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ORIGINAL PAPER

Building a 3D Digital Twin for Geotechnical Monitoring at San Xavier Mine

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Abstract

Assessing ground conditions in underground mines during excavation can be difficult and unsafe for mine workers and engineers. A continuous monitoring system for ground conditions with minimum geohazard exposure to workers is needed to ensure rock mass stability in underground mines. A sensor-based geotechnical monitoring framework that deploys a three-dimensional digital twin for underground mines is proposed and developed. The monitoring framework consists of the determination of variables to be monitored, selection of sensors and layout design, installation of instrumentation, collection of data in near real-time, and visualization of data using a 3D digital twin. The proposed framework is implemented at the San Xavier (SX) Underground Mining Laboratory to develop a tool for monitoring ground displacement. The preliminary result shows that the framework is implemented effectively to collect data automatically for a 3D digital twin that updates visualizations in desired frequencies. This framework can be a significant aid for the mining industry to reduce injury and fatality due to ground fall.

Highlights

1. A systematic framework is required for effective geotechnical monitoring in underground mines.
2. A scalable monitoring system can automate data collection and coordinate sensor streams for visual analytics.
3. A digital twin can be implemented to interactively visualize rock mass displacement on a 3D model in near real-time.

Keywords Underground geomechanics · Rock displacement · Mine safety · 3D visualizations · Digital twins

1 Introduction

Assessing and controlling ground conditions in underground mines that operate 24/7 is a challenging and crucial aspect of a geotechnical engineer's daily job. Since the 1970s, various analytical tools, such as modeling, and methods, such as in-person ground assessment, have been developed to address geotechnical challenges in the mining, civil, soil, and petroleum engineering domains. These tools and methods change depending on the behavior of the rock mass since different ground conditions contribute to the varied behavior of rock mass in underground spaces. Among the factors contributing to change in rock mass behavior are geological structure, in situ stress, excavation sequence, and dynamic disturbance. These factors, especially excavation and dynamic disturbance, may influence rock mass failure in underground mines. Post-excavation failures are categorized into sudden failures and progressive failures (Clero et al. 2022).

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Progressive failures occur over time in longer durations compared to sudden failures, such as ground falls, while sudden failures occur instantaneously in short periods, such as rock falls (Clero et al. 2022). Ground fall, usually occurring after the displacement of rock mass in an excavation, is the second largest cause of fatalities in underground mines in the United States (Fig. 1). To increase safety and improve designs in underground mines, numerical modeling methods provide essential knowledge of displacement behavior. Numerical models can be enhanced with in situ data obtained from instrumentations by comparing the data with numerical model results and by integrating the data within the models (Gioda and Sakurai 1987; Abdellah et al. 2014; Ritala et al. 2016; Esterhuizen et al. 2018; Małkowski and Ostrowski 2019; De Santis 2020; Singh 2022; Fuławka et al. 2022). However, the progressive behavior of rock mass is complex to model, and it mostly requires constant monitoring instead of modeling (Hoek 2006). Since precisely simulating ground conditions pre-excavation is challenging, underground mines must be continuously examined and assessed by engineers and workers to assure the safety and sustainability of a mine. Ground condition assessments can be conducted through in-person visual inspections, in-person measurements of convergence using tape extensometers, and data analysis with instrumentation data. In-person inspections and measurements of the rock around an excavation are crucial to gaining insight into ground behavior but have their limitations (Sandbak et al. 2020; Carri et al. 2021). Observing rock deformation and calculating displacement within a short amount of time is difficult due to the complex nature of geomechanics and the time dependency of the rock behavior. (Wang and Huang 2022). Therefore, there is a need for more consistent and reliable data on rock displacement that does not depend on the stage of the excavation (Wang et al. 2019). Advancements and ground support may face obstacles depending on the scale of displacement, potentially impeding productivity, and necessitating a systematic framework for underground

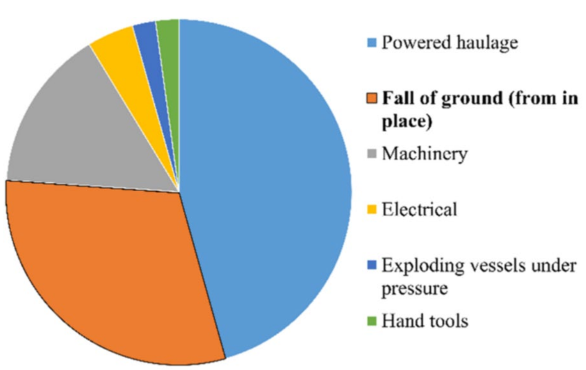

Fig. 1 Cause of fatalities categorized by accident class in underground mines in the United States between 2017 and 2021 (statistics obtained from MSHA)

monitoring. As a result, s everal studies have been conducted on the integration of monitoring systems in underground mine operations (Seymour et al. 2016; Waclawik et al. 2017; Małkowski and Ostrowski 2019; Skrzypkowski 2020; Mai et al. 2021; Fuławka et al. 2022; Liang et al. 2022). The use of Multi-Point Borehole Extensometers (MPBXs) for monitoring rock mass response to underhand longwall mining was investigated at the Lucky Friday Mine, Mullan, ID (Williams and Whyatt 1992). MPBXs were installed up to 1.5–4.5 m and 7.6–15 m to measure fracture zone deformations and elastic deformations, respectively. The report indicated that the installed MPBXs failed due to the inflow of water to the extensometers. Therefore, significant data were not acquired and data visualization was not performed. Sun (2009) also studied the use of sensor-based monitoring systems to improve mine safety and reduce operational costs due to ground support reduction. MPBX and SMART bolts were installed at the Leeville underground Mine and data were recorded and downloaded on the PC for analysis purposes and to support the decision-making process. Despite successful data capturing from the installed sensors, the author employed manual data analysis (Sun 2009). A similar approach measuring MPBX results manually was adopted to monitor rock deformations of an intersection as mining operations progress at the Garson Mine, Canada (Abdellah et al. 2014), for mining-induced seismic activities in Swedish mines (Zhang et al. 2016), and for monitoring coal rib in a room-and-pillar retreat mine (Rashed et al. 2021). Recently, Wang et al. (2021) combined MPBX and fiber optic sensors for measuring the internal strata movement of overburden and mining-induced cracks in the Tingnan Coal Mine. Results indicated that crack propagation and elongation can be noticed and in some cases, cracks can be closed due to stress redistribution. Literature indicates that MPBX and instrumented bolts have been mostly employed for rock displacement monitoring due to technical flexibility, service, cost, and user evaluation compared to other sensors (Zhang et al. 2016). Some monitoring systems in the industry achieve real-time data collection using systems and software from third parties such as MLWeb (Canary 2024), OpenGround (Bentley Solutions 2024), and consulting (ESG 2024). Even though Wang et al., (2021) aim to achieve real-time monitoring methodologies, no findings have been discussed regarding an automated real-time monitoring system.

Rock displacement monitoring systems are considered one of the best methods for assessing ground behavior (Gholinia et al. 2022). However, an issue arises with extensive monitoring systems; working with the data obtained from sensors is still challenging due to the large volumes of varying data sets being collected in high velocities (Qi 2020; Naeem et al. 2022). The overwhelming flow of data can cause a higher possibility of having false positives and uninformative data representation, leading to a serious cognitive load when analyzing data (Zhou et al. 2018). Reducing the cognitive burden of engineers and reaching a "peak" cognitive state, a state when a person can achieve optimal performance in a task (Csikszentmihalyi 1990; Domingo and Tortosa 2021), can be achieved through effective displays and automated management of data. Data visualization for observations and analysis has been proven to raise awareness of assessing space and its conditions (Feibush et al. 2000; Akinci 2014). Digital twins (DT) are a great tool to tackle this issue. DTs are digital or virtual representations of real-world physical systems that update their state in desired frequencies from real-world data (Grieves 2023). Therefore, having a DT of the rock mass at an underground mine that enables visualizations from monitoring data could prove to be beneficial for the mining industry.

Unlike other geotechnical domains, such as tunneling and open pit mining (Dunniclif 2008; Xiaobing 2018; Zhang and Cai 2011; Sharon and Eberhardt 2020;; Sharon 2020), to the best of our knowledge, a logical framework for near-real-time monitoring to utilize DT and visual analytics (VA) does not exist. Therefore, this paper proposes a systematic monitoring framework for underground mines that will assist in mine planning, design, and mitigation of progressive failure.

2 Monitoring Framework

The proposed systematic monitoring framework focuses on visualizing near-real-time data in 3D through a DT displayed in desktop PC and virtual reality (VR) paradigms for underground mines (see Fig. 2). The monitoring framework consists of five major stages: (1) determination of monitored variable(s), (2) plan and design of a monitoring system, (3) installation of the monitoring system, (4) management and storage of monitoring data, and (5) display of monitoring data for underground safety decision and planning. The stages can be adapted for other projects with varying objectives. The first three stages aim to develop and deploy a monitoring system and a data acquisition (DAQ) system. The last two stages aim to manage, store, and visualize the collected data. A near-real-time data collection system is presented for underground mines by determining the geotechnical monitoring variables and required sensors and installation of sensors and DAQ facilities at an underground mine.

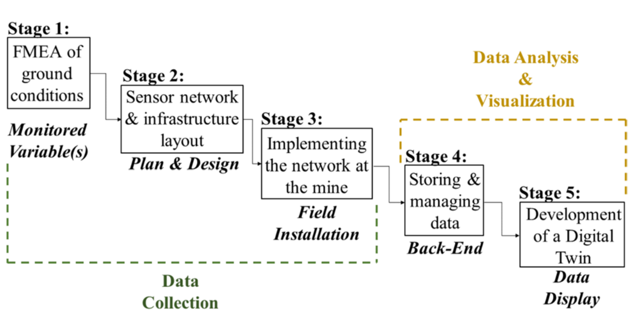

Fig. 2 Stages of the proposed geotechnical monitoring framework for underground mines

The first stage determines the critical geotechnical parameters that are of concern at a mine to establish monitoring goals. A Failure Modes and Effects Analysis (FMEA) (Rausand 2004) must be performed, to allow a risk matrix to be subsequently developed. The second stage focuses on establishing the monitoring system. The monitoring plan and design should include instrument selection, data collection strategy, and implementation planning. Incorporating an automated monitoring system in underground mines as part of the mining cycle could give leverage by having access to information when desired. Thus, one of the goals of this research is to design an automated DAQ system that can feed measurements into a database server. Once an approved design is in place, the instruments can be acquired and installed. The third stage focuses on installation and wiring to ensure data collection from the instrumentation using the DAQ infrastructure.

The fourth stage allows for an automated flow and management of frequent incoming monitoring data in the back-end architecture of a DT. The final stage focuses on presenting data and ground conditions in a user-friendly manner with well-designed visualization that facilitates the systematic analysis of geotechnical data. This streamlined approach can reduce the time required for data interpretation.

In Sect. 3, the background of the proposed framework is given. Section 4 presents the first three stages of the monitoring framework and Sect. 5 covers the last two stages of the monitoring framework. Section 6 reports and discusses the findings, while Sect. 7 concludes the proposed research and future work in the field.

3 Background

The proposed monitoring framework is implemented at the SX underground mining laboratory located approximately 48 km south of Tucson, Arizona, USA (Fig. 3). The SX mine has two sections: the old underground mine, where sulfide ore was mined from 1880 up to 1975 (Sternberg et al. 1988) and the new tunnel named East decline used as a testing ground for equipment, machinery, blasting, ventilation, and underground monitoring research. The development of East decline started in 2020 with a round-arched profile around 5 m by 5 m dimensions and approximately 150 m of advancement has been made to date using blasting. The roof and ribs of the tunnel have sufficient support for the yielded zone with bolts and wire mesh. The ground is reinforced with 2.4–3.6 m long Swellex bolts on 1–1.5 m spacings.

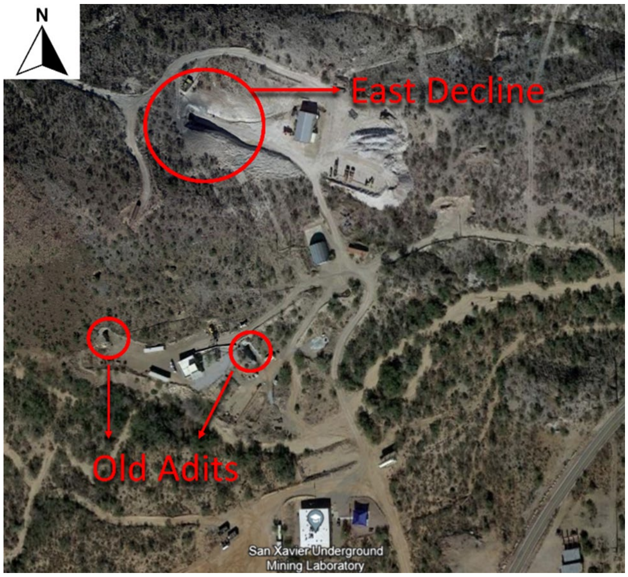

Fig. 3 Ariel view of the SX with the old adits of the old workings and the recently developed East decline

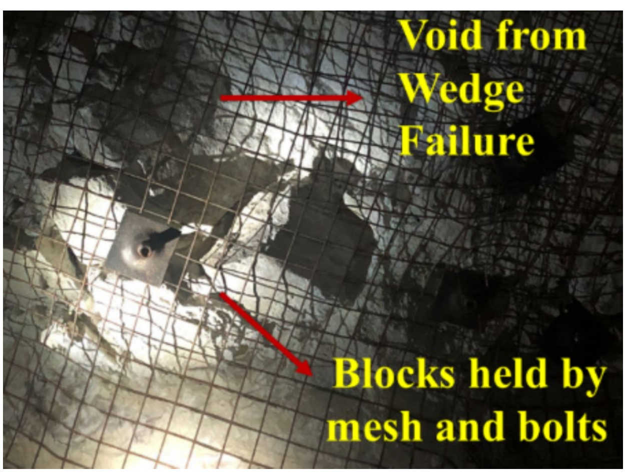

Fig. 4 A wedge failure that has occurred previously and the ground support with meshing and bolts at the East decline

The dimension of the mesh is 7.5 cm by 7.5 cm, eliminating potential rock falls from observed blocks formed by wedges (Fig. 4).

3.1 Geology

The geology of the surrounding area of SX consists of undivided Paleozoic sedimentary rock including limestone, dolostone, quartzite, shale, related sedimentary rocks, and a listric fault striking north–south to the west of SX. The lithology of the East decline is in bedded limestone with occasional skarn alterations. The sulfide minerals at the mine include galena, sphalerite, chalcopyrite, molybdenite, pyrite, and bornite, with calcite and quartz as the main host rocks. Recently, a resistivity study was conducted parallel to the East decline to gain further insight into the subsurface structures, using a Wenner array. Figure 5 shows the electrode layouts for the resistivity study, where red points represent the 90 electrodes. The resistivity study contains two ground truths to ensure the reliability of the results: the river wash with a low resistivity zone (orange circle), and the concrete filling with high resistivity (yellow circle). The zones indicated with red ellipses suggest possible clay-altered faults striking in the northeast direction. As the depth is increased in the results, the other low resistivity zones dissipate which could be due to a change in geology.

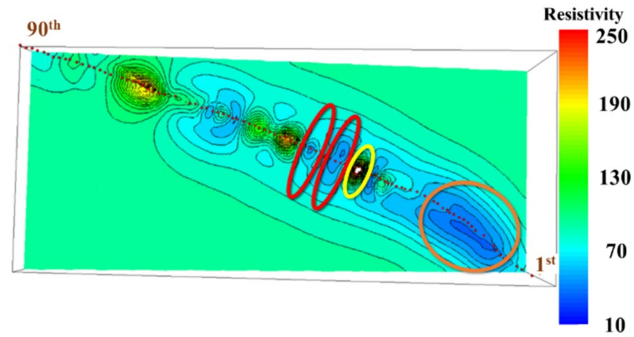

Fig. 5 Resistivity study using the Wenner array showing two possible faults in red ellipses, along with a concrete filling in yellow ellipse and a rivers wash in orange circle (Color figure online)

3.2 Ground Conditions of the Rock Mass

Rock mass data were collected by a professional engineer and students using the scanline (Hudson and Priest 1979) and cell mapping methods (Nicholas and Sims 2000). The rock mass density was estimated as 25 kN/m^3. From the geotechnical mapping, a rock quality designation (RQD) of 30 was estimated while the joint number (Jn), joint roughness (Jr), and joint alteration (Ja) were estimated to be 12, 1.5-rough planar, and 4-clayey, respectively. An intact strength of 16 MPa was measured using a Schmidt Hammer and the simple means test (Hack and Husiman 2002). Using the results from the mapping techniques, a Q value of 1 and a GSI value of 44 were obtained. These conditions are considered "fair" to "poor". Given the poor ground conditions and the two possible faults, rock movement on the ribs, and the roof of the underground opening, convergence may be expected in future excavations. A disturbance factor (D) of 0.8 was estimated.

4 Data Collection by Monitoring System

Replicating the physical rock mass as a 3D DT with effective visualizations requires extensive foundational work by connecting the real-world system to a digital one. The overall objective at the SX is to increase safety and enhance the understanding of current and future ground conditions by visualizing the displacement and strain of the rock mass on a 3D solid model of the East decline. This section focuses on the implementation of the first three stages of the proposed monitoring framework.

4.1 Determining Parameters to Monitor and Goals of Monitoring

The parameters for monitoring the behavior of rock in underground mines can be determined through the failure mechanisms that occur, and the openings in a mine that might have problematic behavior. Over time, progressive instability in the form of rock displacement may lead to ground falls, especially in openings along fault zones. Risk management is another key factor necessitating a monitoring system. Thus, considering historical trends of rock mass instabilities at the SX, further analyses with FMEA (Rausand 2004) were conducted to identify failure modes or occurrences with their causes and effects. Table 1 presents a risk matrix both for rock movement and rock fall at the East decline.

The section splitting into two future advancements (Fig. 6) is one area of concern in the East decline, requiring more monitoring for the safety and sustainability of the mine. The roof of this section is wider than 5 m and at approximately 20 m depth, making it relatively shallow and causing the potential for sagging, which was foreseen by the technical team at the SX after its excavation.

Uninterrupted monitoring is necessary to ensure safety in the East decline since it is used as a long-term testing ground for University of Arizona students, faculty, and third-party companies and researchers. Therefore, an automated monitoring system for displacement and strain of the ground eases the process and provides opportunities for data analysis and further study of ground conditions.

Table 1 Risk matrix of rock movement and rock fall at the East decline (P.M.–rock Movement in the current state, F.M.–rock movement in future advancements, P.F.–rock fall in the current state, F.F.–rock fall in future advancements)

Severity probability	Minor	Major	Critical	Catastrophic
Frequent		F.M	F.F	
Probable			P.F	
Occasional	P.M			
Rare				
Very unlikely				

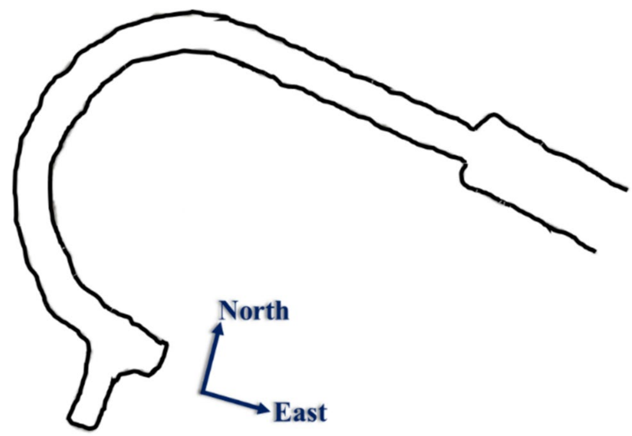

Fig. 6 Plan view of the SX East decline

4.2 Plan and Design of a Monitoring System

The plan and design stage focuses on selecting the optimal sensors and instrumentations, designing the layout around openings, and planning installation spacing and frequency. Each underground mining project has different considerations and concern areas. Therefore, this step depends on the parameter(s) determined to monitor, the goal of monitoring, and the critical thinking of the geotechnical engineer at the corresponding mine site, including the applicability of the installation. In engineering disciplines working in underground spaces, traditional methods of monitoring, including in-person visual inspections, manual data collection from monitoring instruments, and using tape extensometers, expose personnel to potentially dangerous environments (Wang et al. 2020). Many innovative applications of newer sensors, including vibrating wire (VW), micro-electro-mechanical systems (MEMS), and fiber Bragg grating (FGB) sensors, have been studied and installed for rock displacement monitoring (Waclawik et al. 2017; Fuławka et al. 2022, 2023; Małkowski and Ostrowski 2019; Skrzypkowski 2020; Wang et al. 2020; Sharon and Eberhardt 2020; Sharon 2020; Mai et al. 2021; Liang et al. 2022; Zhang and Cai 2011). VW sensors have been a trusted type for geotechnical applications due to their easy applicability to DAQ systems, performance in harsh conditions, long life spans, integrability, affordability, and capability to transmit signals across long distances (Hornby and Noltingk 1974; Park 2013; Yang 2018; Sudhakar and Naik 2019; Wang et al. 2020). VW sensors work based on the measurement of the frequency of a tensioned wire, where the change in the tension caused by external factors corresponds to the change in frequency

Table 2 Instrumentation installed at the East decline

Instrument	Sensor	Producer	Quantity
MPBX	VW transducer	Geokon	6
Instrumented bolt	VW strain gauge	Geokon	6

Table 3 Generalized Hoek–Brown Failure Criterion values used for RS2 model

Value	Data
Material type	Elastic
Compressive strength (Mpa)	5
mb parameter	0.17
s parameter	6.3e–06
a parameter	0.64

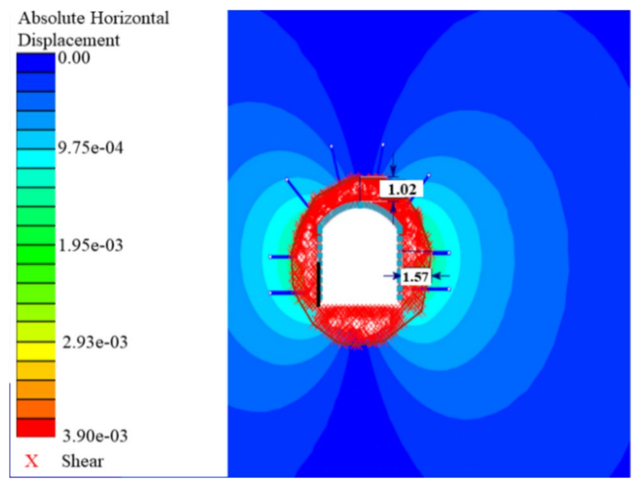

Fig. 7 Absolute horizontal displacement results from RS2

(Hornby and Noltingk 1974). They can be used for measuring many parameters including displacement, deformation, stress, and strain (Cieplok and Bednarski 2019). Therefore, VW sensors have been chosen as the sensor type to use at the East decline.

Due to their wide applications in the geotechnical domains, both MPBXs and instrumented bolts with VW sensors have been chosen to measure displacement and strain, respectively. For displacement measurements, rock convergence arrays and extensometers are widely accepted and used in geotechnical monitoring, making Multi-Point Borehole Extensometers (MPBXs) reliable instrumentations. For strain measurements, there has been a significant interest in instrumented bolts in the last 5 years, for rock mass monitoring and ground support monitoring, with promising results for hazard evaluation and mitigation (Song et al. 2017; Mai et al 2021; Fuławka et al. 2023). The goal of instrumented bolts is to combine ground support and data collection (Mai et al. 2021). Table 2 shows the instrumentation and the sensor type of the instrumentation used at the East decline, provided by Geokon (2024).

4.2.1 Numerical Modeling Using RS2

The selected MPBXs and instrumented bolts were designed according to results from a 2D geotechnical finite element model using RS2 (Rocscience, 2024) and technical support from the instrument manufacturer. To calculate the Generalized Hoek and Brown parameter values, results from ground condition assessments in Sect. 3.2 were used to develop the RS2 model. The GSI value and the D value were used to determine the Generalized Hoek and Brown values for the elastic material in RS2. The external boundaries of the RS2 model were created and the values used for the Generalized Hoek–Brown Failure Criterion can be seen in Table 3. The yield zone of the rock mass is estimated to reach around 1m on the roof, and around 1.6 m on the ribs, while the expected strain is approximately 0.2% calculated from displacement results in RS2 (Fig. 7). This would indicate a maximum expected drift closure of approximately 20 to 25 mm.

4.2.2 Instrumentation Layout Plan and Design

The sensors should be placed in such a manner that sufficient surface area is covered around openings (Hudyma and Potvin 2010). Sensors will be installed in a 'U' shaped array that covers the ribs and the roof. Figure 8 presents the plan view of the arrays (Array0 and Array1). The third MPBX in Array1 will be installed with a slight angle between 30° and 45° to eliminate possible intersection with the ribs of the South tunnel. The boreholes on the ribs were drilled approximately 2 m above ground with a 5° upward angle. The boreholes on the roof were drilled vertically to the ground.

This same pattern of the array was adopted over the split section (Fig. 9a) and near the face (Fig. 9b) of future

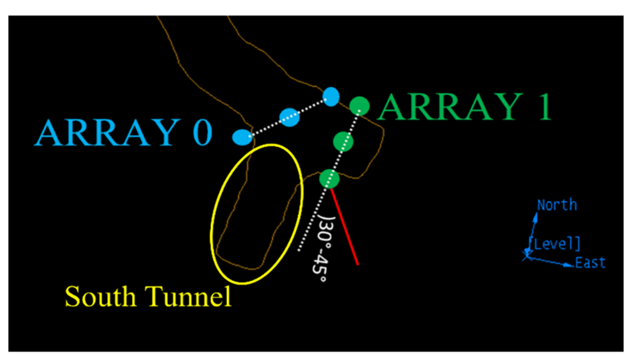

Fig. 8 Plan view of the installation of arrays consisting of MPBXs and instrumented bolts at the East decline

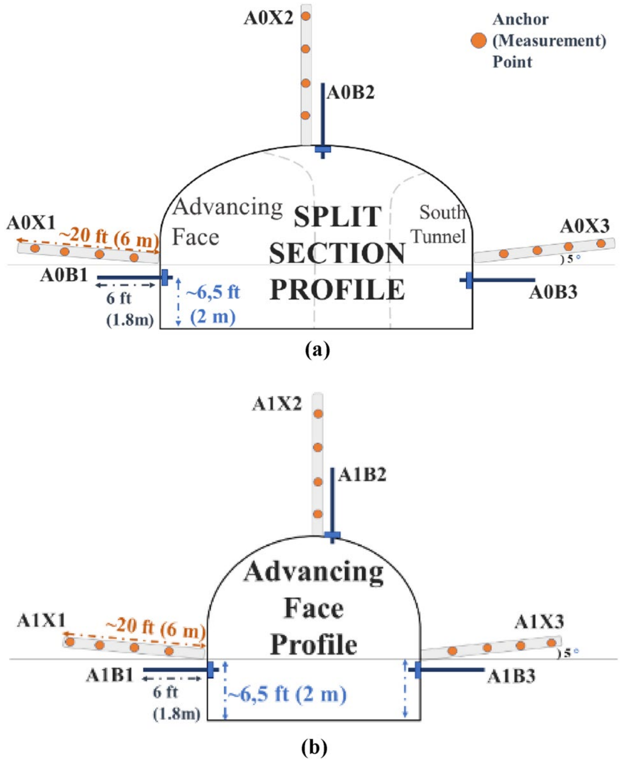

Fig. 9 Layout of sensors in arrays: **a** Array0 around split section and **b** Array1 near advancement face

advancements. To obtain data that adequately represents the underground decline, the arrays are being installed in 5 m increments. As advancement occurs at the indicated face, more sensors will be installed with the already set parameters. It is crucial to always keep track of the ground conditions when excavating the rock, to critically re-plan and re-design as necessary.

Naming conventions are assigned to keep track of the sensors and their locations. Given that this is the first geotechnical monitoring system for the East decline, the first installed array of sensors farthest away from the faces is named Array0, and the second installed array of sensors, currently closest to the face, is named Array1. The corresponding MPBXs of each array are named similarly. While facing the direction of advancement, the MPBX in the far-left rib in Array0 is named A0X1 where A0 represents Array 0, and X1 represents the first MPBX, counting clockwise. The MPBX on the roof of Array0 is named A0X2, and the MPBX on the far-right rib of Array0 is named A0X3. The same logic is followed for the rest of the instrumentation. It is crucial to track sensors comprehensively as it significantly impacts the wiring of the infrastructure, the pulling of data into a database, and assigning the corresponding data into the correct space in the DT.

4.2.3 DAQ Design

Data are collected through a standalone and centralized data logging system for all sensors built from Campbell Scientific (2024) and Canary Systems (2024) instruments. Infrastructure hardware was selected based on their compatibility with VW sensors, sufficiency for the number of sensors, and automation of data flow (Table 4).

VW sensors are wired to a multiplexer, the MiniMux allowing DAQ for 16–32 sensors. The multiplexer is connected to a CR300 data logger through the AVW 200 Module. The communications between the hardware is achieved through the CR300 C1/C2 communication ports and AVW 200 RS-232 port, using the PakBus communication protocols. The communication between the infrastructure is facilitated through programming written in CRBasic. Through the Wireless Interface module as an access point, the CR300 data logger uses a wireless network with large area coverage at the SX provided by MST Global to allow connection to the Internet of Things (IoT). To automate the DAQ process and eliminate manual readings, the data logger will be connected to a cloud database server. A power system is currently deployed at the SX utilizing solar panels to feed two 12-volt batteries, providing sufficient current and voltage to the CR300 that powers the system and the sensors.

The diagram of the data flow from sensors to the DT can be seen in Fig. 10. Due to mining equipment and machinery, and blasting activities, the infrastructure hardware is prone to damage. The excavations at the East

Table 4 Instrumentation for data acquisition

Instrument	Provider	Model
Data logger	Campbell scientific	CR300
VW analyzer module	Campbell scientific	AVW200
Multiplexer	Canary systems	MiniMux
Wireless Interface	Campbell scientific	NL241

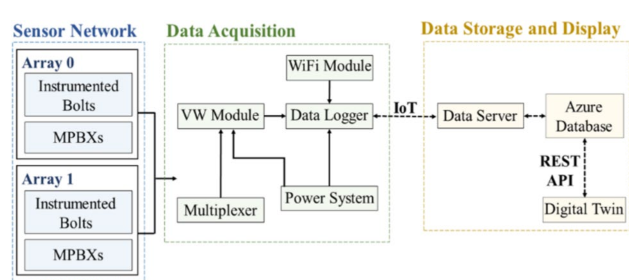

Fig. 10 Flow of data from sensor network to the DAQ system and finally to the digital twin in three major steps

decline have not advanced too deep underground, allowing the standalone data logging system to be installed near the portal of the decline, reducing the risk of possible damage. After all installations are complete, this project will have 30 sensors for geotechnical monitoring.

4.3 Installation of Instrumentation and DAQ

The applicability of the sensors is crucial to reduce the time of installation. For the given purpose, instrumented rock bolts are an optimal option since they are installed as regular rock bolts during ground support. Elements to consider and plan for installation include, but are not limited to, sensor installation time and workforce, DAQ method from sensors (manual vs automated), infrastructure installation and positioning, powering, IoT connection, and cable management.

4.3.1 MPBX with VW Transducers

The selected MPBXs for this project consist of two major components: the body with rods and anchors at desired depths (Fig. 11a), and the head (Fig. 11b) with VW displacement transducers (Fig. 11c). The MPBXs enable linear displacement of the rock mass to be measured through the relative movement between the anchor points and the head, allowing the profile of deformation to be obtained (Ding and Qin 2000; Lunardi 2008; Gholinia et al. 2022). The MPBXs were designed according to manufacturer recommendations and the rock mass conditions at the East decline. The 4 VW transducers of an MPBX measure displacement from the rock mass that is proportional to the relative movement of an anchor point with a range of 100 mm, 50 mm in compression, and 50 mm in expansion of the rock mass. Hydraulic anchor-type MPBXs are installed for their applicability in soft ground such as the East decline. Currently, only one of six MPBXs, A0X3 has been successfully installed. The body of the MPBX consists of a total of five anchors, four used for measuring longitudinal movement, and the shallowest one used to stabilize the head of the MPBX in place. The MPBXs are installed in 6 m boreholes inside the rock mass. The boreholes for the MPBXs were drilled with 100 mm drill bits and the N3116–AD/E bolter (Flecther & Co., 2024) according to the layout design. The first anchor point is 1.8 m deep inside the rock mass, and the following anchor points are 1.2 m deep relative to the previous anchor point. The increments between the anchor points have been selected to advance beyond the yield zone of the rock mass. The assembly was done underground near the boreholes to ease installation. The heads of the MPBXs are recessed in the rock mass to protect them from blasts and machinery. For the head, an overcore was drilled with a 150 mm diameter to allow for recessing (Fig. 12). Each anchor point is connected

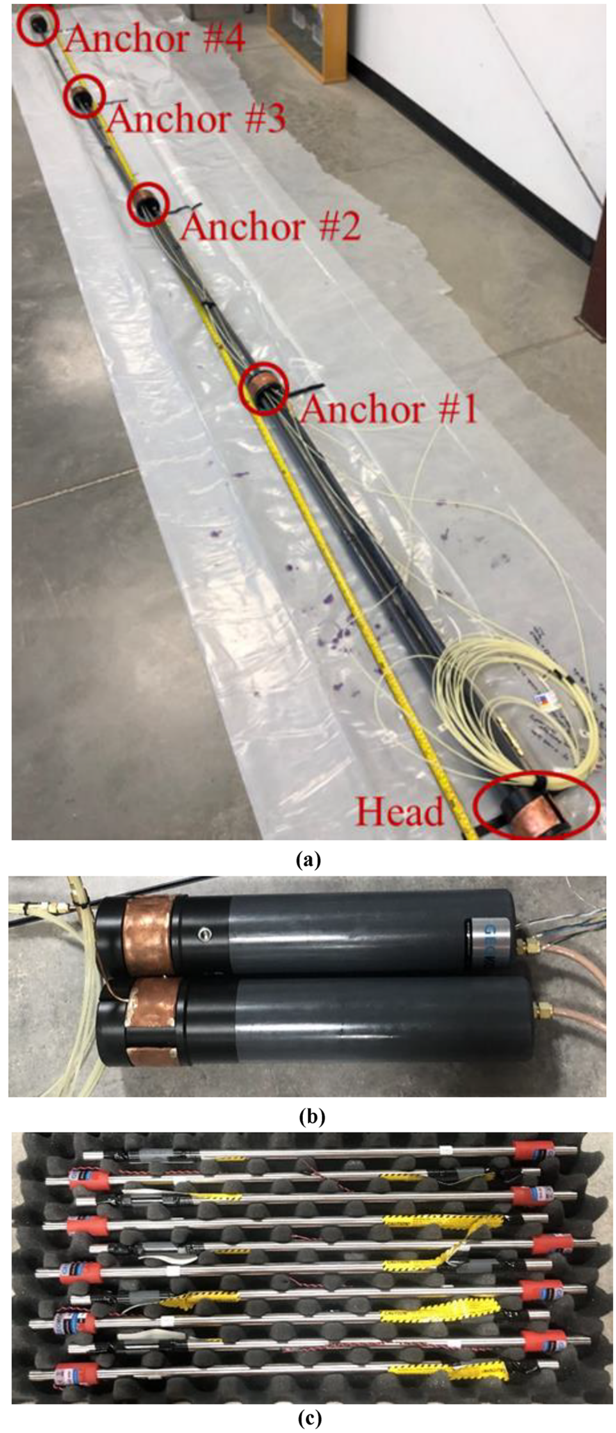

Fig. 11 **a** Assembled MPBX body, **b** head of MPBXs, and **c** VW transducers

to rods in their corresponding lengths in the borehole. After the body is assembled underground, it is lifted and placed into the borehole with a labor force. Then the MPBX is secured by inflating the anchor points using a hydraulic

Fig. 12 MPBX A0X3 installed in the borehole, recessed in overcore

pump, eliminating the need for grouting. To complete the assembly of the head, the VW transducers are installed.

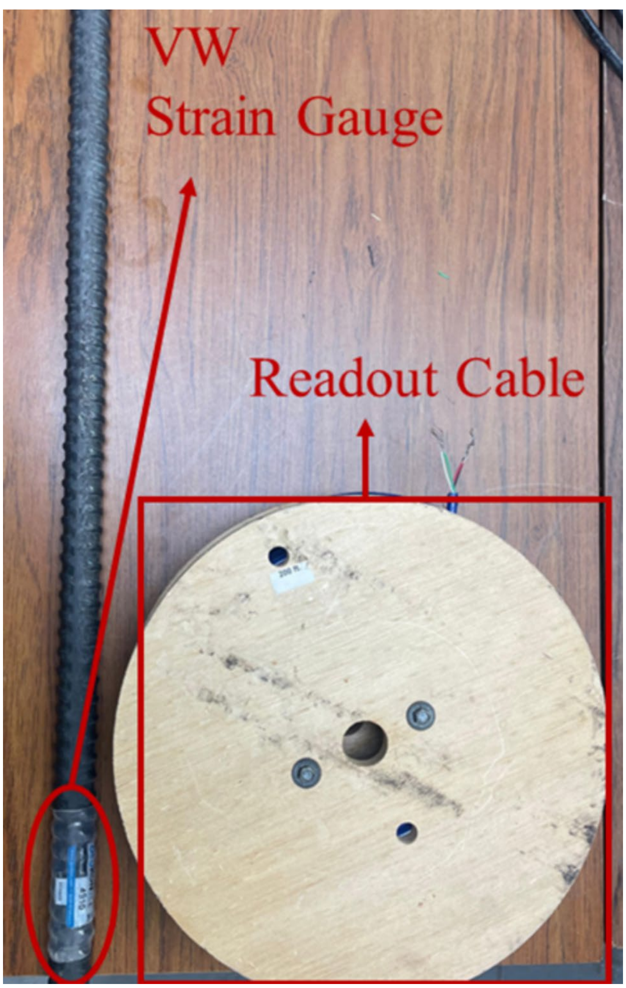

Fig. 13 Rock bolt instrumented with a VW strain gauge

4.3.2 Instrumented Bolts with VW Strain Gauges

The VW strain gauge is installed parallel to the rebar rock bolt by the producer, allowing measurements of axial strain along the bolt axis. Strain in other directions is not measured. Each bolt is 1.8 m in length and consists of a strain gauge located at 0.3 m at the head of the bolt (Fig. 13). The bolts were designed to be in the yield zone of the rock mass. The installation of instrumented bolts is similar to the common practice of installing rebar bolts allowing any worker familiar with bolt installation to install them. At the SX, the bolts will be installed and grouted as rebar bolts. Instrumented bolt installation is cheaper and easier compared to other instrumentation and monitoring methods used in underground mines since most underground mines utilize rock bolts as a part of ground support.

4.3.3 Installation and Wiring of Infrastructure

Before any installation, the wiring of the hardware for the infrastructure was done in a lab setting and tested with a VW sensor (Fig. 14). To ensure correct data collection execution when the DAQ system is deployed at the mine, the instruments were tested. When the wiring and testing were completed, the hardware components were placed in an enclosure protecting the components from environmental conditions (e.g., dust, water) and installed near the portal of the decline.

5 Data Management, Digital Twins, and Visual Analysis

The proposed monitoring framework offers a suitable foundation to develop a 3D DT to visualize rock displacement in near real-time. To facilitate this visualization system, data from the installed instrumentation must be managed using a server-based backend that includes a relational database

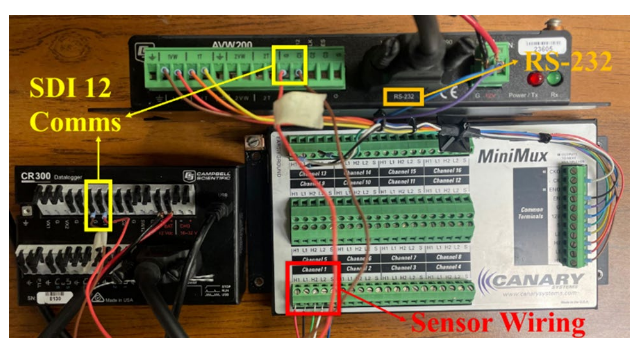

Fig. 14 Wiring of DAQ system in a lab setting (WiFi module not pictured)

and application programming interfaces (APIs) for extraction, transformation, loading, and serving of data to the DT front-end. The monitoring system yields only raw data—the frequency (Hz) of the VW vibration—so further calculations and storage of engineering data, e.g., displacement and strain data, are necessary. These functions may be handled by the relational database. In this section, the development of the backend, DT, and visualization methods are discussed.

5.1 Data Management and Storage

The main goal of the fourth stage in the proposed framework is to automate data flow and interpret data into its desired format for implementation in the DT. Dynamic simulations need near-real-time data collection, extraction, and integration, making this stage crucial (Akhavian 2012).

The CR300 datalogger sends and stores the raw data to an SQL database based on a Microsoft Azure server (Microsoft Corporation 2024). The engineered data of the MPBXs and instrumented bolts are calculated in a relational database. The calculation of strain from vibration frequency is based on the following formula (Hornby and Noltingk 1974; Park et al. 2013):

$$\varepsilon = k \times \left(f_1^2 + f_0^2\right) \tag{1}$$

where k is the gauge factor based on the VW properties, f_0 is the initial frequency (Hz) recorded before a change in strain occurs, f_1 is the frequency (Hz) after a change in strain, and strain is in microstrains ($\mu\varepsilon$). Geokon, the producer of the VW displacement transducers and VW strain gauges, uses a manufactured unit called *Digits*, calculated from the frequency in the following formula:

$$\text{Digits} = \frac{f^2}{1000} \tag{2}$$

where f^2 is the square of frequency (Hz^2) at a given moment. Thus, when calculating the strain from instrumented bolts, the *Digits* in formula (2), replace the *frequencies* in formula (1) resulting in the following equation used for this project:

$$\varepsilon_{\text{apparent}} = \left(R_1 - R_0\right) \times C \tag{3}$$

where C ($\frac{\mu\varepsilon}{Digit}$) is the gauge factor, R_0 is the initial Digit recorded before a change in strain, R_1 is the *Digit* after a change in strain, and apparent strain is in microstrains ($\mu\varepsilon$).

The displacement from the displacement transducers is calculated by the following formula below that uses *Digits* in formula (2):

$$U = (R_1 - R_0) \times G \tag{4}$$

where $G\frac{mm}{Digit}$ is the gauge factor, R_0 is the initial Digit recorded before a change in strain, R_1 is the Digit after a change in strain, and displacement is in mm.

The calculations are done in the relational database to minimize memory usage on the data logger, have access to raw data for troubleshooting, and have flexibility in creating data tables in the database. The next step is to map the data into an intuitive visualization and user interface (UI) where it can be analyzed via a DT. This step requires bridging the database with the DT using APIs for querying the required data in desired frequencies. A representational State Transfer (RESTful) API is being developed to streamline communication and data exchange between the DT and the database. RESTful APIs utilize hypertext transfer protocol (HTTP) methods, including GET, POST, PUT, and DELETE. Authentication and authorization mechanisms may also be deployed to enhance data security.

In this work, the DT was developed with Unity (Unity Technologies 2024), a 3D development platform suitable for interactive simulations and virtual environments. The UnityWebRequest class is employed to execute HTTP requests directed at the API and to manage responses in JSON format. This integration enables real-time retrieval, update, and manipulation of data from the Azure database via Unity.

5.2 DT Technologies for Data Interpretation and Visual Analytics

Previous studies conducted on monitoring had promising outcomes (Ding and Qin 2000; Dunniclif 2008; Bassett 2011; Waclawik et al. 2017; Fuławka et al. 2022, 2023; Małkowski and Ostrowski 2019; Skrzypkowski 2020; Wang et al. 2020; Sharon and Eberhardt 2020; Sharon 2020; Mai et al. 2021; Liang et al. 2022; Zhang and Cai 2011). Even though they provide innovative and effective technologies to monitor rock mass movement in an underground structure, one gap found in these methods is the lack of focus on presenting the data obtained from monitoring. In similar industries, such as civil engineering, the same challenges are observed, where monitoring for long durations with a coherent system focusing on user-friendly representations seems to be absent (Wynne et al. 2022). Although engineers are technically good at interpreting sensory data effectively (Tomai 2023), underground mine environments are different from most industries' working environments. Underground mines are hard to reach, thus limiting the accessibility to assess ground conditions; assessment can be neglected since the focus of engineers can shift more to ongoing excavation rather than observing and maintaining other areas of the mine. These conditions can decrease the situational awareness of the engineer and workers, cause work fatigue, and increase unnecessary multi-tasking. Considering the limited time to act in an underground mine, interpreting data can pose challenges. Therefore, a more holistic approach that considers near-real-time data can improve underground operations and safety by reducing the time for decision-making.

Utilizing VA through visualization methods, such as heat maps as risk levels, can help this approach. To extract knowledge, Atif et al. (2021) emphasized the importance of data visualizations in underground mines. They focused on visualizing data that are collected through an IoT-based monitoring system. A dashboard displaying monitoring data was created for the Sibanye-Stillwater Digital Mining Laboratory (DigiMine) following the DIKW (data information knowledge wisdom) paradigm. To visualize seismic activity, Seymour et al. (2016) at the National Institute for Occupational Safety and Health (NIOSH) implemented a 3D virtual model of the underground Lucky Friday mine's Gold Hunter workings, along with pertinent geologic structures and photogrammetric surveys for areas of concern. These initiatives provide new insights into the visualization and interpretation of underground workings. However, there is not yet a systematic approach for creating VA tools. The last stage of the proposed framework gives users a novel, visually coordinated way to understand and interpret the data collected from large sensor arrays.

5.2.1 Establishing a DT Methodology for Underground Geotechnical Monitoring

The objectives of well-executed visualizations are (1) communication and (2) scientific discoveries (Friendly 2020)—either to declare results from datasets or to explore them. By visualizing near-real-time data on top of a 3D model, a DT enables communication and discovery by providing four components of a DT (Tao et al. 2019):

(i) Models of physical objects/systems
(ii) Data from physical objects/systems
(iii) Connections linking the model, physical objects/systems, and their datasets
(iv) Services for evaluation, optimization, prediction, and validation.

The proposed framework addresses all four of these components. First, a 3D model of the opening through the rock mass in the East decline was generated using scanning technologies. Second, the sensor arrays collect supplemental data on rock mass displacement as part of an automated DAQ system. Third, the data are transformed and streamed to the DT via a custom database and rendering pipeline. Finally, the data are presented using a multi-scale, interactive model to enable hazard assessment for safety, optimization of ground support and excavations, and cross-validation of in-person inspections.

By generating meaningful information, fostering knowledge, and delivering "the right information to the right place at the right time" (Tao et al. 2019), a DT can offer valuable insights into the current ground conditions of the mine. Instead of investing time in the preparation and cleansing of geotechnical data, a DT allows for more focused analysis. In the mining sector, significant DT implementations are found in mineral processing plants, resembling frameworks applied in manufacturing projects (Schug et al. 2019; Servin et al. 2021; Hasidi et al. 2022; Ohenoja et al. 2023) and some studies in open pit mining (Hazrathosseini and Afrapoli 2023). Wang et al. (2022) monitored machinery for an underground longwall coal mine through a DT, where real-world scale 3D models of coal shearer, hydraulic supports, and a scraper conveyer were created. Sensors on the physical machinery supplied real-time data to the DT, which were continuously updated based on their spatial position and maintenance status.

In the realm of geotechnical monitoring and geomechanical simulations, there appears to be a lack of emphasis on DTs. Although the study by Seymour et al. (2016) did not explicitly label their 3D model and visualizations as a DT, it stands as one of the closest implementations in geotechnical engineering. Notably, their study did not incorporate real-time monitoring data into their 3D mine rendering, resulting in a static visualization rather than a dynamic one. While not DT tools, MLWeb by Canary Systems, or Instrumentation applications by mXrap can be considered examples of a DT paradigm, offering dashboards with 3D mapping of datasets.

DTs can aid the assessment process by increasing the observability of underground rock conditions easing the monitoring process. DTs focus on real-time data providing the industry with mechanisms to integrate sensor networks for near-real-time monitoring (Marshall and Garcia 2020). This technology can provide early warnings before failures or hazards occur, enabling engineers to 'see it before it happens' with near-real-time data inputs. DTs also have the power to communicate through a team across different expertise and provide a common ground (Gageldonk and Weterings 2019), increasing the interoperability of the project. Some of the challenges of a DT are the connection to analytical tools, gaining access to data, and visualizing multiple sources of data through the lifecycle of a project (Marshall and Garcia 2020). Our proposed framework aims to address these challenges while aiding the overall monitoring process.

5.2.2 Creating Visualizations on a 3D Model for VA

The objective of the DT architecture is to support daily ground condition assessments, data analysis, and prediction of hazards via an intuitive visualization method that coordinates the data and highlights changes. The data collected through the monitoring system are multi-dimensional, with attributes dependent on physical dimensions (e.g., time, space), effectively illustrating the nature of rock conditions in a 24/7 operating underground mine when incorporated into a DT. There are numerous challenges in the development of a dynamic DT. In particular, rendering and updating the 3D virtual environment with data inflow from the real world requires significant computational power. Although modern computers can render and display complex dynamic models, data must be acquired and transformed for display in the virtual environment with frame rates suitable for interaction. Development of the front-end for the dynamic DT involves two major steps: (1) creation of a 3D model of the mine site; and (2) overlay and visualization of engineering data onto the 3D model.

Creation of a 3D model. The 3D model for the DT can be created either by point cloud data from Lidar scans or by photogrammetry data. Both datasets use different pipelines to be rendered in Unity. Currently, the project is using 3D models generated from point cloud data triangulation in.fbx format as they are more flexible to manipulate using the Universal Rendering Pipeline (URP) in Unity. The lidar scans were conducted with the SLAM-based Hovermap (Emesent 2024). Unity can render different file formats (0.3 ds,.obj,.ply, etc.); this study used point cloud data formats (.ply) and photogrammetry data (.fbx).

Overlay and visualization of engineering data Visualizations for this project will render data as dynamic TARP levels on the 3D model in relation to its real-world geo-space at the mine. The Unity URP was selected as the rendering system for this project, as it offers good performance on the modest graphics hardware of mid-range desktop computers, with the versatility to create real-time visual effects needed for the DT. In particular, the visualizations are rendered as dynamic heat maps using Shaders, small scripts executed for each pixel on a screen (Vivo and Lowe 2015).

In this study, results from 3D finite element analysis using RS3 were used to create preliminary visualizations. As the development of a data API is still in progress, the flow of the RS3 results was conducted locally on a personal computer (PC) instead of a cloud-based data flow. The RS3 model was solely developed to produce results that are visualized in the DT since sufficient monitoring data does not exist. The total displacement from the RS3 simulation was reported into a file (.csv) where a C# script was created to read the file in increments of time to mimic real-time data flow into the visualization. Future work will use data from sensors after the installation of all instrumentation (Sect. 4.2, Table 2) is completed. After the data are parsed from the file (.csv) every 5 s, it is rendered using a custom-designed URP shader program to colorize the surface geometry based on movement. Specifically, the shader was developed using Unity's Shader Graph tool to manipulate the 3D model's material properties at each sensor position. Color is manipulated based on the total displacement value, resulting in the color change of the 3D model according to a TARP level. A summary of this method is given in Algorithm 1.

Input: *Variable from CSV parsing script*
Output: *Color and illumination change of material*

```
Initialize serialized variables: displacementData; glow = 100f; rockMaterial; min = 1f; max=3f;
Awake (): Prior to the simulation loop, access data from CSV parsing script using GetComponent<CSVScript>;
Update (): Run DisplacementChanges () function continuously in the simulation loop;
DisplacementChanges()
  displacementData = CSVScript.CSVdata (CSVdata from CSVscript is displacement data)
  if (displacementData >=max)
     rockMaterial(Color.Green); rockMaterial(glow*displacementData);
 else
     rockMaterial(Color.red); rockMaterial(glow*displacementData);
```

Algorithm 1: Manipulating Shader Variable with Data

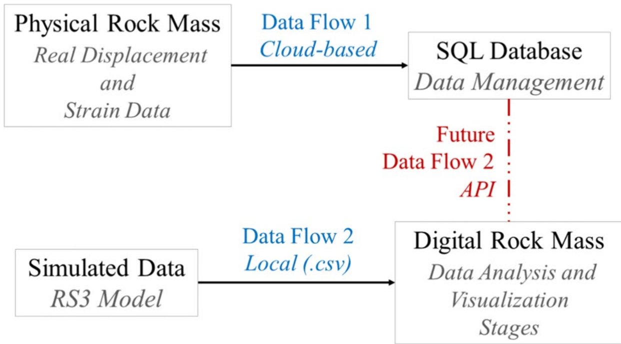

Fig. 15 Diagram of the data pipeline for the sensor data from the monitoring system to the database (data flow 1), the data pipeline for the simulated data from the local file to the DT (data flow 2), and the data pipeline currently under development for the sensor data (future data flow 2)

Table 5 Generalized Hoek–Brown Failure Criterion values used for RS3 model

Value	Data
Material type	Elastic
UCS of intact rock (MPa)	16
GSI	45
mi	10
D factor	0.8

To maximize the utility of the DT for collaborative analysis and monitoring, the data visualization must be easy to explore and easy to understand. A multi-scale viewing capability allows users to dynamically zoom their viewpoints; they may zoom out to understand the general context and zoom in to examine localized changes in sensor data. For example, at the highest level, users may observe the entire mine environment, using color palettes to distinguish specific mine sections, declines, and other labeled features, as well as heat maps to identify areas of significant change. Representations of the engineered data from each sensor are also displayed over the 3D model.

Studies further suggest that visualizations of DTs may be enhanced by XR technologies (Tao et al. 2019). Using XR technologies for VA is defined as Immersive Analytics (IA) (Chandler et al. 2015), which can provide a deeper analysis experience than traditional methods (Batch et al. 2020). For example, at the lowest level, the DT enables users to experience a first-person "life-size" view of the virtual mine and to observe readings from individual sensors. A preliminary mouse and keyboard interface has been developed for desktop–PC interaction; future work will address the use of VR head-mounted displays (HMDs) to increase immersion and afford new interaction capabilities.

6 Results and Discussion

The monitoring infrastructure and a demo DT have been successfully deployed at the SX mine as a proof of concept. Although the backend services (e.g., the RESTful API discussed in Sect. 5.1) enabling flow of displacement and strain data from the monitoring system to the DT are not yet complete, this proof of concept provides two essential levels of validation: (1) a successful monitoring system that collects, stores, and manages the data (see in Sect. 6.1) and (2) a successful visualization of simulated data on a digital 3D model of the East decline for use as a safety assessment (see in Sect. 6.2). These components represent the bulk of the novel system framework (Fig. 15). The API to facilitate data transfer from the physical rock mass database to the digital rock mass twin is principally a matter of implementation using standard networking and querying protocols and is ongoing work.

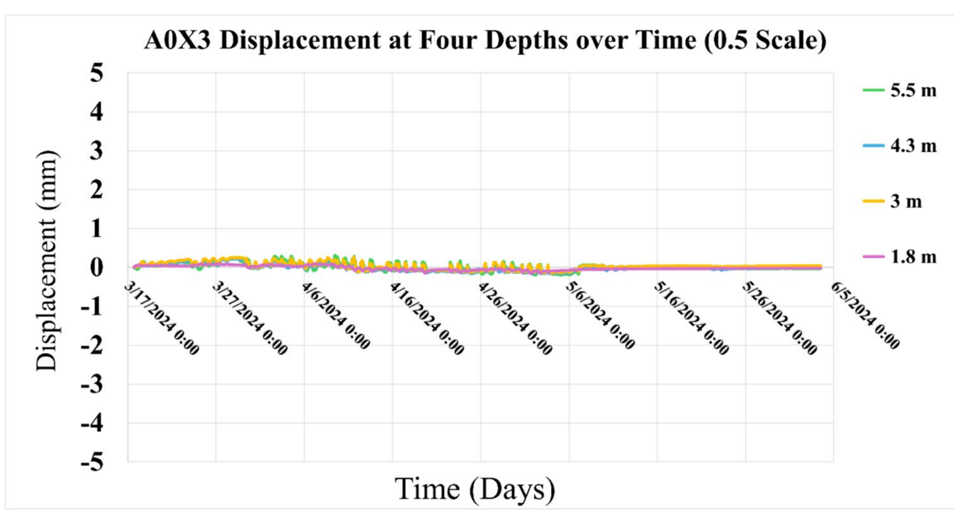

Fig. 16 The displacement data from the four measurement depths of A0X3 on a 5 mm scale between 3/17/2024 and 06/03/2024

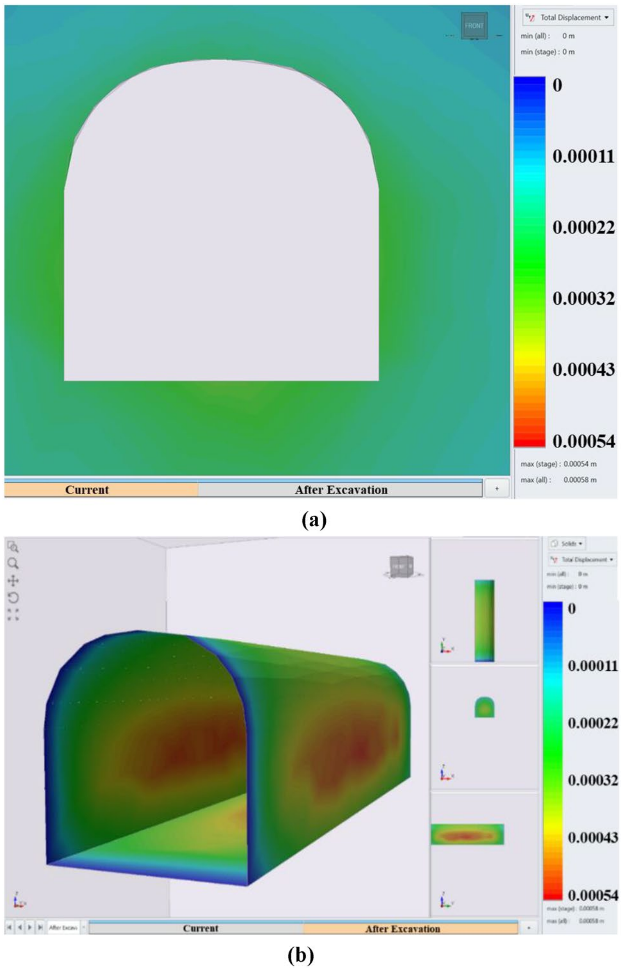

Fig. 17 Result from RS3 model, **(a)** 2D results of total displacement around the opening before excavation, **(b)** 3D result of total displacement after excavation

6.1 Data Collection from the Monitoring System

By deploying Stages 1 through 3 of the proposed framework, a monitoring system has been implemented in the East decline. Although instrument installation is continuing, the monitoring system is able to automatically transfer data from the sensors to a relational database in the cloud, which may be accessed remotely. Currently, the data collected from instrument A0X3 are being used for baseline monitoring which will benefit future longitudinal analysis of ground displacement in the East decline. Since the installation of the A0X3, the baseline monitoring data indicates insignificant movement, with less than 0.1 mm of displacement even though advancements have been made in the East decline. During the 2 months of data collection, the overall displacement was observed to be close to zero for each depth of the A0X3 (Fig. 16), indicating a TARP level of 1. Given this analysis, the current state of the East decline poses no significant risks of ground falls, convergence, or other operational drawbacks due to ground displacement even when blasting occurs. However, as the installation of instrumentation arrays has not been completed, these data are not yet sufficient to construct a 3D visualization.

The instruments and DAQ system are crucial for monitoring ground conditions and supporting traditional analyses of ground movement in the East decline. However, the true impact of these systems comes from the data pipeline, which achieves automated, near-real-time data for use in the DT, validating Stages 1 through 3 of the proposed framework.

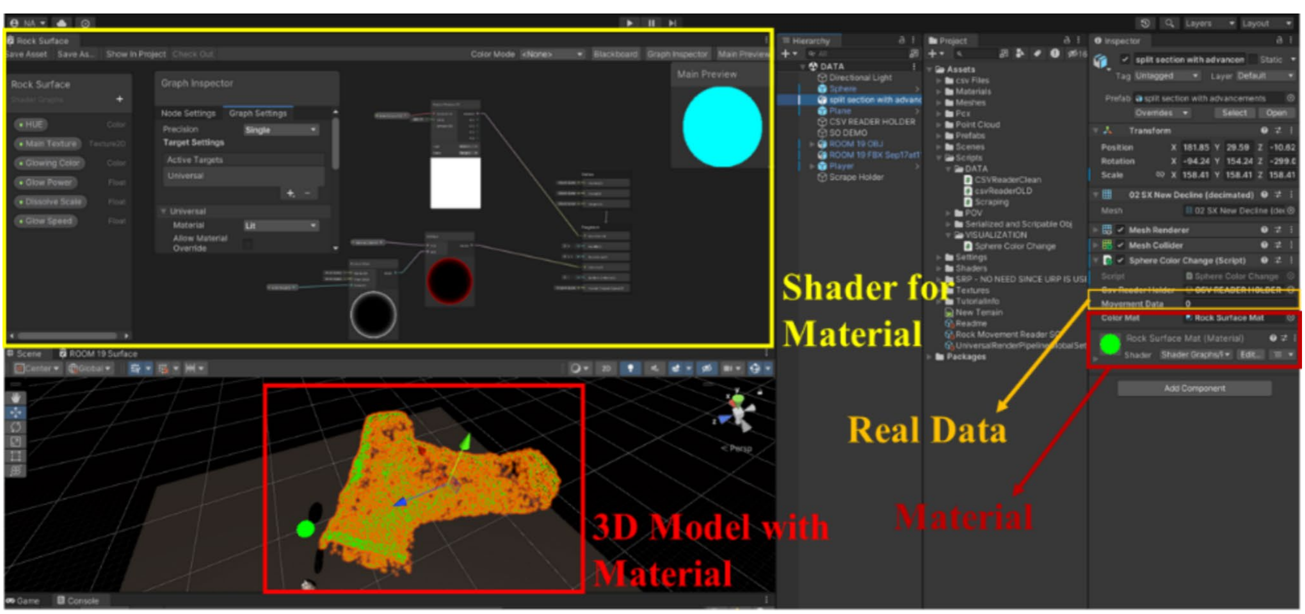

Fig. 18 Unity interface showcasing Shader Graph, shader manipulation script, material, and 3D model

6.2 DT Development

Addressing Stages 4 and 5 of the framework, a DT was developed to demonstrate its use as a 3D visualization tool for safety assessment. In this demo, the expected ground behavior of the East decline was simulated, since installation of all instruments has not been finalized, and the RESTful API development (Sect. 5.1) is still underway. However, this demo visualization outlines the utility of an end-to-end system in which the DT will be driven by data collected from the monitoring systems deployed in the East decline.

In this demo, a simulated dataset was collected using a 3D finite element model with the RS3 geotechnical software (Rocscience, 2024). The Generalized Hoek–Brown Failure Criterion was used to develop the RS3 model. The previous results from the geotechnical scanline and cell mapping techniques in Sect. 4.2. were used to determine the Generalized Hoek and Brown values. The values used for the Generalized Hoek–Brown Failure Criterion can be seen in Table 5. The external boundaries of the RS3 model were created with 25 KN/m^3 unit weight of elastic material.

The RS3 model consisted of two stages: Stage 1—1 m behind the face at East decline before advancements 20 m below ground (Fig. 17a) and Stage 2—1 m behind the face at East decline after 3 m of excavation 20 m below ground (Fig. 17b). A 0.3 mm increase in total displacement was expected around the ribs of the opening where Array 1 will be installed. The total displacement results from the simulation were recorded to file (.csv) and used as a data source for the DT demo.

The simulated data were transferred from.csv file to Unity in real-time using a C# script that parsed the data rows in 5 s intervals (Fig. 18). The data were then fed into Algorithm 1, where it was visually updated on the surface of a 3D model of the East decline. For example, at time-stamp 11:26:55 AM (hour:minutes:seconds), a total displacement of 0.2 mm was indicated by the RS3 model and reflected on the surface of the 3D model (Fig. 19a). After 5 s, at time-stamp of 11:27:00 AM, the data transfer continued and a total displacement of 0.3 mm was reflected on the surface (Fig. 19b). After a further 5 s, at time-stamp 11:27:05, a total displacement of 0.5 mm was apparent on the surface (Fig. 19c). The simulated data were visualized using a heatmap representing TARP levels, with green indicating a TARP level of 1 and orange indicating a TARP level of 4. To emphasize the visual effect on the 3D model, narrow thresholds were used for the TARP levels (between 0.2 mm and 0.5 mm), as per the results of the RS3 model. These TARP thresholds were selected only for demonstration purposes. The heatmap was implemented using a simple linear interpolation node in Unity's Shadergraph and is not a precise representation of each point in the East decline. Despite these considerations, this demo underscores the DT's ability to effectively visualize ground displacement data and characterize risk levels on a 3D model in near real-time, validating Stages 4 and 5 of the proposed framework.

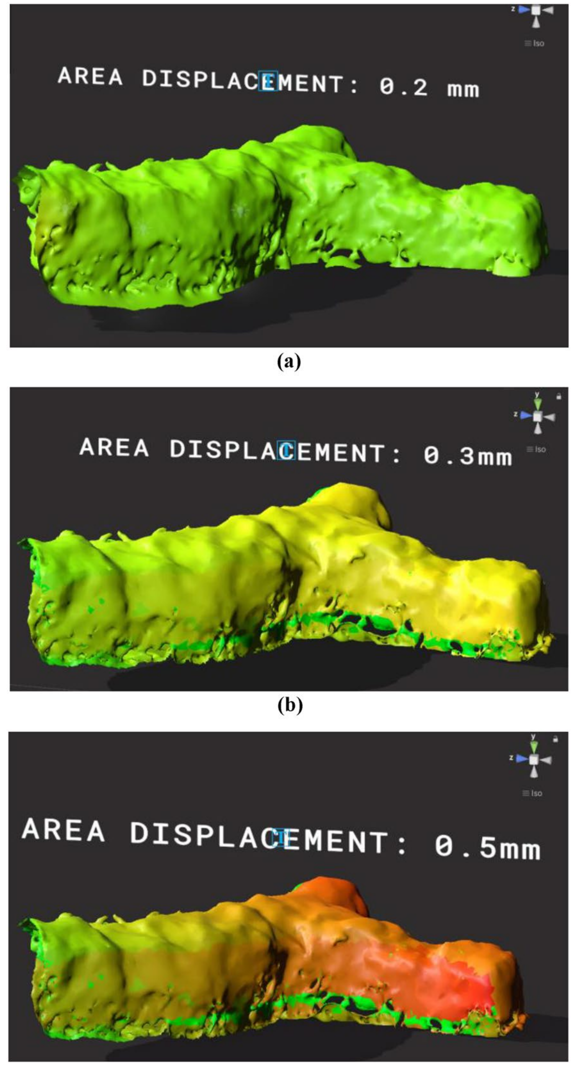

Fig. 19 Visualizing TARP levels on a DT a 0.2 mm displacement at 11:26:55 AM as TARP 1, **b** 0.3 mm displacement at 12:57:00 AM as TARP 2, and **c** 0.5 mm displacement at 12:57:05 AM as TARP 4

The visualizations enabled by this prototype system will allow users to assess rock mass intuitively and analyze the displacement data in 3D in a significantly shorter period of time compared to traditional in-person visual assessments. The DT can access data and render its corresponding visualizations in near real-time, improving the assessment of ground conditions by engineers and workers and increasing overall safety.

7 Conclusion

Monitoring plays a crucial role in keeping engineers aware of displacement and its rate, resulting in a proactive approach that contributes to a safer working environment and efficient production, aligning with the financial objectives of a mining company. Mathematical models of ground displacement can give great insight into what to expect after an opening has been excavated. Regular in-person observations and assessments are crucial to understanding ground conditions. Both modeling and inspections give important information for safe and productive underground mines but have several limitations. Some technical and human-related factors can create challenges for underground mines that risk safety and production. Openings such as drifts, access roads, drawbells, etc., need to be stable for long durations. Support systems need to be installed at advancing faces quickly, limiting the time to collect geological and geotechnical data. As a result, it is crucial to have sensors installed through an automated monitoring system, to have a second set of eyes where the observatory system's outcome is data. Processing this data and utilizing it for mining decisions involves complexities across multiple areas of expertise. Hence, the development of a DT stands to significantly benefit the mining industry.

Future work at the San Xavier Experimental Mine will consist of completing the installation of the instrumentations according to the array design. In addition to the two initial arrays given in this paper, Array0, and Array1, two more sensor arrays consisting of instrumented bolts will be added as advancements continue at the East decline. After the collection of displacement data over longer durations, longitudinal analysis will be conducted to observe possible changes in ground conditions. The collected data will be used to create visualizations in the DT, in place of simulated data from RS3. The data will be queried once a day to update the DT and its corresponding TARP-level visualization. As the DT is in its preliminary stages, future work will consider automatically updating the 3D model using scanning data from georeferenced scans. The interpolation method will also be enhanced to increase the rendering precision of the heatmaps used to represent displacement data on the 3D model. There is a pressing need for advanced visualization systems that allow mining engineers to make timely decisions regarding mitigations, mine plan updates, and the design and installation of stabilization measures. Digital twins fulfill this need by offering a detailed and interactive model of the underground environment.

Furthermore, the Unity Shader Graph offers great versatility to explore and customize the data visualization methods for the DT. For example, different interpolation methods may be explored for rendering (e.g., quadratic, Gaussian) on the surface of the 3D model based on the movement of the rock mass using High-Level Shader Language (HLSL). Additional sensor data may also be overlaid onto the visualization using texture combines (algorithms that render two or more textures onto the same area) and changed selectively by the user at runtime. Upon full development, mining companies can seamlessly integrate these tools into the daily cycle of underground mine production.

The ultimate objective is to develop a comprehensive tool that integrates geologic, geotechnical, and mining engineering data. This tool will be a collaborative platform, ensuring safe and economically viable underground mine production. Digital twin technology represents a significant advancement in geotechnical data visualization for underground mining. By providing a detailed and dynamic model of the underground environment, digital twins empower mining engineers to make informed decisions that enhance safety, efficiency, and sustainability in mining operations.

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Data availability The authors confirm that most of the data supporting the findings of this study are available within the article [and/or] its supplementary materials. Data not within the article are available on request from the corresponding author, [NA].

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