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ENHANCING SAFETY AND EFFICIENCY IN UNDERGROUND MARBLE QUARRIES THROUGH STATISTICAL ANALYSIS OF GEOTECHNICAL DATA

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ABSTRACT

The integrity and stability of excavation environments are critical for the safety and operational efficiency of underground marble quarries. This thesis investigates the use of statistical analysis techniques to process and interpret geotechnical data collected from monitoring equipment in these quarries. By employing tools such as extensometers, tilt meters, and crack sensors, detailed data on rock displacement and movement are obtained. Statistical methods, including descriptive statistics, inferential statistics, time-series analysis, and multivariate analysis, are applied to this data to identify trends, predict potential geotechnical failures, and uncover relationships between variables. The study demonstrates the practical applications of these analyses in quarry operations. Real-time data analysis enables immediate response to detected anomalies, enhancing worker safety and operational efficiency. Long-term data trends assist in strategic planning for quarry expansion and optimization, while historical data models serve as benchmarks for current conditions, aiding in early detection of emerging risks. The integration of statistical analysis with geotechnical monitoring significantly advances quarry management by providing a robust framework for risk assessment and decision-making. As monitoring technologies and statistical methodologies evolve, their potential to improve safety and productivity in marble quarries continues to grow, marking a new era in sustainable mineral extraction.

Keywords: underground marble quarrying, geotechnical data, statistical analysis, risk assessment, operational efficiency.

1. INTRODUCTION

The integrity of the excavation environment is paramount for both safety and operational efficiency in the field of underground marble quarrying. The advent of sophisticated monitoring equipment has ushered in an era where vast amounts of geotechnical data can be collected, presenting an opportunity to leverage statistical analysis for informed decision-making [Zhou *et al.* (2024)]. This paper discusses the significance of applying statistical analysis to geotechnical data derived from monitoring equipment in underground marble quarries, and the related analytical methods based on a real underground marble quarry study (Figure 1).

Figure 1. *Access area of the underground marble quarry of the study.*

1.1 Background on underground marble quarries

Underground marble quarries have been a significant part of the natural stone industry for centuries, providing high-quality marble that is prized for its aesthetic appeal and durability. Marble extraction from underground quarries involves the removal of large blocks of stone from beneath the earth's surface, a process that requires meticulous planning and sophisticated technology to ensure the quality of the extracted marble and the safety of the workers.

1.2 Importance of Geotechnical Data

Geotechnical data plays a pivotal role in the planning, design, and operation of underground marble quarries [Segalini *et al.* (2017)]. This data encompasses information about the geological conditions of the quarry site, including rock quality, fault lines, and groundwater conditions. Understanding these parameters is crucial for several reasons:

- **Safety**: Accurate geotechnical data helps in assessing the stability of underground structures, thereby preventing collapses and ensuring the safety of workers. It aids in designing support systems and in planning the layout of tunnels and rooms to maintain structural integrity.

- **Efficiency**: By analyzing geotechnical data, engineers can optimize the extraction process, reducing waste and ensuring that the marble blocks are extracted in the most efficient manner possible. This can lead to cost savings and increased productivity.
- **Environmental Protection**: Proper geotechnical analysis helps in minimizing the environmental impact of quarrying activities. It allows for the identification of potential hazards such as groundwater contamination and facilitates the implementation of measures to mitigate these risks.
- **Sustainability**: Long-term sustainability of quarrying operations is enhanced through the informed management of geological resources. Geotechnical data aids in planning for the sustainable extraction of marble, ensuring that the quarry can continue to operate without depleting its resources prematurely.

1.3 Objectives of the Study

The primary objective of this study is to enhance the safety and efficiency of underground marble quarries through the comprehensive analysis of geotechnical data. Specifically, the study aims to establish the way that the caves and pillars are behaving in relation to the progress of excavation and how the rock mass is behaving in conjunction to the effects of blasting.

2. GEOTECHNICAL DATA ACQUISITION

2.1 Monitoring Data

Underground marble quarries are dynamic environments with variable stress conditions, moisture levels, and potential for micro-displacement activity. Monitoring equipment such as extensometers, tilt meters, and crack sensors collect data on rock displacement and movement. Data collection is crucial for understanding the geomechanical behavior of the quarry under different operational and environmental conditions [Franqueira (2020)].

The monitoring of geotechnical parameters in underground marble quarries involves a variety of specialized equipment designed to measure and record data related to the stability and condition of the quarry environment. The primary types of monitoring equipment include extensometers, tilt meters, and crack sensors. These instruments play a crucial role in ensuring the safety and efficiency of quarry operations by providing real-time data on the structural integrity of the underground workings. Figure 2 shows a plan view of the location of geotechnical sensors installed in the underground marble quarry of our study.

2.2 Types of installed sensors

Sensors used in this study include tilt and displacement sensors. Tilt sensors measure the angle of inclination or tilt of a structure or slope, offering insights into shifts or deformations that might indicate instability. Displacement sensors track the movement of soil, rock, or structural elements over time, providing precise measurements of vertical, horizontal, or lateral displacement. Together, tilt and displacement sensors enable comprehensive monitoring of geotechnical conditions, like stability in room and pillar large excavations. Table 1 gives a detailed overview of the geotechnical equipment used for data collection from the rooms and pillars of the underground quarry.

Figure 2. *Plan view of the underground quarry showing the locations of installed geotechnical sensors.*

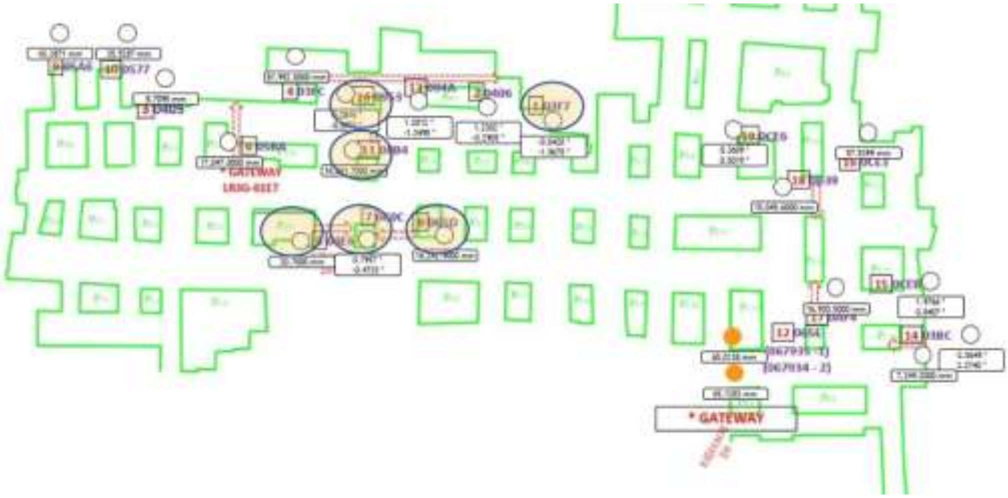


Table 1. *type of installed sensors inside underground quarry.*

Number	Pillar	INSTRUMENT	Type
1	Cave 5	03F7	Tilt X, Y axis
5	P2.4	03E6	Tilt X, Y axis
7	P2.5	0C0C	Tilt X, Y axis
8	P2.6	065D	Tilt X, Y axis & displacement
11	P3.3	0884	Tilt X, Y axis
14	P4.1	0953	Tilt X, Y axis

2.3 Data Collection Processes and Protocols

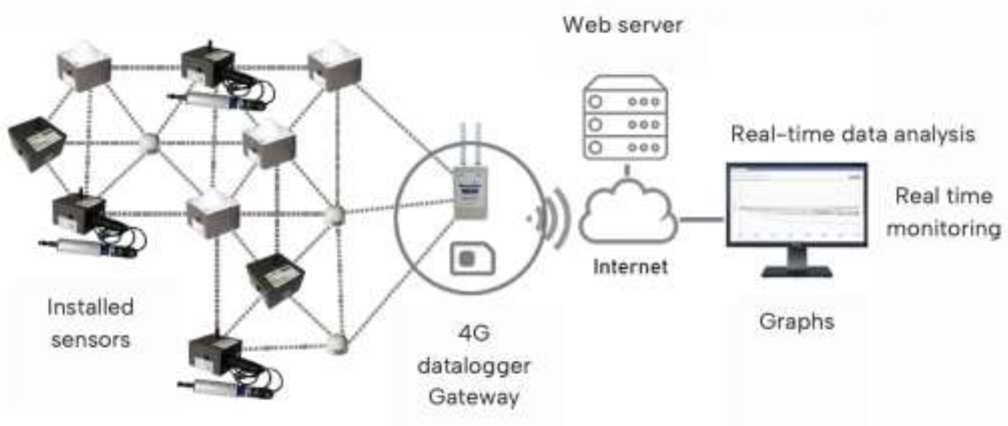
Gabriel *et al.* (2021) mention that data collected during investigations represent "potential" information becoming "effective" information thanks to interpretation. In other words, geological model is a "picture" in which the various observed elements are connected one to the other. The collection of geotechnical data in underground marble quarries follows a systematic process designed to ensure accuracy, reliability, and safety. Figure 3 shows the key components of the monitoring network. Main steps in the data collection process include:

- **Site Assessment**: Initial assessment of the quarry site to identify critical areas for monitoring and determine the appropriate types of sensors and equipment needed.
- **Sensor Installation**: Careful installation of monitoring equipment at selected locations. This involves drilling boreholes for extensometers, mounting tilt meters on rock surfaces, and placing crack sensors across identified cracks.
- **Calibration and Testing**: Calibration of sensors to ensure accurate measurements. This step often includes baseline measurements to establish initial conditions.
- **Data Logging and Transmission**: Continuous or periodic logging of data from the sensors. Advanced systems use data loggers and wireless transmission to collect data in real-time, reducing the need for manual readings.
- **Data Analysis**: Regular analysis of collected data to identify trends, detect anomalies, and assess the stability of the quarry. This involves statistical analysis and modeling to interpret the data accurately.
- **Reporting and Action**: Generation of reports summarizing the findings and recommending actions. These reports are used by quarry managers to make informed decisions regarding safety measures and operational adjustments.

3. STATISTICAL AND GEOTECHNICAL ANALYSIS

The application of statistical analysis to geotechnical data involves several techniques [Botsialas (2020)]. Descriptive statistics provide a preliminary overview of the data distribution, identifying mean values, variability, and trends over time. Inferential statistics enable the extrapolation from sample data to make predictions about future quarry behavior under similar conditions. Time-series analysis is particularly relevant for detecting patterns and forecasting potential geotechnical failures (Figure 4, 5, and 6). Moreover, multivariate analysis can uncover complex relationships between different geotechnical variables, enhancing the predictive accuracy of potential hazard assessments (Figure 7).

__Figure 3.__ Network interconnection along with installed geotechnical sensors



4. CONCLUSIONS

The integration of statistical analysis with geotechnical data from monitoring equipment in underground marble quarries represents a significant advancement in quarry management. It not only enhances the safety and health conditions for workers by providing a robust framework for risk assessment and mitigation but also improves operational efficiency through data-driven decision-making. As monitoring technologies and statistical methodologies continue to evolve, the potential for their application in enhancing quarry safety and productivity is boundless, marking a new era in sustainable mineral extraction.

The statistical analysis of the installed geotechnical sensors showed that the pillars under investigation were subjected to a tilt movement in both directions simultaneously: NW and SW. The amount of this tilt was in the order between millimeters of degrees up to tenths of degrees. The effect of blasting was very well established in the analysis. Blasting can accelerate the tilt trend or even change the direction of tilting. The pillars intersecting discontinuities are showing the greatest tilt values. Under these conditions the pillars must sustain the weight of overburden and the stress regime of the excavation. Blasting is contributing negatively at the geomechanical properties of the pillars. Despite that there is no immediate risk for a large-scale collapse or failure, it is essential to keep monitoring the situation and to combine these results with the final edition of the geotechnical model.

Further work will include the application of machine learning techniques in the identification of geotechnical events based on the data collected, with the aim to develop a system that will allow real-time risk assessment and aid decision making.

Figure 4. *Time series chart of tilt sensor in room-cave No5.*

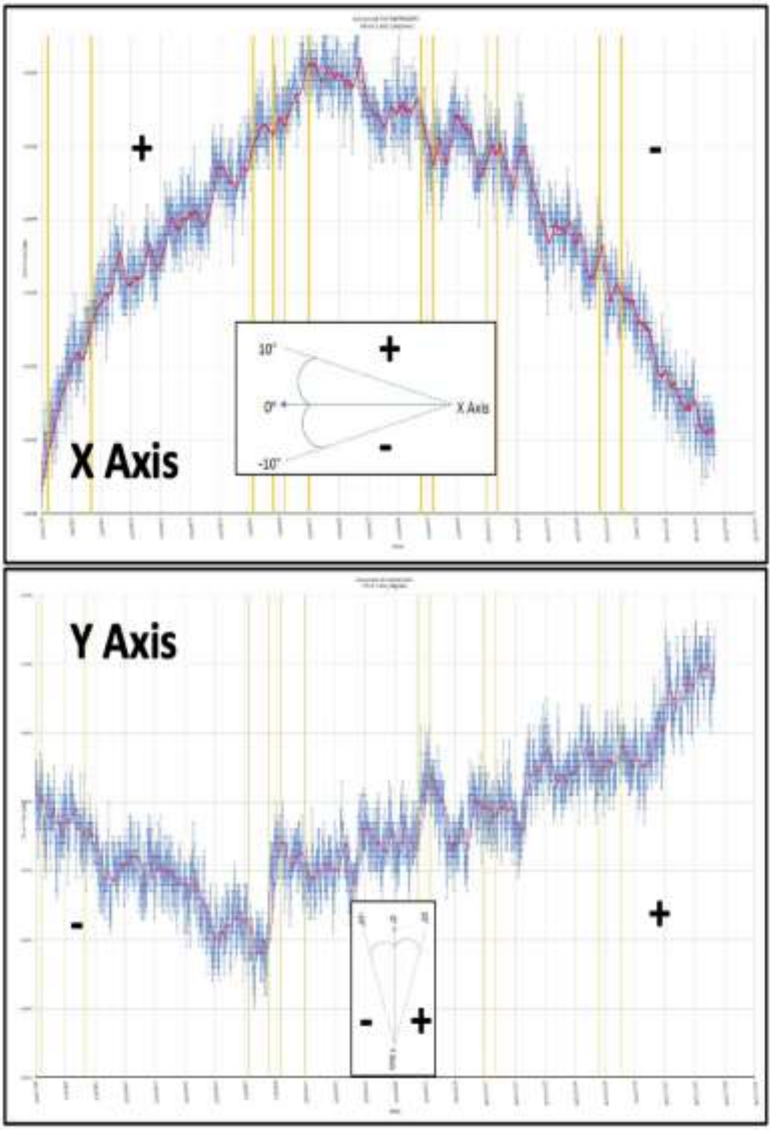


Figure 5. *Time series chart of tilt sensor in pillar 2.4.*

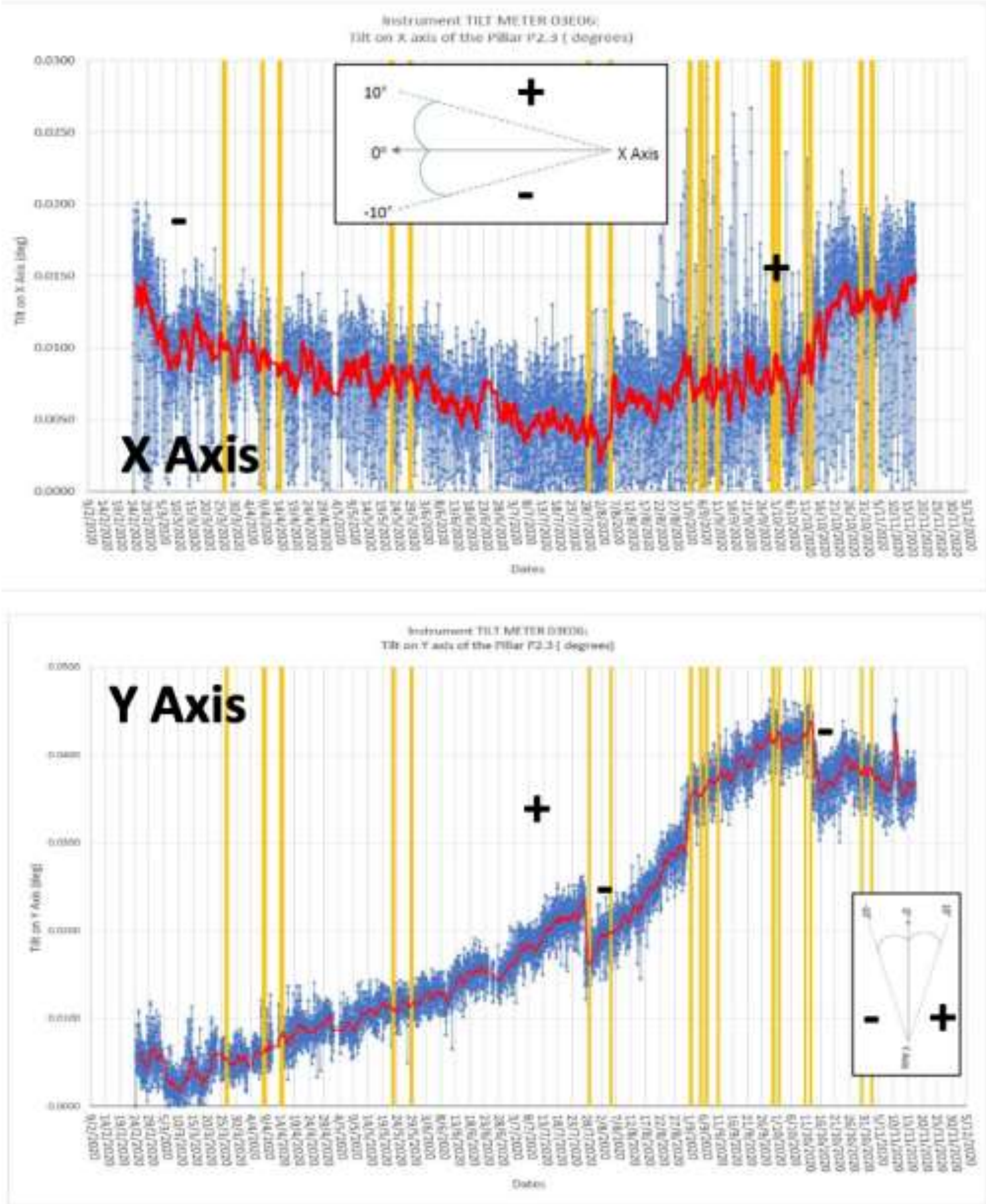


Figure 6. *Time series chart of tilt sensor in pillar 2.4.*

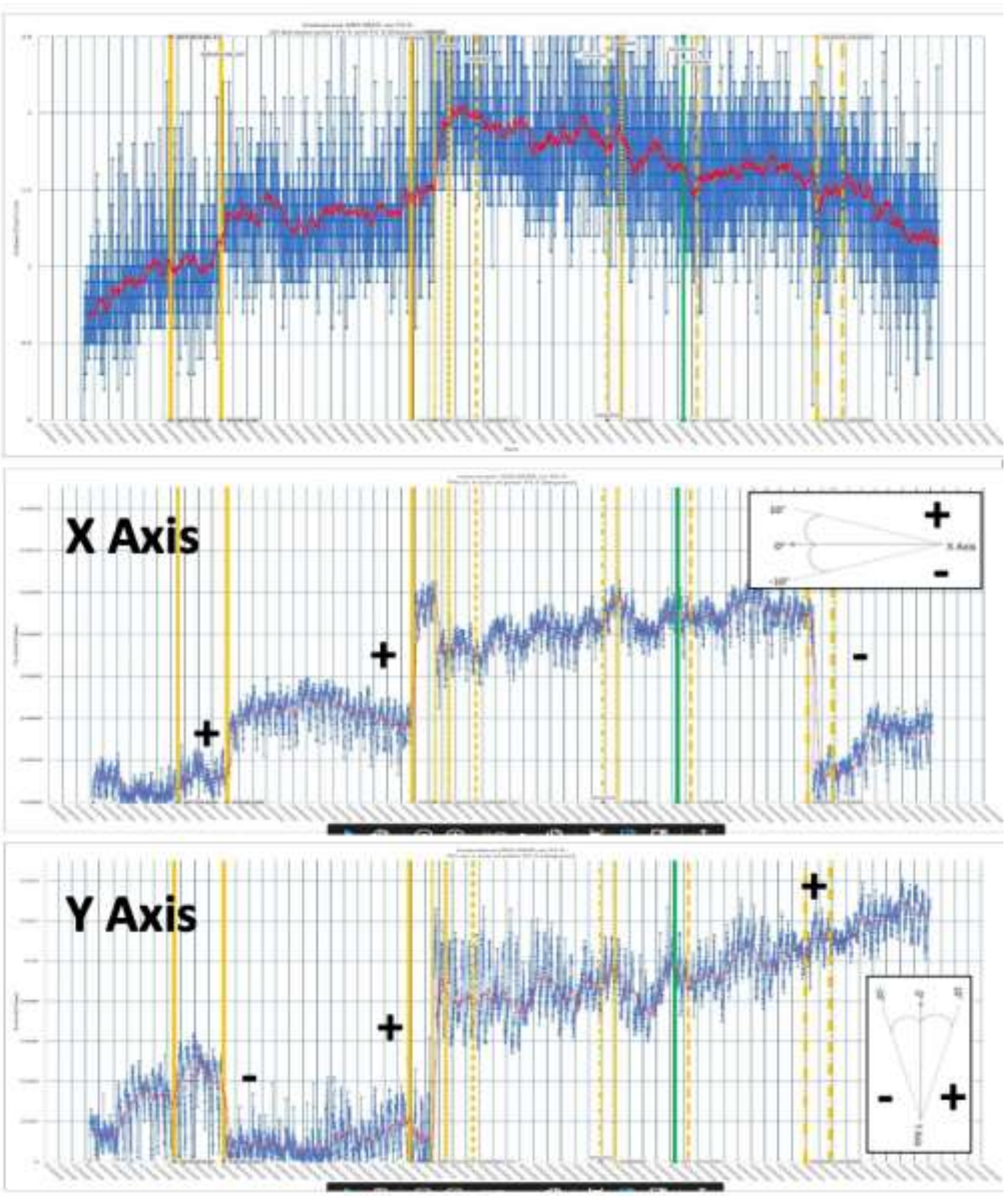
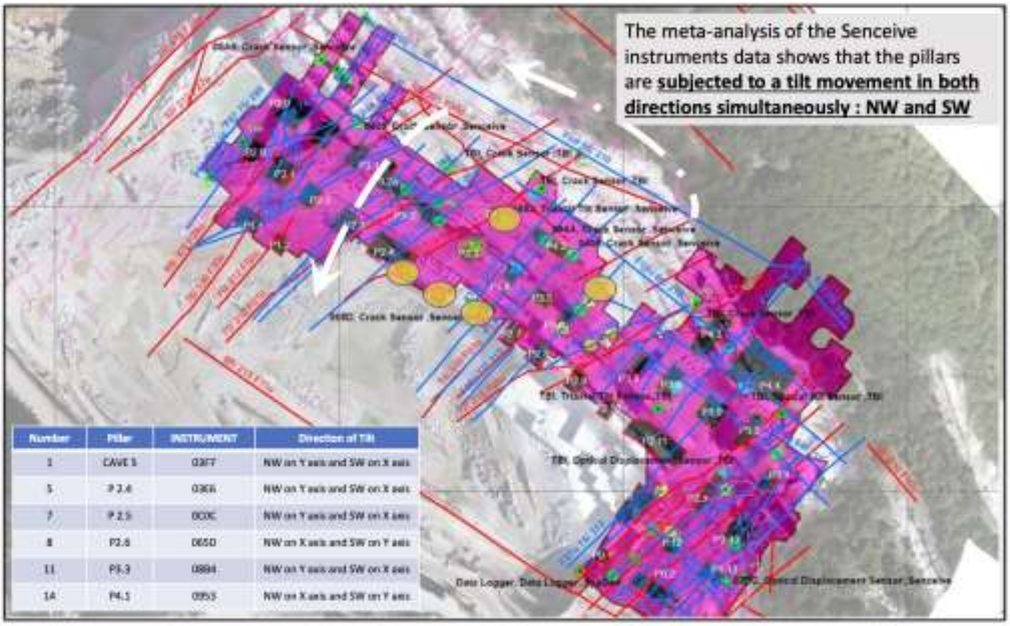


Figure 7. *Top view of rooms and pillar along with fracture and installed sensors.*



ΠΕΡΙΛΗΨΗ

Η ακεραιότητα και η σταθερότητα των περιβαλλόντων εκσκαφής είναι κρίσιμες για την ασφάλεια και την επιχειρησιακή αποτελεσματικότητα των υπόγειων λατομείων μαρμάρου. Αυτή η διατριβή διερευνά τη χρήση τεχνικών στατιστικής ανάλυσης για την επεξεργασία και ερμηνεία γεωτεχνικών δεδομένων που συλλέγονται από εξοπλισμό παρακολούθησης σε αυτά τα λατομεία. Με τη χρήση εργαλείων όπως οι εκτασιόμετρα, οι αισθητήρες κλίσεων και οι αισθητήρες ρωγμών, λαμβάνονται λεπτομερή δεδομένα για τις μετατοπίσεις και τις κινήσεις των βράχων. Στατιστικές μέθοδοι, συμπεριλαμβανομένων των περιγραφικών στατιστικών, των επαγωγικών στατιστικών, της ανάλυσης χρονοσειρών και της πολυμεταβλητής ανάλυσης, εφαρμόζονται σε αυτά τα δεδομένα για την αναγνώριση τάσεων, την πρόβλεψη πιθανών γεωτεχνικών αποτυχιών και την αποκάλυψη σχέσεων μεταξύ μεταβλητών. Η μελέτη καταδεικνύει τις πρακτικές εφαρμογές αυτών των αναλύσεων στις λειτουργίες των λατομείων. Η ανάλυση δεδομένων σε πραγματικό χρόνο επιτρέπει την άμεση απόκριση σε ανιχνευόμενες ανωμαλίες, βελτιώνοντας την ασφάλεια των εργαζομένων και την επιχειρησιακή αποτελεσματικότητα. Οι μακροπρόθεσμες τάσεις των δεδομένων βοηθούν στον στρατηγικό σχεδιασμό για την επέκταση και τη βελτιστοποίηση των λατομείων, ενώ τα ιστορικά μοντέλα δεδομένων χρησιμεύουν ως σημεία αναφοράς για τις τρέχουσες συνθήκες, συμβάλλοντας στην έγκαιρη ανίχνευση αναδυόμενων κινδύνων.

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