Combined analysis of 2-D electrical resistivity, seismic refraction and geotechnical investigations for Bukit Bunuh complex crater

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Abstract. Interest in studying impact crater on earth has increased tremendously due to its importance in geologic events, earth inhabitant history as well as economic value. The existences of few shock metamorphism and crater morphology evidences are discovered in Bukit Bunuh, Malaysia thus detailed studies are performed using geophysical and geotechnical methods to verify the type of the crater and characteristics accordingly. This paper presents the combined analysis of 2-D electrical resistivity, seismic refraction, geotechnical SPT N value, moisture content and RQD within the study area. Three stages of data acquisition are made starting with regional study followed by detailed study on West side and East side. Bulk resistivity and p-wave seismic velocity were digitized from 2-D resistivity and seismic sections at specific distance and depth for corresponding boreholes and samples taken. Generally, Bukit Bunuh shows the complex crater characteristics. Standard table of bulk resistivity and p-wave seismic velocity against SPT N value, moisture content and RQD are produce according to geological classifications of impact crater; inside crater, rim/slumped terrace and outside crater.

1. Introduction

The collision of meteorite with earth surface produce a bowl-like shape crater, disturbed its crust and altered its geological history [1]. It is easy to identify based on its unique shape however, earth processes cover the effect of the impacts, causing the crater to gradually fade away [2] and leave a very long-lasting, though not indelible, signature in soils and rocks [3]. The characteristics can be discovered using geophysical methods that efficiently imaged the earth subsurface. This study consists of field investigation and laboratory analysis. Field investigation employed two geophysical methods; 2-D electrical resistivity and seismic refraction methods and geotechnical boreholes drilling to identify the crater’s type and its characteristics. It measures the resistivity, p-wave seismic velocity and number of blow in Standard Penetration, SPT N value. Soil and rock samples taken from boreholes are then analyzed in the laboratory to identify their moisture content and Rock Quality Designation (RQD) values. Based on characteristic shown from all the methods, standard parameter table is produced according to the geological classification; inside crater, rim/slumped terrace and outside crater.
2. General Geology and background

Study area is located at Bukit Bunuh, about 10 km from Lenggong town in the upper part of Perak state. Bukit Bunuh lies between two mountain ranges; Titiwangsa and Bintang Ranges and made up of Quaternary sediment and small lithology unit of Tertiary tefra ash and metasediments. The whole Lenggong Valley is underlain by granitic rock from Jurassic end to Carbonaceous low era which is originated from Bintang Range at the West of Lenggong [4]. Bukit Bunuh is suspected as meteorite impact crater due to more than 10000 surface suevite rocks associated with hypervelocity impact have been counted and accidently unearthed as a result of plantation activities. The suevites have been dated using the fission-track dating method by the Japan Geochronology Laboratory, Tokyo, Japan. The suevites are dated to be approximately $1.83 \pm 0.61$ million years ago that lies in the Quaternary period [5]. In order to register Bukit Bunuh as one of the world meteorite impact site and first to be discovered in tropical region, the boundary of the crater need to be verified accordingly.

3. Research methodology

Research methodology used in this paper comprises of field investigation and laboratory analysis. Field investigations are performed by utilizing 2-D electrical resistivity, seismic refraction and geotechnical borehole drilling methods. Samples taken from boreholes are tested for moisture content and RQD tests.

3.1. 2-D electrical resistivity

Resistivity method basically measures the resistivity distribution of the subsurface materials. Currents were injected through two current electrodes, $C_1$ and $C_2$ and potential difference at two potential electrodes $P_1$ and $P_2$ were measured. In this study, 41 units of stainless steel electrodes were connected to 4 ABEM Lund multi cables that lay in a straight line with 5m spacing resulting in 400m of total length in one spread. ABEM terrameter SAS 4000 and ABEM electrode selector ES 1064 were placed at the center.

Electrode configuration used in this survey was pole-dipole array where current electrode, $C_2$ was placed perpendicular and far from survey line and act as infinity. Roll along technique was also executed in order to cover the total length of survey lines. The inversion of field data was done using least-squares inversion scheme and processed using the model refinement cells with widths of half the unit spacing.

3.2. Seismic refraction

Seismic method measures the elastic wave that travelling through the subsurface. In this research, seismic refraction was performed using ABEM MK8 24 channel seismograph (display) with 24 units of 14Hz geophones (detector) and 40kg weight drop (source). Geophone spacing used is 5m resulting in 115m in one spread. Basically, geophones are connected to the seismic cable and planted the spike firmly into the ground. There are total of 5 inline shotpoints and 2 offset points. Survey continues by overlapping 1 geophone for the next spread until reached the total length of survey lines. In general, seismic wave is generated from seismic source, propagate downward through the subsurface and critically refracted when it encounter different density medium. Seismic refraction is based on the first arrival of signal that travels through a layer with higher velocity.

Critical refraction occurs when velocity of beneath layer is greater than velocity of the layer above it. Seismic refraction data is processed using tomography technique which known as velocity gradient or diving wave tomography. It uses first arrival travel time of seismic wave as input and uses the generalized simulated annealing where the algorithm performed repeated forward modeling, and new models are conditionally accepted or rejected based on probability criterion. This criterion allows the algorithm to escape from non-unique, local, travel-time minima to achieve a unique, globally optimized model of subsurface velocity structure.
3.3. **Standard Penetration Test (SPT) N value**

The SPT was carried out using the split barrel sampler and a self tripping hammer of 63.5 ±0.5 kg weights. The number of blows count for each 75 mm penetration of the sampling tube is known as N value. The test was carried out 1.5 m interval. The soil samples obtained from the split barrel were conserved as disturbed samples for laboratory analysis.

3.4. **Moisture content test**

Moisture content can be defined into two main basis which are weight basis or volume basis. Measurement of moisture content in the weight basis is known as gravimetric moisture content where the ratio of amount of water present in the void to the amount of solids is known as moisture content. However, it is often to express water content in the volume basis which is applied in this research that defined as the volume of water per bulk volume of soil.

3.5. **Rock Quality Designation (RQD)**

RQD is the ratio of the total length of good quality cores each exceeding 100 mm in length over the drilling. RQD is measured by taking the percentage of good rock sample from core barrel based on the quantity of intact pieces which is greater than 100 mm in length with the total length of the core barrel.

4. **Survey lines and boreholes**

The research covers approximately 8 km² assuming Bukit Bunuh as the center of the study area with Perak River separated the area between West and East part. The research divided into a three stages, starting with regional study consist of four survey lines with two lines of 8 km length oriented South-North (S-N) and West-East (W-E), 6.6 km lines cover the Northwest-Southeast (NW-SE) and 2 km line oriented Southwest (SW). Second stage focused on the West area of the Perak River with 5 parallel lines performed with total length approximately of 2 km (W1-W5). The research continues for the last stages that focus on the East boundary of study area. 12 survey lines were conducted with length varies from 200-1200 m (E1-E12). Total of 21 boreholes scattered in the study area. Figure 1 (a and b) shows the survey lines for three stages and location of boreholes respectively.

![Figure 1](image_url)

**Figure 1.** Survey lines and borehole location, a) survey lines for three stages and b) boreholes location of expected inside crater, on rim/slumped terrace and outside crater.

5. **Results and discussions**

Bedrock depths from 2-D electrical resistivity and seismic refraction results are digitized to produce bedrock topography contour map of Bukit Bunuh ancient impact crater. Bedrocks are digitized every 5-10 m based on resistivity and velocity of granite rocks at Lenggong area. Generally, bedrock depth varies from 5-50 m. Crater is found with diameter of 4.5-5 km surrounded with high elevated bedrock which defined as the crater rim consists of slumped terraces. Shallow level bedrock detected almost at
the center which denoted as central uplifts or rebound zones. The Bukit Bunuh impact crater is classified as complex crater type, Figure 2 (a and b) shows the bedrock topography contour map of 2-D electrical resistivity and seismic refraction results respectively.

**Figure 2.** Bedrock topography contour map digitized from a) 2-D electrical resistivity and b) seismic refraction.

Generally, results obtained from 2-D electrical resistivity and seismic refraction methods show a lot of fractures detected within the survey lines inside the crater as well as on the rim. This is suggested due to high impact of meteorite inside the crater and extensive inward collapse around the rim. However, minor fractures detected at survey lines outside the crater. Figure 3 (a, b and c) and figure 4 (a, b and c) shows the 2-D electrical resistivity and seismic refraction sections for area inside, on the rim/slumped terrace and outside the crater respectively.

**Figure 3.** 2-D electrical resistivity section for a) inside crater, b) on the rim/slumped terrace and c) outside crater

**Figure 4.** Seismic refraction section for a) inside crater, b) on the rim/slumped terrace and c) outside crater

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Results from 2-D electrical resistivity and seismic refraction were correlated with boreholes data that inline and nearest to the survey lines. Standard table of bulk resistivity and p-wave seismic velocity against SPT N value, moisture content and RQD is produce for impacted soils and rock inside the crater, on the rim/slumped terrace and outside crater are generated and presented in Table 1-3 respectively.

**Table 1.** Impacted soil and rock standard table for inside crater of Bukit Bunuh impact crater

| Geological classification                  | Resistivity, $\rho$ (\(\Omega\)m) | P-wave velocity, $V_p$ (ms\(^{-1}\)) | N value | Moisture content, MC | RQD (%) |
|------------------------------------------|-----------------------------------|------------------------------------|---------|----------------------|---------|
| Post-impact sediment fill deposit        |                                   |                                    |         |                      |         |
| - clay and silt                          | 100-700                           | 375-800                            | 0-24    | 18-59                | 12-27   |
| - sand and gravel                        | 300-5000                          | 800-2100                           | 10-23   |                      |         |
| Rocks                                    |                                   |                                    |         |                      |         |
| - Slightly weathered granite             | 1050-2500                         | 1500-2500                          |         | 70-100               | 27-50   |
| Class C                                  | 900-5800                          | 1200-2700                          |         |                      |         |
| Class D                                  |                                   |                                    |         |                      |         |

**Table 2.** Impacted soil and rock standard table on rim/slumped terrace of Bukit Bunuh impact crater

| Geological classification                  | Resistivity, $\rho$ (\(\Omega\)m) | P-wave velocity, $V_p$ (ms\(^{-1}\)) | N value | Moisture content, MC | RQD (%) |
|------------------------------------------|-----------------------------------|------------------------------------|---------|----------------------|---------|
| Post-impact sediment fill deposit        |                                   |                                    |         |                      |         |
| - silt                                   | 70-500                            | 400-800                            | 2-39    | 17-30                | 14-26   |
| - sand and gravel                        | 540-3150                          | 900-3600                           | 10-50   |                      |         |
| Rocks                                    |                                   |                                    |         |                      |         |
| - Highly weathered granite               | 290-530                           | 3200                               |         | 0                    | 0       |
| - Moderately weathered granite           | 250-620                           | 1800-3300                          |         |                      |         |
| - Slightly weathered granite             | 330-500                           | 1700-3100                          |         |                      |         |
| Class D                                  |                                   |                                    |         |                      |         |

**Table 3.** Impacted soil and rock standard table for outside crater of Bukit Bunuh impact crater

| Geological classification                  | Resistivity, $\rho$ (\(\Omega\)m) | P-wave velocity, $V_p$ (ms\(^{-1}\)) | N value | Moisture content, MC | RQD (%) |
|------------------------------------------|-----------------------------------|------------------------------------|---------|----------------------|---------|
| Post-impact sediment fill deposit        |                                   |                                    |         |                      |         |
| - silt                                   | 55-60                             | 650-700                            | 16-19   | 18-22                | 7-19    |
| - sand and gravel                        | 100-420                           | 740-1100                           | 17-50   |                      |         |
| Rocks                                    |                                   |                                    |         |                      |         |
| - Slightly weathered granite             | 1545-1600                         | 2100-2200                          |         | 0                    | 0       |
| Class C                                  | 870-1150                          | 1500-1900                          |         |                      | 67-77   |
| Class D                                  | 650-700                           | 1260-1300                          |         |                      | 91.6    |

Generated standard table for Bukit Bunuh ancient impact crater clearly shows that resistivity value of cohesive soils in overburden layer varies from 100-700 \(\Omega\)m for both inside crater and on the rim/slumped terrace. While for non-cohesive soils, resistivity value is ranging from 300-5000 \(\Omega\)m. P-wave velocity of 375-800 ms\(^{-1}\) and 800-3600 ms\(^{-1}\) is detected for cohesive and non-cohesive soils.
respectively. Non-homogeneous overburden is identified which mainly due to the high impact of meteorite inside the crater, ejection of basement rocks and fallback of the ejecta. The occurrence of impact melt sheets and suevite breccia also influence the non consistence value of resistivity and p-wave velocity of the overburden. For outside crater area, overburden consists of silt and sand with little gravel has uniform resistivity and velocity distribution. Silt has low resistivity and velocity of 55-60 $\Omega$m and 650-700 ms$^{-1}$ while sand has slightly higher resistivity and velocity value of 100-420 $\Omega$m and 740-1100 ms$^{-1}$ respectively.

Slightly and highly weathered granite bedrock is detected with resistivity and velocity of 900-5800 $\Omega$m and 1200-2700 ms$^{-1}$ respectively for inside crater while low resistivity value of 250-620 $\Omega$m is detected for rim/slumped terrace area. Velocity is distributed in range of 1700-3200 ms$^{-1}$ with totally fractured samples of 0 RQD is observed. While for outside crater area, slightly high and uniform resistivity and velocity of 650-1600 $\Omega$m and 1500-2200 ms$^{-1}$ is obtained respectively which represent by slightly weathered granite indicate that the area is not much affected by the meteorite impact. High SPT N value is identified at crater rim and outside of crater with low percentage of moisture content while low SPT N value is observed inside crater with high percentage of moisture content.

6. Conclusion
Quantitative use of geophysical parameter is less straightforward and typically required the use of correlations with geotechnical parameters. As the in-situ behavioral of soils is complex due to totally site-dependent factors, combined analysis of geophysical and geotechnical parameters are generated for Bukit Bunuh ancient impact crater area based on the crater classification respectively. Impact crater is clearly defined as a complex crater type due to circular pattern observed with some rebound at the center.

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