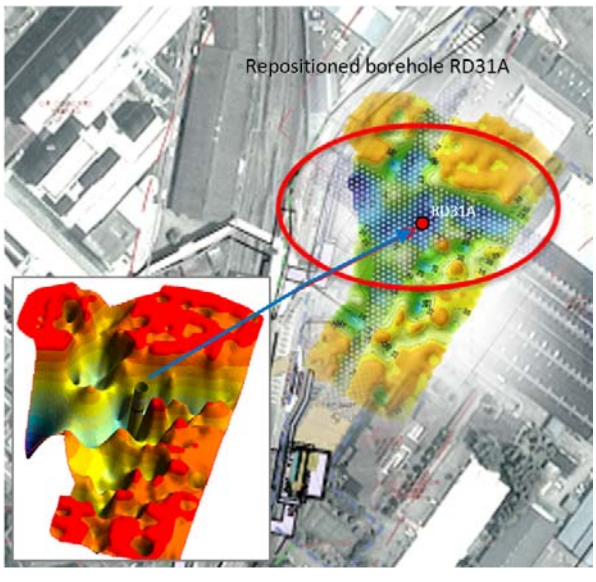


Figure 14 Gravity survey output model at Chan Sow Lin site

Over the central part of the data coverage the model is significantly deeper though, depressing steeply to levels of 0 metres or lower and that much of the central area appears to be highly irregular. The model suggests deep karstic solution conditions here, possibly with linear connecting solution channels or large cavities, which would not have been apparent from the two pre-existing boreholes. The linearity of those implied channels suggests a geological structural control. A vertical borehole, namely RD31A, was repositioned close to the centre of the survey area to investigate the contrasting conditions of locally deep depression indicated by the interpretation model.

Results of the borehole indicate that rock was first encountered at 42m below ground surface (-1.5mRL), which is in good agreement with the gravity model apparent rock head -1.0mRL. However, in this environment of very steep karst topography, significant discrepancy could be incurred through non-verticality of the borehole, inexact location and the averaging characteristic of the gravity model. It is therefore quite possible that apparent rock head in the close vicinity of the borehole may be even deeper than the borehole or the apparent rockhead model appear to suggest.

On hindsight, without proper geophysical survey as our guiding tool for repositioning the borehole GI location, karstic features within the limestone may be frequently unrecognized by adding boreholes in random or conveniently available locations.

Figures 15 and 16 illustrate the geological model before and after the gravity survey and the subsequent controlled borehole GI.

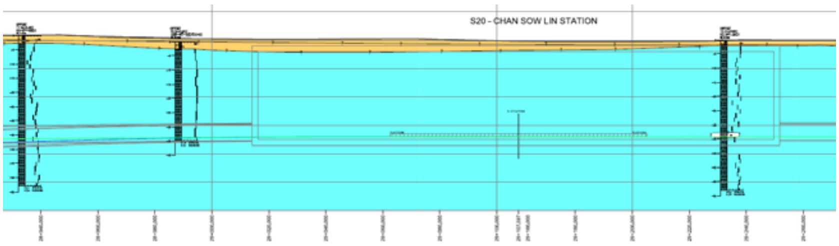


Figure 15 Before Gravity Survey

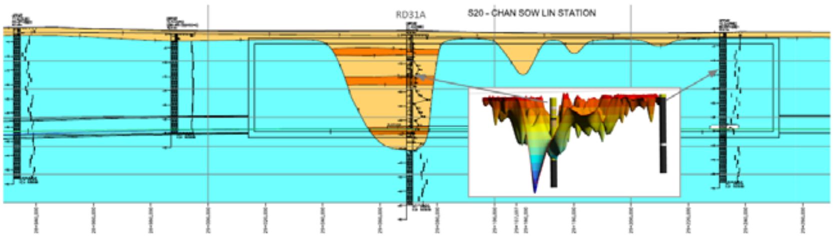


Figure 16 After Gravity Survey and verified by borehole GI at the targeted location

8. CONCLUSION

The gravity method responds directly to a mass excess or deficiency. The method requires a relatively small portable instrument and is a non-intrusive method able to be conducted in urban and environmentally sensitive areas. It is a straightforward passive geophysical technique which requires no energy be put into the ground in order to acquire data, however it requires significant care by the instrument observer/operator, and diligent data processing and interpretation. A set of proper QA/QC procedures being executed during data acquisition stage properly are crucial for the quality outcome of the survey.

The gravity method is subject to some limitations: -

- Some effects of artefacts will remain and they will have influenced the results slightly.
- In the urban environment, drains and culverts that remain unaccounted for will have effectively depressed the implied limestone surface of the model locally, but not excessively.
- The accuracy with which the method can define the distribution of apparent rock head elevation is determined by several factors. The method is an averaging technique and therefore the resolution of rapid lateral variations of apparent rock head is dependent upon the spacing of the measured data.
- The numerical accuracy of apparent rock head depth determination is subject to the availability of adequate borehole control combined with the accuracy of adopted density contrasts between the less consolidated materials and the underlying rock. Errors of density assignment may be countered to a degree by the borehole control but will influence the results at least proportionately in areas of very variable topography. As a general rule, an error of depth determination may be expected within the range +/- 15% as a consequence of density contrast definition, which is a parameter that realistically cannot be determined exactly for all geological columns in all places.
- Although the gravity method will not yield high accuracy point definition, the degree of discrepancies against drill holes can be used as a measure of rock head irregularity.
- In karstic limestone conditions, individual voids cannot be resolved and an area of multiple voids would be interpreted as an effective depression of rock head. However in those karstic limestone cases, where the gravity defined rock head is significantly below the point definition of drill hole rock head, the increased probability of further cavities or voids can be clearly recognised and subject to overall conformance with boreholes, can possibly be evaluated.

In summary, the Gravity survey method should be regarded fundamentally as a reconnaissance tool which can identify those locations where, taking into account the potential level of uncertainty, indicates potential risk from the ground conditions that warrants direct ground investigation by drilling. The method reduces the uncertainty for underground construction.

9. REFERENCES

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