Methodology for cavity detection under multi-level buildings in the karstic island of Boracay, Philippines

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ABSTRACT: Most islands in the tropics with beautiful white sandy beaches are karstic in nature. One such island is Boracay, in the Philippines, with its stunning white sand beaches and world-class resorts. In the last two decades, the development of the inland areas of Boracay has been progressing at a more hurried pace in order to provide tourists and visitors the needed facilities and amenities. Most basic of these is the construction of multi-level hotels and exclusive villas, resting on cliffs and terrain offering fantastic views of the turquoise sea and golden sunset. However, since the topography of Boracay was formed through the dissolution of soluble rocks such as limestone, the island is characterized by underground drainage systems littered with sinkholes and cavities. This dissolved bedrock is often covered by residual soils thereby concealing the distinctive karst features which occur at subsurface levels only. This poses a challenge to geotechnical and foundation engineers especially when determining the stability of the underlying bedrock to support multi-level buildings. This paper focuses on the methodology used to map out the extent of subsurface cavities through the use of geophysical means, specifically the geo-electrical resistivity method. It discusses how the investigation plan for the underlying ground formation was formulated and how the locations and extent of cavities were determined. Moreover, it compares the results of the geophysical investigation with the actual cavities encountered during the foundation excavation stage. Lastly, it tackles the various technical and non-technical considerations which had to be factored in the final design in order to make the building's foundation system safe and economical.

Keywords: karstic region; geophysical methods; cavity detection

1. Introduction

Subsurface cavities are often a major risk in areas underlain by soluble rock formation. These are often encountered during excavation prior to the construction of the foundation level of a structure. It poses risks to the stability of the subsoil overlying it, as well as the structures which will be constructed on top [1,2,3,4]. Several problems associated with these include subsidence or collapse of building foundations, roads, and other above ground structures. Hence, detection and mapping of subsurface voids or cavities are imperative especially for multi-level buildings prior to construction to properly locate the foundation of the proposed structures.

To prevent and mitigate the expected structural damage due to possible subsidence of underlying soil or collapse of underground void, various geophysical surveys have been utilized to map and monitor the presence of subsurface cavities [5,6,7,8].

Some of the geophysical methods that are currently implemented in the Philippines include Ground Penetrating Radar (GPR), Seismic Refraction Survey (SRS), and Geo-Electrical Resistivity Survey. The applicability of each method may depend on the existing ground condition, extent, and depth of subject area.

2. Regional geology

Based on the geologic map published by Mines and Geosciences Bureau shown in Fig. 1, a government agency under the Philippines' Department of Environment and Natural Resources, Boracay Island is generally underlain by two rock formations: Quaternary Alluvium and Sta. Cruz Sediments.

The Quaternary Alluvium is composed of unconsolidated to poorly consolidated sand, silt, clay, and gravel. This formation occurs mostly along the central portion of the island. Minor occurrences of this formation are noted at the northern and southern portions of the island.

The Sta. Cruz Sediments, on the other hand, is composed of gently to moderately dipping beds of coralline limestone underlain by calcareous mudstone, siltstone, shale, and conglomerate at the base. This formation is dated by previous workers as Pliocene and occurs extensively at the north and south parts of the island.

3. Study area

This paper focuses on one of the structures being built in Boracay. Based on the results of a geotechnical investigation program, the project area is generally underlain by highly weathered limestone a few meters from the ground surface and by slightly weathered to fresh limestone at greater depths [9]. Limestones are known to be porous materials and usually contain cavities on the subsurface. Thus, cavity detection survey was conducted using geophysical investigation employing resistivity technique to unearth latent cavities that lie beneath the study area.

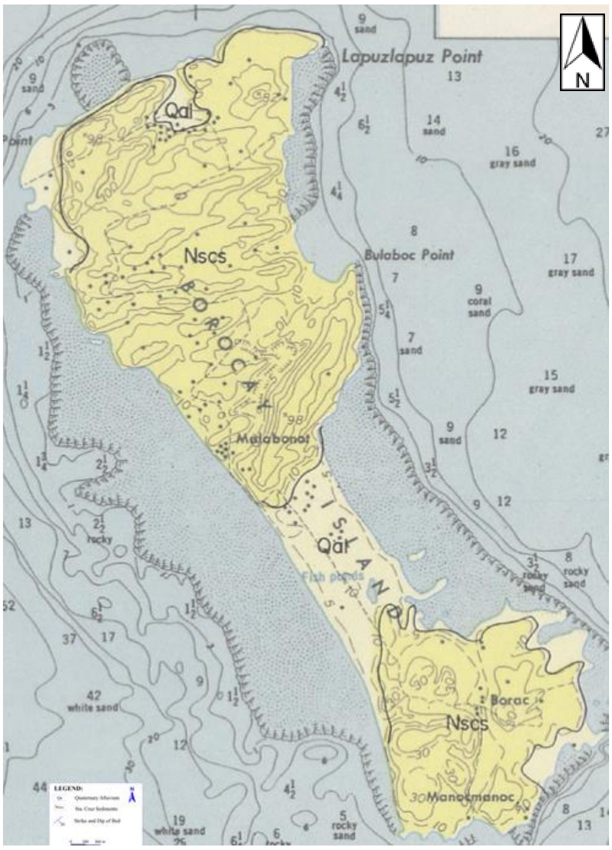

Figure 1. Geologic map of Boracay Island (Source: Mines and Geosciences Bureau)

4. Geo-electrical resistivity survey

Geo-Electrical Resistivity Survey is a geophysical technique used to indirectly investigate physical characteristics of the subsurface earth layers. This technique operates on the theory that each earth material has certain characteristics of resistance to the flow of electric current [10,11].

4.1. Principles

Resistivity surveys involve the introduction of electrical current into the ground through two pairs of electrodes. When the electric current is introduced into the ground; the ground acts as a weak conductor. Any variation in the subsurface conductivity due to size, shape, and electrical resistivity of underlying earth layers will alter the flow of current. If another set of electrodes is placed close to the current electrodes, a difference in potentials can be measured using an instrument, which can measure extremely low voltage difference. The resistivity technique used is the Pole-Pole Array. Pole-pole array is a modernized two-dimensional resistivity profiling technique which provides a comprehensive geological interpretation by examining subsurface electric characteristics such as resistivity, permittivity, and chargeability.

4.2. Pole to pole array

The Pole-Pole Array uses four electrodes: two of which serve as C1 and P1 and the other two are remote electrodes designated as C2 and P2. These electrodes are placed at a location 10 times of the maximum electrode interval from the measuring points. C1 and P1, two moving active electrodes, are used to profile along the line at 5 meters interval.

The ground surface of every traverse line is prepared by putting pegs indicating detector (electrode) points at a horizontal interval of 5 meters and are numbered continuously from the beginning to the end of each traverse line. At an initial stage, with the C1 fixed at zero point, the P1 is set at 5-m point and the resistivity is measured. P1 is then shifted from 5-m point to 10-m point for the next measurement and so on up to the end of the line. Once the measurement has been made at P1 = end of line, C1 is then moved to 5-m point, P1 to 10-m point and the measurement is continued up until P1 is at the end of the line. The shifting of C1 and P1 is continued until the end of the line is reached. Since C2 and P2 are placed about 500 meters from the resistivity profile lines, about 10 times of the maximum C1-P1 distance will be used for the array. The geometric factor can be computed from the equation below, where r_1 is equal to $C_1 - P_1$.

$$Geometric\ Factor = 2\pi r_1 \qquad (1)$$

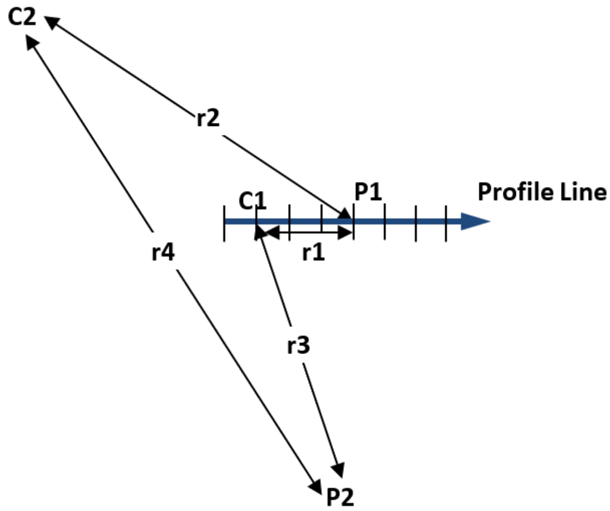

Figure 2. Schematic diagram of the pole-pole array

The measured data is then converted to an apparent resistivity value, which is processed by an inverse software to produce 2D-resistivity model profiles while true resistivity values are obtained.

5. Field survey and analyses results

In order to ensure the stability of the foundation for the proposed structure, cavities present at the site was mapped out. Similar to the methodology implemented for a previous project adjacent the subject area, the foundation plan was used as a guide to determine the location of the resistivity lines. Longitudinal lines are placed at the center of the spread footing. Transverse lines were also laid out as additional verification to the results of the longitudinal lines [1]. The following flowchart shown in Fig.3 presents the methodology used for this survey.

Stakes were then laid out by the surveying team at the site to ensure the correct locations of each lines. The first survey was conducted in February 2017. During this time, the site was not yet excavated.

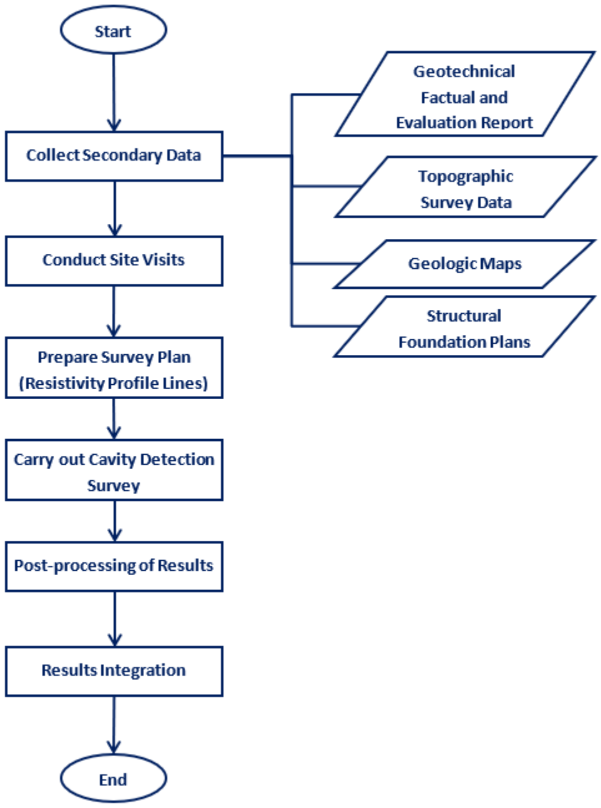

Figure 3. Flowchart of Methodology implemented in the study

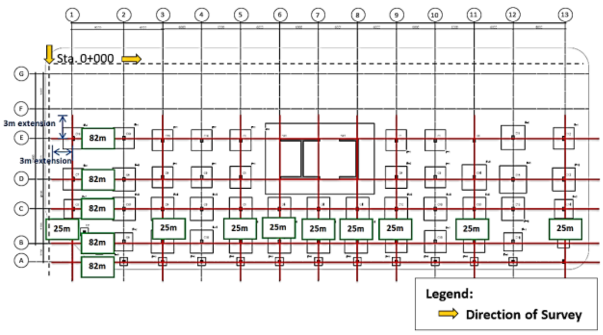

Figure 4. Resistivity profile lines (Survey 1)

To facilitate the identification of cavities at resistivity profiles, resistivity calibration carried out at the adjacent property was used. The resistivity profiles are presented in the form of Inverse Model Resistivity Section. The low resistivity anomalies with assigned colors of light blue to dark blue are believed to be resistivity signatures of cavities filled with clay while the high resistivity anomalies with assigned colors of bright yellow to dark red represent cavities filled with air.

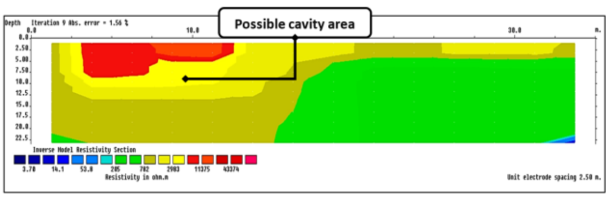

Figure 5. Resistivity profile used for cavity calibration

Most of the low resistivity anomalies detected are relatively deep except at Grids 11 and A where the low resistivity anomaly lies at around 9 meters.

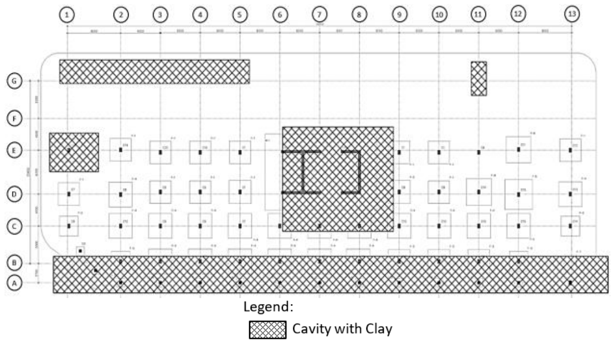

Figure 6. Possible locations of detected cavities (Survey 1)

Table 1. Summary of locations of cavities identified (Survey 1)

Line Name	Depth from Original Ground Line (m) (Top and Bottom of Cavities)
Grid 1	21-23 (Clay)
Grid 3	21-23 (Clay)
Grid 5	-
Grid 6	-
Grid 7	-
Grid 8	21-23 (Clay); 1-3 (Clay)
Grid 9	-
Grid 11	9-18 (Clay)
Grid 13	22-23 (Clay)
Grid A	8-23 (Clay)
Grid B	21-23 (Clay)
Grid C	21-23 (Clay)
Grid D	21-23 (Clay)
Grid E	21-23 (Clay)

A second survey was conducted in August 2017. During this time, the project site was already excavated at the foundation level. A cavity was also discovered on the edge of the footing excavation at Grid F-12 which was not included in the original survey lines. The opening of the cavity is around 2 meters, with an approximate width and depth of 3 meters and 8 meters, respectively.

Additional resistivity lines were set and surveyed, following the updated foundation plan provided. Same with the first survey, the resistivity lines were placed at the center of each footing.

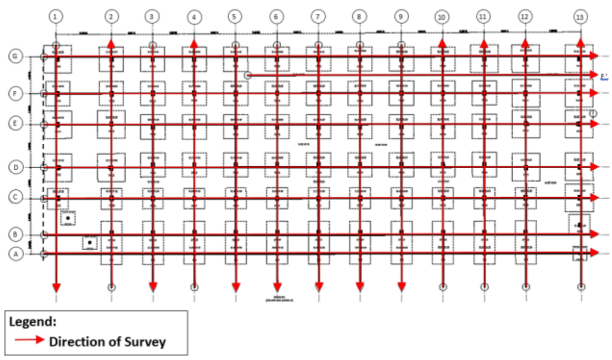

Figure 7. Resistivity profile lines (Survey 2)

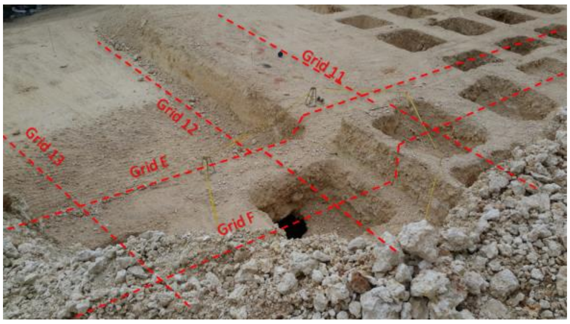

Figure 8. View of the footing excavations with grid lines (Survey 2)


Figure 9. View of the cavity at Grid F-12 (Survey 2)

A verification survey was also conducted to establish the extent of the cavity found at Grid F-12. Three (3) verification survey lines were laid around the cavity area. The survey lines were composed of one (1) longitudinal and two (2) transverse lines with 35 meters length each. Two of the lines were placed at the boundary of the foundations while the other line was placed in between two foundations.

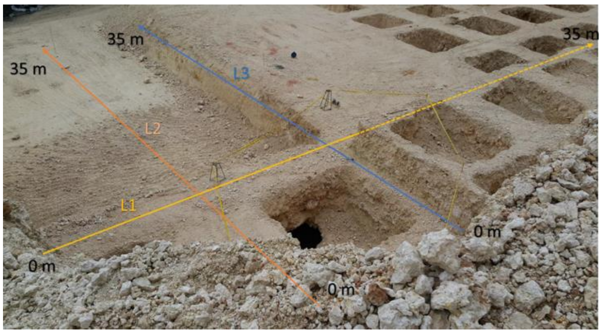

Figure 10. View of the footing excavations with grid lines (Survey 3)

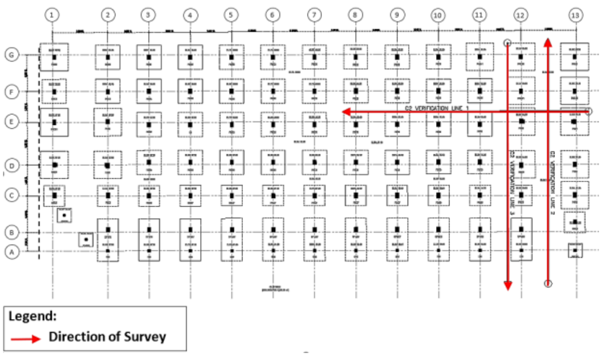

Figure 11. Additional resistivity profile lines (Survey 3)

Fig. 11 presents the possible locations of detected cavities. The detected anomalies along the Grid 12, Grid F, and Lines 1 to 3 are translated as cavities filled with air. These matched the discovered cavity at the area. Based on the recorded depths of anomalies, the exposed cavity is most likely centered along Line 1 (verification survey line), where the depth of the cavity is the largest. Long high resistivity anomaly was detected along Grid F' while patches of high resistivity anomalies were also detected at Grid F.

A few high resistivity anomalies were presumed to be footing excavations, based on their location and depth.

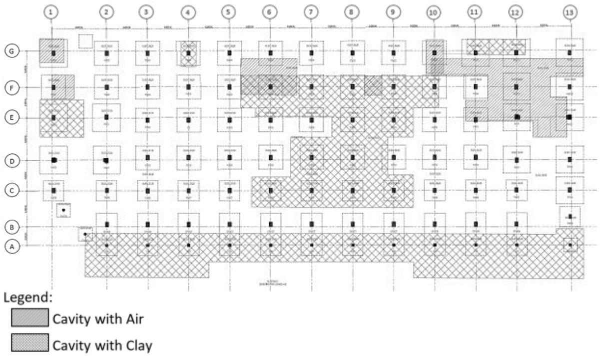

Figure 12. Possible locations of detected cavities (Surveys 2 & 3)

Table 2. Summary of locations of cavities identified (Survey 2)

Line Name	Depth from Existing Ground Line (m) (Top and Bottom of Cavities)
Grid F	0-2.5 (Air);
Grid F'	10-23 (Clay); 0-7.5 (Air); 0-2.5 (Air); 0-2.5 (Air)
Grid G	0-7.5 (Air); 0-3 (Clay); 0-8 (Air)
Grid 2	0-2.5 (Air)
Grid 4	20-23 (Clay)
Grid 10	15-23 (Clay)
Grid 11	0-2.5 (Air); 21-23 (Clay)
Grid 12	0-3 (Air); 21-23 (Clay)
Grid 13	0-3 (Air); 21-23 (Clay)

Table 3. Summary of locations of cavities identified (Survey 3)

Line Name	Depth from Existing Ground Line (m) (Top and Bottom of Cavities)
Line 1	0-10 (Air); 21-23 (Clay)
Line 2	0-4 (Air); 21-23 (Clay)
Line 3	0-4 (Air); 21-23 (Clay)

6. Conclusions

Based on the results of the survey, it is vital to conduct geophysical surveys in karstic regions to make sure that the foundation is located on a stable soil or rock. In this study, it was recommended to revisit the structural design and elevation of the footings. Footings near cavities would need to be lowered until the bottom of the cavity. Alternatively, the cavity area may be allotted for the utility tanks of the building. The bottom slab of the tanks may be designed to act as the mat footing on areas with big cavities. Another option would be to fill the voids/cavity with concrete. However, the required concrete volume to fill the voids might be large, considering the width and depth of the anomalies detected in the survey. Furthermore, it should be noted that there might be some small openings which can cause concrete leaks.

7. Limitations of the methodology

One of the limitations encountered in this project is that the results of the analysis is in 2D form (planar). A good example is the cavity found at the edge of the footing excavation at Grid F-12 which was not initially captured since survey lines were placed at the center of the foundations. Considering the extent and shape of cavities which are highly irregular, closely spaced grid lines should be adopted. This, however, is not practical for buildings with large footprints. Verification surveys may also be conducted to further confirm the extent and depth of these cavities.

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