Proceedings of the 7th International Conference on Geotechnical and Geophysical Site Characterization
Barcelona, 18 - 21 June 2024

Comprehensive geometric characterization of the subsurface using Microseismic Resonance: identifying sinkholes by modelling the bedrock surface and karstic features in a challenging environment

Mitchell Green *P.G.*[1], *Mike* Jessop *P.Gp.*[2], and *Patrick* Pires *P.E.*[3]

[1]*Pogonip Group LLC, Geology, 1930 Village Center Circle #3-3481, Las Vegas, Nevada, 89134, United States*
[2]*Willowstick Technologies LLC, Geophysics, Box 754 165 E. 900N #754, Spanish Fork, UT, 84660, United States*
[3]*PCP Engenharia, Engineering, Av. Montreal, 501, Jardim Canada, Nova Lima, MG 34007-720, Brasil*

ABSTRACT

This study presents a comprehensive assessment of the subsurface characteristics at a Unigel processing facility in Pedra Blanca, Sergipe, Brazil, utilizing Microseismic Resonance (MSR). The facility experienced the emergence of sinkholes and depressional features near critical infrastructure, prompting the need for a thorough subsurface characterization. MSR, a burgeoning microseismic technique, was employed due to its ability to geometrically characterize subsurface structures without the limitations of large geophone arrays. Fieldwork involved MSR data collection on a 10m by 10m grid over a 37.14 hectare area, complemented by borehole data and a gravity survey. Results revealed the intricacies of complex stratigraphy with Quaternary fluvial deposits overlying Early Cretaceous carbonates with karstic morphology. MSR data processing produced a holistic geometric model of the subsurface, including the identification of karstic features. Comparison with borehole data demonstrated high accuracy, with MSR Local Component (LC) data rendering a bedrock surface of approximately 99% accuracy. MSR Full Spectrum data (FS) is correlated with the gravity study validating the presence of karstic structures. This study showcases MSR as a powerful, non-invasive tool for rapid and accurate subsurface characterization, crucial for infrastructure security and environmental assessment.

Keywords: microseismic resonance; geometric characterization; karstic features; sinkholes

1. Introduction

Unigel operates a large processing facility in the town of Pedra Blanca state of Sergipe in eastern Brasil. After the site was constructed, minor sinkholes began appearing in numerous locations across the facility, which covered approximately 37.14 hectares. A surface depression began forming at on the east side of a large ammonia storage tank. In order to primitively characterize the subsurface and take remediatory action to secure this critical infrastructure, Unigel employed Microseismic Resonance (MSR) (Fig. 1). MSR was selected to geometrically characterize the surface of a carbonate bedrock and the suspected karstic features within. MSR not being restricted by large geophone arrays or hindered by interference from human activity was an ideal candidate for such a task. MSR results were compared and correlated with boreholes and a gravity survey allowing for the construction of a holistic geometric model of the subsurface within LeapFrog Works with the most focus placed in the areas directly adjacent to the large ammonia storage tank.

Figure 1. Project layout and study area.

2. Stratigraphy

Within the study area, Quaternary fluvial deposits comprised of clays, silts, sands, gravels, and cobbles of Paleocene and Pliocene mudstones of the Barreiras Group are deposited atop Early Cretaceous Carbonates of the Martin Member. Five exploratory boreholes, each about 70m deep, were drilled in an 'X' pattern around the ammonia storage tank in the focus area to the east. The boreholes were positioned roughly 13m apart from the central hole SM-05, radiating outwards at specific angles: 031° for SM-03, 112° for SM-02, 209° for SM-04, and 301° for SM-01. These boreholes revealed that the fluvial deposits were between 8m and 10m thick. Macropores greater than 10 cm were observed within the carbonates on all holes; some of the macropores that were recovered were infilled with fluvial deposits while cavities were observed both infilled with fluvial deposits, notably the ones closer to the bedrock surface, while others are observed completely void of material; mostly those beyond 60m in depth from the surface. The depth to bedrock was varied between 8m and 10m, between the five boreholes consistent with karstic morphology, which is believed to be the characteristic of the bedrock surface. The depth at which micropores and cavities were encountered varied among the five boreholes, and karstic features were observed throughout the carbonate sequence. These features extended from approximately 8m to 10m in depth up to the borehole's termination at around 70m (see Table 1).

Table 1. Generalized Borehole Logs of the SM Series

	From	To	Description
SM-01	0	15.67	Fluvium
SM-01	15.67	70.03	Limestone
SM-02	0	16.41	Fluvium
SM-02	16.41	39.67	Limestone
SM-02	39.67	42.31	Cavity
SM-02	42.31	70	Limestone
SM-03	0	16.95	Fluvium
SM-03	16.95	37.07	Limestone
SM-03	37.07	38.57	Cavity
SM-03	38.57	64.57	Limestone
SM-03	64.57	66.27	Cavity
SM-03	66.27	70	Limestone
SM-04	0	15.67	Fluvium
SM-04	15.67	70.03	Limestone
SM-05	0	23.9	Fluvium
SM-05	23.9	40.23	Limestone
SM-05	40.23	43.25	Fluvium
SM-05	43.25	70.04	Limestone

3. Microseismic Resonance (MSR)

MSR is a burgeoning microseismic technique that measures resonance intensity generated by both passive and active sources of energy. This is achieved with a patented wide spectrum geophone and data collector, which together are the MSR data acquisition unit (Jessop et al. 2023). The MSR data acquisition unit captures primary wave seismic energy derived from both gravitational elastic stress generated by earth tides (Kouznetsov et. al. 2004) and a small amount of input energy. The capture includes broad-spectrum data ranging from less than 1Hz to approximately 10 kHz.

MSR operates on a fundamental principle that relates frequency (f) to depth, Equation (1).

$$f \approx \frac{(2n-1)\alpha}{4H} \quad (1)$$

where n = 1,2,3 …, α = P-wave velocity of the layer, and H = thickness of the layer. The numerical model for MSR data is additionally refined based on the recording window during which the geophone samples are taken. This sampling process defines frequency (f) as a function of time (t), as outlined in Equation (2)

$$t = \frac{(2n-1)}{4f} \quad (2)$$

This mathematical formulation draws inspiration from Fourier transformations, a powerful tool for analysing and decomposing signals into their constituent sinusoids. In the context of the MSR technique, the equation serves as a modified application of the Fourier transform, tailored to capture the intricacies of subsurface resonances, and based on previous research (Lewis 1985). Advanced statistical and numerical modelling, enhanced by two proprietary post-processing techniques developed in MATLAB and Python, establishes MSR as a unique and independent microseismic method. Full Spectrum (FS) processing characterizes the overall depth sequence numerically as a relative resonance intensity, which has a high degree of correlation to relative porosity and the presence of void space. Local Component (LC) processing yields similar results to reflective seismic and defines the resonance acoustical interfaces between subsurface materials identified as pseudo reflectors.

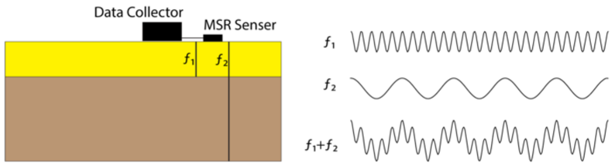

Figure 2. Visual representation of MSR principles.

4. Data Acquisition

Field work was conducted over a period of eight days from 29/05/2023 to 06/06/2023 at the 37.14 hectare study area. Data acquisition was split between two operators each with their own MSR data acquisition unit. MSR stations were collected on a 10m by 10m grid. The MSR data acquisition unit was set to capture data up to 100m deep, with optimal resolution down to 66m, requiring about 15 seconds of acquisition time per station. Where MSR data was collected the operator simultaneously recorded the positioning information of the measurement location using a Real-time kinematic positioning (RTK) corrected GPS unit integrated into the MSR data acquisition unit.

5. Post-processing

Due to the leveling and development of the study area, which resulted in a uniform elevation, the RTK positional data for surface elevations at all MSR stations has been averaged. A consistent elevation of 13m is established as the baseline for rendering surface topography in Sequent LeapFrog Works.

MSR acoustic data and its attached positional information are transferred to the geophysics team, where it is post processed into a .csv table, where each MSR station is broken down into a depth sequence with elevation values being associated with both FS and LC numerical values at each station; all data for this study is referenced in WGS 84 / UTM Zone 24S (EPSG:32724).

Processed MSR data is imported as a table into Sequent LeapFrog Works as two point clouds; one for FS data and one for LC data.

LC data being superior at defining the transitions between two acoustically different material is utilized to render the transition between fluvial deposits and carbonates of the Martin Member. LC data is filtered using an iterative numerical model to isolate the highest LC values resulting in the isolation of a collection of points between approximately 8m and 21m below ground surface. The resulting point cloud is filtered from the original LC dataset and is resampled along the Z dimension using a mode bias, resulting in a single X, Y, and Z point for each MSR station across the study area. The result is a point cloud which represents the most statistically likely position of the bedrock surface at that station. The resampled mode distribution point cloud of the high LC values is used to render the bedrock surface at 2m polygonal resolution.

FS data is then cropped using the bedrock surface generated using the LC data. Cropped FS data is then utilized to render a numerical model with isosurfaces, and interval constrained volumes based on intervals established on the total range of FS values. Bespoke statistical isolation is used to determine the value at which FS data begins to indicate areas of high resonance intensity and therefore areas of karstic features within the study area. The Resulting filtered numerical model is exported as volumes to represent areas of high resonance, which are analogous to zones of karstic features.

6. Discussion

Within LeapFrog Works a holistic model is created; comprised of the ground surface, bedrocks surface, and areas of high resonance intensity within the carbonate bedrock (analogous to karstic features). Supplemental information from the "SM" series of exploratory boreholes is included to allow for a comprehensive analysis and comparison between the surface as rendered by the MSR LC data and the observed interface within the boreholes. Three boreholes MS-04, MS-05, and MS-03 were compared to the bedrock surface rendered from the MSR LC data. MS-04 and MS-03 have a log indicated depth to bedrock of 15.67m and 16.95m respectively. At the X, Y positions of Boreholes MS-04 and MS-03, the bedrock surface, as rendered from LC data, was at depths of 15.56m and 16.59m, respectively (see Fig. 3). Therefore, the resulting discrepancy between the bore log for MS-04 and the MSR data was 41cm at a depth of 15.67m or an accuracy of 99.7% while the log for MS-03 has a discrepancy of 36cm at a depth of 16.59m or an accuracy of 99.97%.

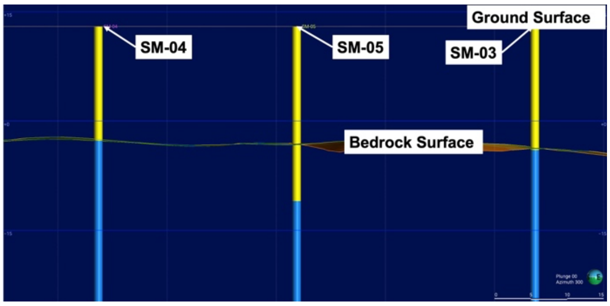

Figure 3. Section along SM-04, SM-05, and SM-03 with logs and bedrock surface.

Borehole SM-05 had a high degree of discrepancy with a difference of approximately 7.9m. Intriguingly, on the perpendicular axes when looking at SM-01, SM-05, and SM-02 the discrepancy between the log and MSR data for borehole SM-01 was off by approximately 10.8m; significantly greater than the high degree of correlation between the borehole data and bedrock surface rendered from the MSR LC data. SM-02 has a bedrock depth of 16.41m, with a 30cm discrepancy observed on the MSR LC surface at 16.71m, resulting in 99.98% accuracy. This level of correlation is similar to that of MS-04 and MS-03 (see Fig. 4).

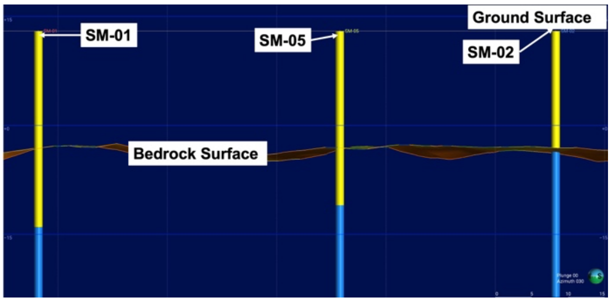

Figure 4. Section along SM-01, SM-05, and SM-02 with logs and bedrock surface.

Boreholes SM-01 and SM-05 are located along a trend where the bedrock deepens by approximately 1.5m, as observed in the LC MSR data-rendered surface, indicating a morphological difference in the carbonate bedrock at this location. When the linear trend is analysed alongside the volume rendered from the high resonance intensity data of the MSR FS dataset, a linear feature becomes evident. It is possible that this feature indicates a karstic structure that has created a sinkhole along the bedrock surface. Therefore, the boreholes SM-01 and SM-05 are drilled through this karstic feature and the fill material has recompacted at the bottom of the sinkhole resulting in a slightly higher interpreted bedrock surface within the permitter of the sinkholes as rendered in the bedrock surface from the MSR LC data (Fig. 5).

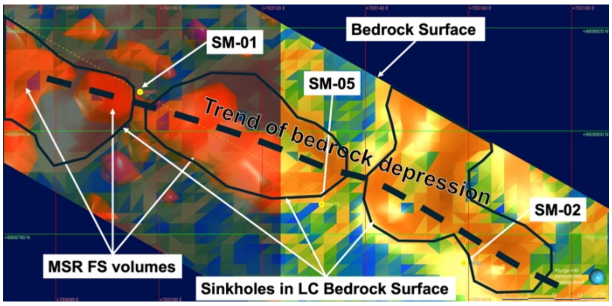

Figure 5. Map view of bedrock trend along SM-01, SM-05, SM-02

In Quantum Geographic Information System (QGIS), the high resonance intensity volumes rendered in LeapFrog Works are overlaid on the study area and compared with a gravity study conducted by another geotechnical firm around the ammonia storage tank. High degree of correlation is observed between areas of high resonance intensity as represented by the volumes rendered from the FS dataset and that of low density anomalies observed in the gravity study, which are believed to indicate karstic features. This is most notable around boreholes SM-01 and SM-05, which again show to be along a linear trend of low density as seen in the gravity study. Therefore, the two datasets corroborate one another and indicate the existence of a large karstic structure within the focus area around the ammonia storage tank (Fig. 6).

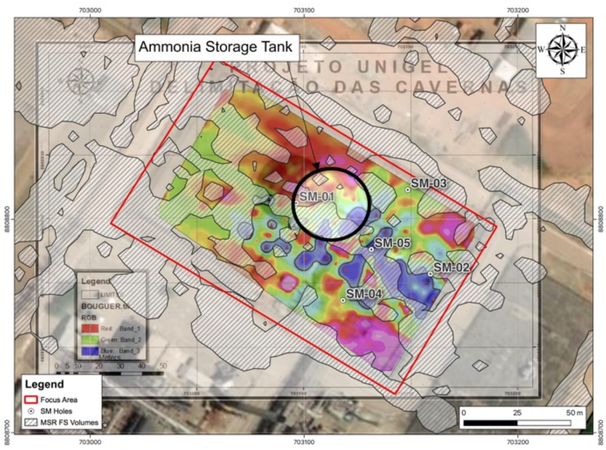

Figure 6. MSR FS volumes overlayed on gravity study in focus area.

7. Conclusion

In conclusion, statistical and numerical models of the MSR LC and MSR FS datasets respectively can yield a high degree of accuracy. MSR LC data, when collected on a 10m by 10m grid, can be used to render a bedrock surface that is approximately 99% accurate vertically with a horizontal resolution of approximately 5m given the survey grid across a 37.1ha site. MSR FS data can be used to model areas of high resonance intensity which have a high degree of correlation to areas of karstic anomalies and is supported by a gravity study as compared within the focus area.

The results demonstrate that MSR can be a powerful tool for geometric characterization of the subsurface. It is not limited by the constraints of large geophone arrays or long acquisition times like many other classical seismic methods. MSR results yield an accurate representation of pseudo-reflective features as in this case a bedrock surface that was rendered by the difference in acoustic properties of fluvial overburden atop carbonates with a karstic morphology. Accurate, non-invasive, and quick to deploy; microseismic resonance (MSR) is established as an effective tool for geometric characterization of the subsurface.

Acknowledgements

The authors are grateful for the generosity of Unigel in allowing for the publication of or joint investigation of their facility.

References

Geological Survey of Brazil. "State Geological Maps of Brazil: CPRM - Geobank", Geological Survey of Brazil, 2016. Available at: http://geobank.cprm.gov.br/, accessed: 15 April 2024.

Jessop, M. L., Val, O. K., "Subsurface Fluid Mapping and Detection", U.S. Patent and Trademark Office, Patent Application No. 3295-007.PROV, filed 30 June 2023.

Kouznetsov, O. L., Lyasch, Y. F., Chirkin, I. A., Rizanov, E. G., LeRoy, S. D., & Koligaev, S. O. "Long-term monitoring of microseismic emissions: Earth tides, fracture distribution, and fluid content", Interpretation, Vol. 4(2), pp. T191–T204, May 2016. http://dx.doi.org/10.1190/INT-2015-0047.1, accessed: 15 April 2024.

Lewis, J. K. "Passive Seismic Groundnoise: A Novel Approach to Exploration", 1985 SEG Annual Meeting, Volume(SEG85), pp. 181-183, 1985. (Available at: [https://onepetro.org/SEGAM/proceedings-abstract/SEG85/All-SEG85/SEG-1985-0181/80264], accessed: 15/04/2024).

MathWorks "MATLAB, (R2020a [s])", [MATLAB] Available at: https://matlab.mathworks.com, accessed: 06/06/2023).

QGIS "QGIS, (3.34.5 LTR)", [QGIS] Available at: https://www.qgis.org/en/site/, accessed: 06/06/2023).

Sequent "LeapFrog Works, (2023.1)", [LeapFrog] Available at: https://www.seequent.com/products-solutions/leapfrog-works/, accessed: 15/04/2024).