Identification of Karstic Features with Extensive Geophysical Investigation for Underground Infrastructure - South of Wakrah Pumping Station and Outfall (SWPSO) Project

Ali Akbar
Stantec UK Limited, Doha, Qatar
ali.akbar@stantec.com

Fathelrahman Dafalla
Stantec UK Limited, Doha, Qatar
fathelrahman.dafalla@stantec.com

Ilayaraja Kumba Krishnamurthi
Public Works Authority (Ashghal), Doha, Qatar
ikrishnamurthi@ashghal.gov.qa

Andres E. Pinto Candia
Stantec UK Limited, Doha, Qatar
andres.pinto@stantec.com

Abstract

There has been a significant increase in the number of underground infrastructure projects built in a short period because of Qatar's goal of effective mass transit and robust urban drainage infrastructure, as well as the country's recent fast urbanization and harsh weather events. The Doha Metro, the Inner Doha Re-sewerage Implementation Strategy (IDRIS), and most recently the Doha South Terminal Pumping Station (DSTPS) and the Musaimeer Pumping Station and Outfall (MPSO) projects faced difficulties in identifying and quantifying the Karstic features and the remedial approach for underground works to ensure the completion of the projects on schedule and within budget due to the unknown ground conditions. One of the most important risks for underground construction in Qatar is the presence of karst environments, which are concentrated mainly within the limestone, dolomite, gypsum, and anhydrite horizons of the Eocene strata. The proper assessment of Karstic features requires an appropriate selection of geophysical methods and a high level of skills and expertise to interpret the data. To do so, a comprehensive geophysical survey campaign was deployed at the early stages of the project's execution to identify the Karstic features of concern associated with subsurface conditions at shallow and deeper depths up to 80 meters below ground level. This paper presents an example of a recently developed geophysical investigation program for the pre-tender design of the South of Wakrah Pumping Station and Outfall project. The project team carried out a comprehensive geophysical study to identify the Karstic features of concern along the tunnel alignments, shaft locations, and at the pump station area. Most of the identified Karstic features are categorized as low risk, but there was a high-risk anomaly (cavern) identified, and the extent of this cavern was verified with well-known geophysical methods like Multichannel Analysis of Surface Waves (MASW), seismic refraction, and 3D crosshole seismic tomography.

Keywords: Karstification; Caverns; Cavities; Geophysical methods; 3D model

1 Introduction

In most civil engineering works, it is critically important to characterize the mechanical behavior of geotechnical materials under various types of loading. This characterization has normally been expressed in terms of elastic moduli, of which shear modulus is most important because it is directly related to the stiffness of the subsurface material. In general, there are two methods to characterize the mechanical behavior of geotechnical sites under various types of loading. One is the deflection-response method which measures stress-strain behavior of the sites caused by static or dynamic load. The major drawbacks of this method are that the overall stiffness is measured and, therefore, it is not possible to measure the stiffness at different depths, and the method can be destructive to the sites. The other method of characterization is the wave-propagation method which estimates the shear moduli at different depths by measuring seismic velocities with different methods. These methods offer the most direct and non-destructive approach to determining stiffness at different depths of geotechnical sites. Advantages of mapping the bedrock surface with the shear wave velocity field calculated from surface waves include the insensitivity of geophysical methods to velocity inversions, ease of generating and propagating surface wave energy in comparison to body wave energy, and sensitivity to lateral changes in velocity.

2 Geological Setting

The Tertiary to Quaternary periods account for all of Qatar peninsula's formations. The Simsima Limestone, middle Eocene, makes up most Qatar's territory. The Midra Shales member of the Lower Dammam Formation, middle Eocene, lies beneath the Simsima Limestone, which is a component of the Upper Dammam Formation. The Rus Formation, lower Eocene, is beneath the Midra Shales. A thin layer of loose to medium-dense silty, gravelly sand covers the solid geology.

3 Geophysical Investigations

Combination of multi-channel analysis of surface waves (MASW), seismic refraction seismic crosshole tomography and geophysical borehole logging methods were utilized to achieve the objective of the geophysical study in order to investigate the underground cavities and/or weak zones to a depth of 60-80 meters below ground level (BGL); the methods provide an accurate and consistent technique for estimating near-surface shear wave and P wave velocities, respectively.

3.1 Multichannel Analysis of Surface Waves (MASW) and Seismic Refraction Tomography

The surveys were performed as fixed static spreads and the collected data was processed for both MASW and refraction. The geophones were planted into soil and because of the direct receiver coupling, the signal-to-noise (SN) ratio of acquired data was higher than surveys made by the land streamer. To determine phase velocities at low frequencies precisely, Park et al. (1999a) pointed out that it is essential for the MASW method to use as long a receiver array as possible. However, a longer receiver array might decrease the lateral resolution of the survey, because the conventional MASW method provides a velocity model averaged over the total length of the array. A smaller array is better for increasing lateral resolution. Improved lateral resolution offsets the accuracy of phase velocity. CMP cross-correlation analysis will be used to overcome this trade-off.

Two different geophone arrays were used over parallel lines separated by 5-10 meters to provide the necessary depth of investigation and resolution. For high resolution and shallow depth of investigations (less than 25 meters), a geophone array consisting of at least 48 geophones spaced at 2.5 meters (120 meters receiver spread length) was used. For deeper investigation (greater than 25 meters) with moderate resolution, a geophone array consisting of 48 geophones spaced at 5 meters (240 meters receiver spread length) was used.

(a) **(b)**

Fig. 1: (a) and **(b)** view of XLR8-1450

A crawler-mounted accelerated weight drop (XLR8-1450) was used to create seismic energy for both shallow and deep investigations (Figure 1a) and (Fig 1 b).

For deep works, an array consisting of 96 active geophones with 5 meters spacing was used to investigate until 80-meters with moderate resolution. For shallow works, an array consisting of 96 active geophones with 2.5 meters spacing was used to investigate up to 25 meters with high resolution.

A mixed geophone array configuration (the first -near to AWD- 24 geophones with 0.5-meters and the last 24 geophones 1-meter spacing) land streamer was used to have a shallower resolvable depth while maintaining at least 15-meters depth of investigation.

3.2 Seismic Crosshole Tomography

Seismic crosshole tomography surveys were conducted by lowering the seismic source in one of the four boreholes and the string of geophones in another borehole. The seismic source used was a Geotomographie BIS-SH-DS electro-mechanical probe capable of producing both P waves and horizontally polarized S-waves. During the tests, the source probe was lowered into each of the test boreholes at a depth interval of two meters and locked into position by inflating the packer so that it is tightly clamped to the borehole wall. The receiver system consisted of a string of ten 30Hz-geophone stations with a station interval of one meter. Each individual station contained three geophones arranged in a tri-axial orthogonal manner and a digitizer for the analogue- to-digital conversion (24 bit). Crosshole tomography program; both P-wave and S-wave crosshole seismic tomography were carried out between borehole pairs at 11 shafts location across the project area. Crosshole tomography was performed from top to bottom of borehole, with boreholes depth ranging from 45 to 70-meters, which were drilled at 10-14 meters BH spacing.

3.3 Geophysical Borehole Logging

3.3.1 P-S Logging

The main purpose of this test is to acquire shear wave velocities (V_s) and compressional wave velocities (V_p) as a function of depth of engineering and environmental concern, which in turn, can be used with density to derive the dynamic soil parameters. P-S logging offers very high resolution (typically one meter) to resolve thin layers that can have a dramatic effect on surface response. The shear wave velocities (V_s) and compressional wave velocities (V_p) were calculated at one-meter depth intervals. The dynamic ground parameters obtained by considering the seismic velocities from the PS log measurement were calculated for each testing location. PS logging tests were carried out in thirty-five (35) exploratory boreholes in the project site. After completion of drilling, the P-S logging was performed in uncased-well conditions.

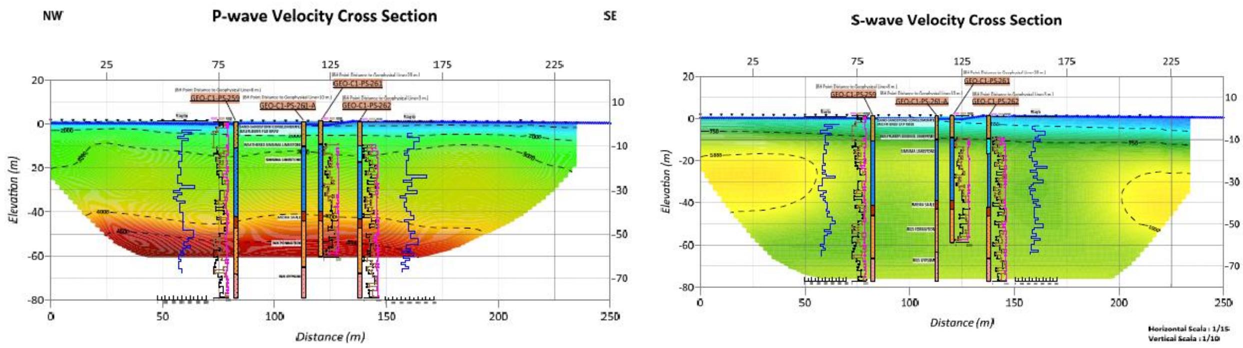
Data measurements were performed at 1-meter interval by drawing the probe from bottom to top in the water-saturated section of the open hole. To acquire data, the probe was stopped at the required depth and the source was fired under surface command. The resultant signals were created from the measuring software as two horizontal and one vertical shot to allow measuring P and S wave velocities. The graphical representation of the P and S wave velocities is presented in the below section.

3.3.2 Acoustic & Optic Televiewer (ATV & OPTV) Logging

The HRAT (high resolution acoustic televiewer) logging was carried out in 10 exploratory boreholes and optic televiewer logging was carried out in 25 exploratory boreholes in compliance with ASTM-D-5753-05 *Standard Guide for planning and conducting borehole geophysical logging*. ATV & OTV logging were applied in designated open holes before any other in situ testing was conducted after completing drilling, ATV or OTV probe was lowered to the bottom of the open hole (filled with clean water) to scan the features of the borehole wall as it travelled up to the ground. Each borehole location was left to rest in order to stabilize the groundwater condition since it does not offer travel time measurements and is unsuitable for boreholes containing mud or cloudy fluids. Measurement was taken in both directions, from top to bottom and from bottom to top. The final measurement was taken while pulling up to get a better-quality image, and to prevent vibration of the probe. When the probe was taken down, the amplitude settings were adjusted to find the optimum setting and additionally the vibration of the probe was less when pulling up. HiRAT software was used during measurements. The levels, depths, and speed of the probe down the hole were monitored using a computer unit during data acquisition.

4 Correlation of Geophysical Results with Borehole Data

Comparison of the geophysical results with rock core information allowed calibration of the geophysical data interpretation. The top-made ground, significant notable fractures/voids, and drilling conditions for each boring were compared to the velocity signature for each MASW profile. A good correlation was assigned if two or more of the previously stated conditions could be correlated to the modeled velocity profile. For example, if the boring log indicated the overburden was relatively weak rock existed at 10 meters below ground level and the corresponding S-wave velocity profile identified low velocity at this depth, and then a good correlation existed. Conversely, if the boring log did not indicate conditions that correlated to the modeled velocity value, a poor correlation was assigned. The interpreted 2-D section shear-wave velocity correlates very well with subsurface materials encountered in the geotechnical boreholes. Examples of correlation between geophysical results and geotechnical boreholes are presented in Figure 2. Based on the above observed anomalies, verification diagraphy boreholes were recommended to be drilled to verify the nature of the anomalies in geophysical profiles.



(a) **(b)**

Fig. 2: Comparison of the MASW & Refraction data with the borehole controls

Fortunately, low V_s values in the first 5 meters (less than 1000 m/s correspond to the soft unconsolidated topsoil) followed by a V_s increase (as also observed in the PS-logging data). The blue line in-between the two boreholes illustrates the base of the Simsima Limestone and the base of the Midra Shale and the orange line indicates the transition from the Rus Formation to the Rus Gypsum formation. Apart from the change from unconsolidated soil to Simsima Limestone, only minor variations in V_s are visible in the MASW result.

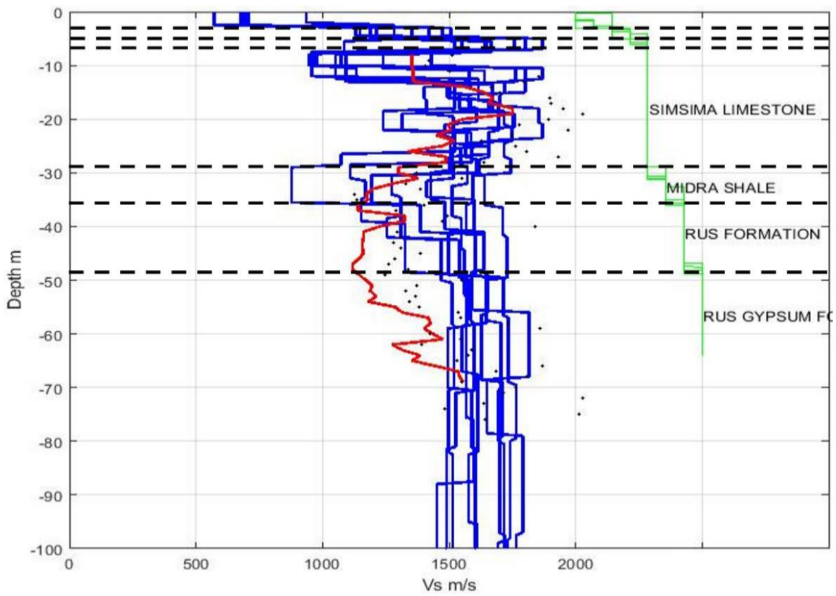


Fig. 3: Plot showing the average of all PS-logging values and the geological interpretation (The black dashed lines map the geological transitions onto the geophysical profiles

Crosshole tomograms showed high shear wave velocities except at one critical shaft location. At this location, a zone of medium velocity (the moderately weathered/fractured zone with $750<V_s<1000$ m/s) was observed (Figure 3). This zone started at the surface and continued till final depth (60 meters). A cavern was discovered during drilling which starts around 55-60 meters under this shaft location. It is believed that this weak zone is the result of settling of the zones above the cavern roof. It was observed that, the P and S-wave velocity models seem to agree well with the trends in the borehole log values.

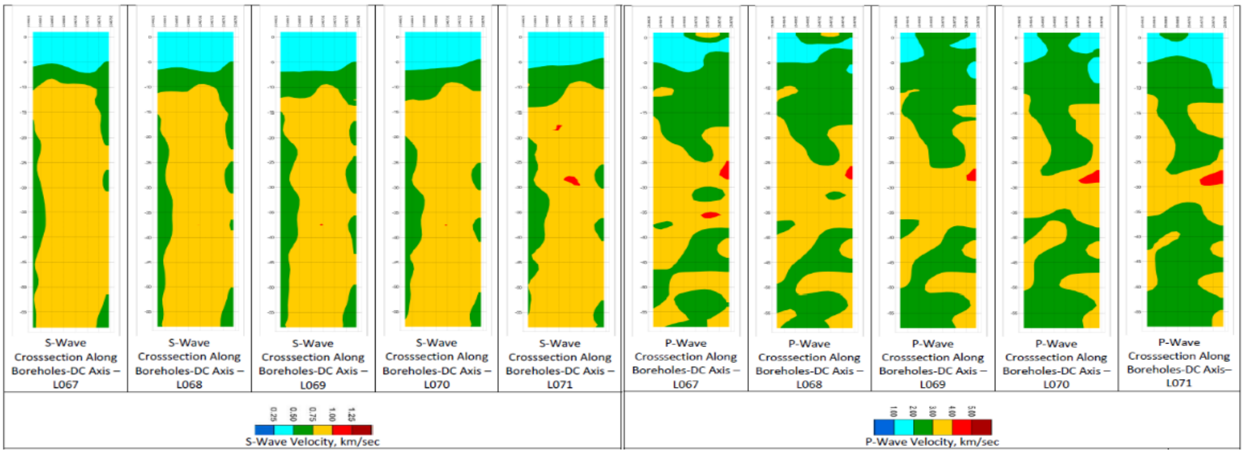


Fig. 4: 2D presentation of Results of Seismic Crosshole Tomography

Based on the correlation of all geophysical results presented in Figure 4 and Figure 5, it is observed that the P and S-wave velocity models, OTV and OTV and Crosshole results seem to agree well with the trends in the core borehole (RQD, TCR and SCR) and diagraphy log values.

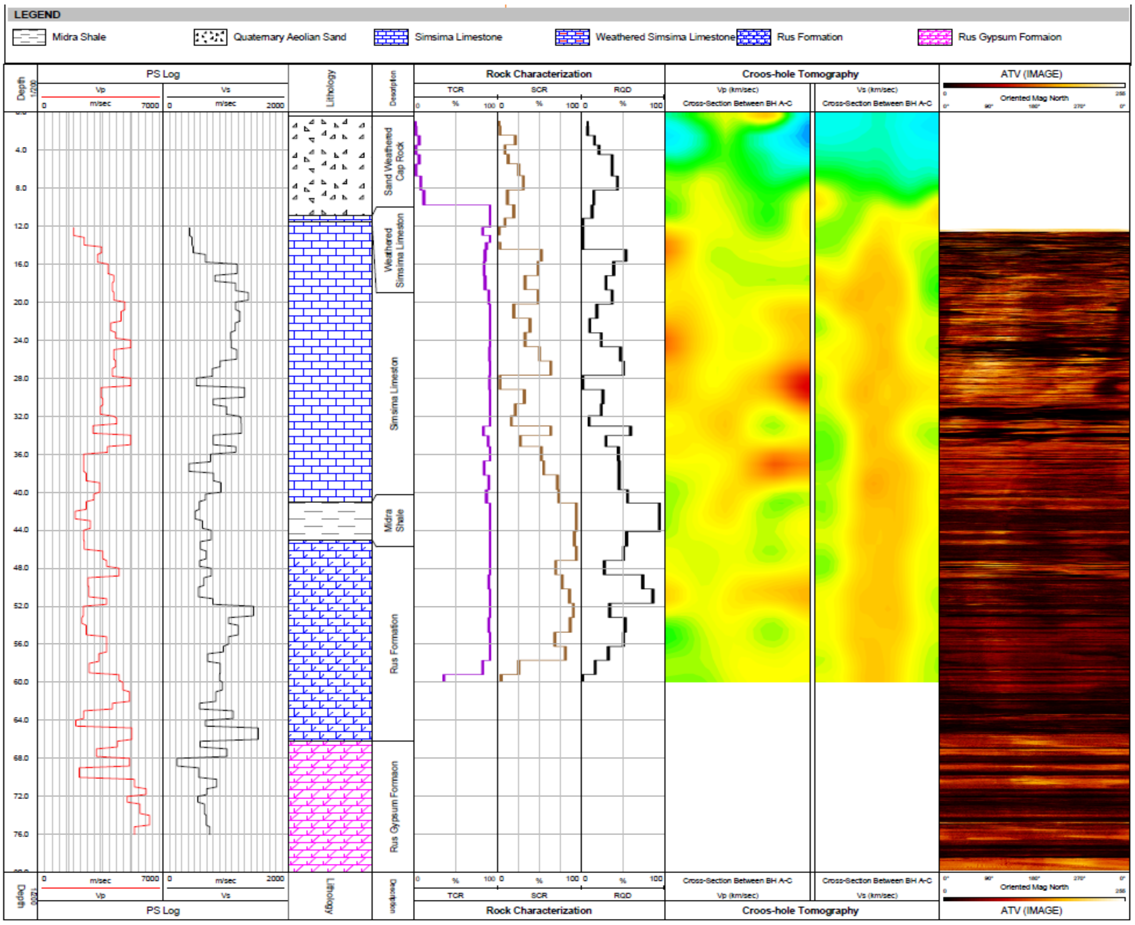
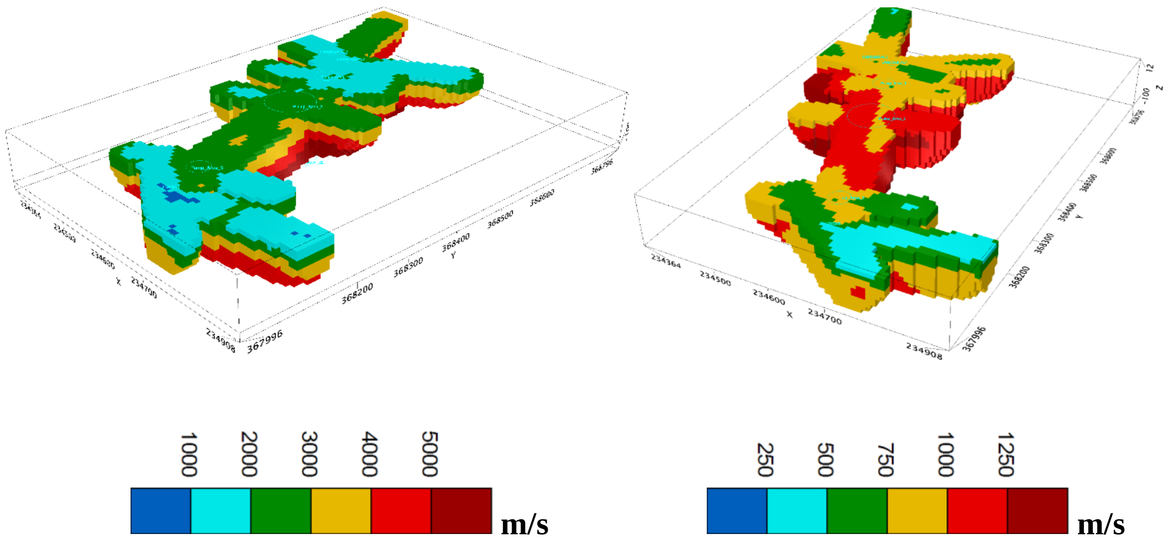


Fig. 5: Correlation of Geophysical methods results with the borehole control

5 Results and Discussion

5.1 MASW and Seismic Refraction

The MASW and refraction survey was completed as a “screening tool” to provide subsurface information that would ultimately be used to determine the above-mentioned geotechnical areas of concern. The shear wave and P wave velocity surveys provided a two-dimensional image of the subsurface along the proposed tunnel and shaft locations at specific traverse line locations. The shear wave velocity results indicated that the study area of the project site exhibited distinct velocity conditions and contrasts. Low-velocity areas within the MASW profiles were consistent with unconsolidated surficial materials and deep highly fractured/weathered bedrock with a high percentage of *attapulgite* clay, while higher velocity materials were consistent with harder materials. Within this type of geologic setting, unconsolidated materials are attributed to soft, weak (less competent) rock. The shear wave and P wave velocity profiles across the project area is characterized by several geologically significant changes in material properties. Unique signatures of low, medium, and high shear wave velocity values across the site at different depths have been recorded on the processed shear wave velocity sections. Summary of Geological Strata Shear Wave Velocity Values for all MASW profiles is presented in Table 1 and 3D models P and S wave at one of the critical locations are presented in Figure 6 below.

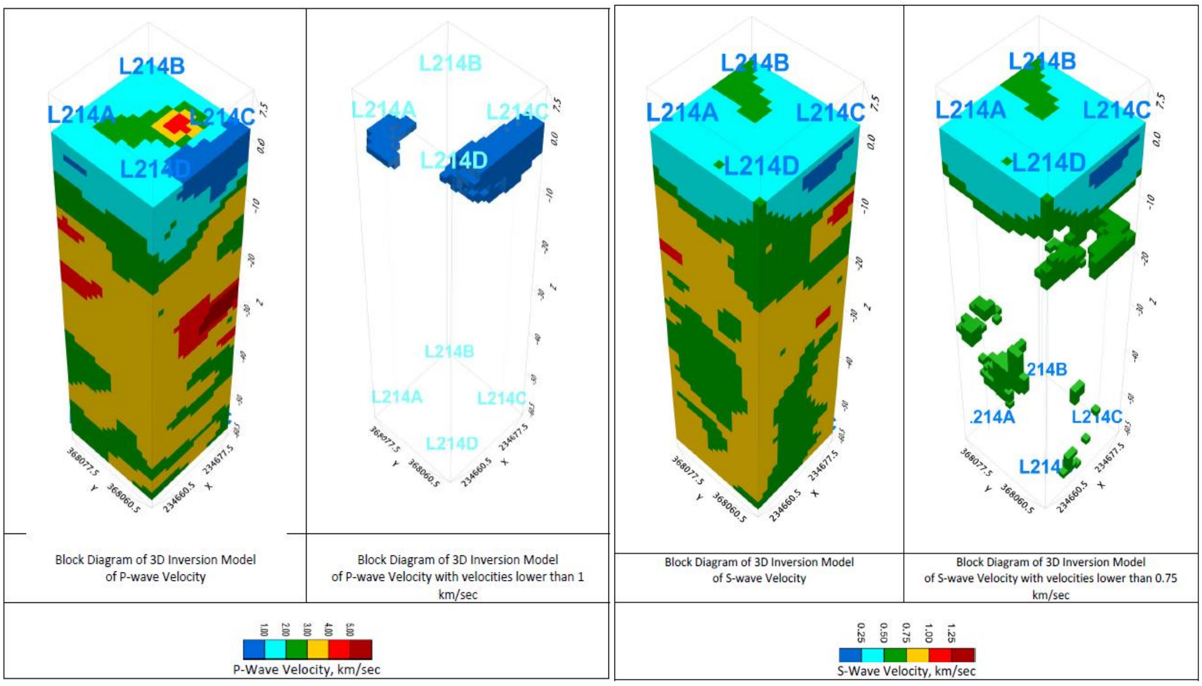


(a) **(b)**

Fig. 6: P and S wave 3D Velocity model of one of the critical locations of the project

5.2 Seismic Crosshole Tomography

After inversion of the travel time data, 3D models were prepared after which level maps and vertical cross-sections were produced. And the resulting velocity tomograms were then compared with the available borehole log data (RQD, SCR, TCR, Lithology, ATV and PS-log) of the nearby boreholes. At the critical shaft location, there was a zone of medium velocity (the moderately weathered/fractured zone with $750<V_s<1000$ m/s). This zone started at surface and continued till final depth (60m). A cavern was discovered during drilling which starts 55-60 m under this shaft location. It is believed that this weak zone is the result of settling of the zones above the cavern roof. It is observed that the P and S-wave velocity model seems to agree well with the trends in the borehole log values. The results of crosshole tomography are presented as 3D in Figure 7 below.



(a) **(b)**

Fig. 7: The inverted V_p and V_s 3D models at one of the critical shaft locations

6 Conclusions

Comparison with conventional geophysical methods (PS-logging, seismic Refraction, MASW and seismic Crosshole Tomography), shows the result describes the vertical geological sequences along the site well and allows for a 2D and 3D interpretation of lithology and geotechnical parameters derived from V_s. Based on the review of the geotechnical boring logs, shear wave and P wave velocity results, the following conclusions can be drawn from the present survey:

- 2D Sections for shear wave (V_s) and P wave (V_p) from MASW Refraction and Crosshole tomography data versus Depth (m) were presented.
- Poison's Ratio, Shear Modulus, Young 's Modulus and Bulk Modulus values were calculated from (V_s) and (V_p) data and 2D sections for these engineering parameters versus depth (m) were also calculated and presented.
- The geotechnical boreholes were proposed and considered to correlate and calibrate the obtained results within the site to verify the nature of the identified anomalies in MASW profiles.
- To know the extent of the cavern, additional diagraphy boreholes were drilled and OPTV was performed to map the roof of the cavern at various levels at each borehole location.

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