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Application of mixed and virtual reality in deep mining

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Abstract

The immersive 3D capabilities within mixed and virtual reality (MR/VR) provide significant new opportunities in mining including rock mass characterisation, monitoring, and modelling. Innovative examples of applications in rock mass characterisation will be presented in this paper, including engineering core logging, and visualisation of discrete fracture networks.

A virtual core shed in MR/VR has been pioneered and it shows high potential for improving quality control/assurance, as it enables remote geological and engineering examination at different experience levels. Supplementary core data can also be juxtaposed allowing further assessment. Borehole wall imagery is also added in VR, demonstrating the ability to travel down virtual boreholes and examine specific features.

An innovative MR visualisation platform of discrete fracture networks (DFN) offers the potential to improve characterisation of properties such as fracture intensity, connectivity, and rock bridge distribution with significant implications in understanding rock failure mechanisms. Virtual boreholes of varying orientations can easily be inserted into the DFN holograph, allowing for the examination of spatial distribution of fractures, fracture sampling bias, and assessment of potential rock mass kinematic instability; all leading to improved subsurface rock mass characterisation.

Applications of MR/VR to characterise underground excavations and monitor ground-induced subsidence above deep mines are briefly outlined, along with numerical modelling of deep mines.

Complex 3D problems can be investigated from a unique perspective overcoming the significant constraints of 2D screens and enabling optimal characterisation of the rock mass and ground performance within the virtual paradigm. Increased use of these instrumentation in deep mining will provide new insights and allow more informative decisions involving multi-disciplines and multi-levels of engineering/geological experience. With continuing and rapid technological advancements in both hardware and software, we suggest that MR/VR has the promise of revolutionising deep mine design.

Keywords: *virtual reality, mixed reality, discrete fracture network*

1 Introduction

The rapid advancement in virtual reality (VR) and mixed reality (MR) technology continues to narrow the separation between the physical and the virtual world. VR allows users to immerse themselves in a virtual environment, typically using a headset display. This facilitates real-time navigation of 3D virtual space through physical interaction or input devices. MR differs from VR in that it does not occlude a user's perspective, thereby allowing seamless engagement between physical and virtual objects (Microsoft 2024a; Apple 2024; Meta 2024; Chang 2021). Extended reality (XR) is an umbrella term encompassing both VR and MR (Milgram & Kishino 1994) (Figure 1).

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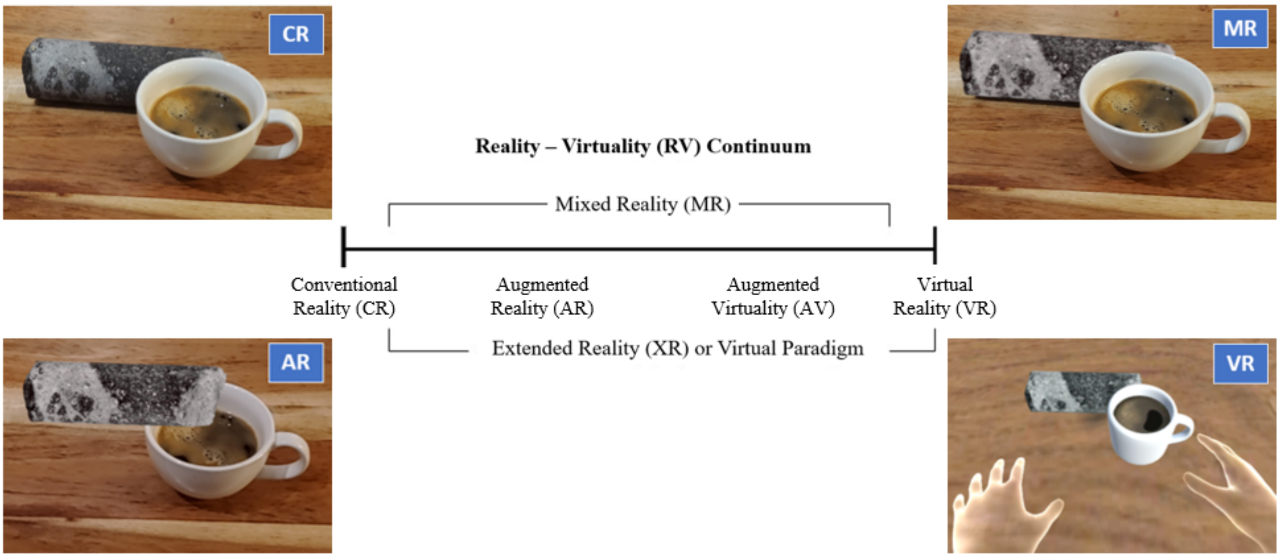


Figure 1 Comparison of a conventional reality (CR) core sample to a virtual core sample in mixed reality (MR), augmented reality (AR), and virtual reality (VR) within the reality – virtuality continuum (after Chang 2021; Milgram & Kishino 1994)

The versatility of XR platforms allows various applications to be constructed surrounding complex 3D models, offering potential to revolutionise the mining industry where complex multidimensional data is abundant and requires visual optimisation (Onsel et al. 2019; Chang, 2021). Collaboration between mining professionals in MR/VR can enable a more detailed understanding of geological, geotechnical, and engineering problems, thereby facilitating more informed decision process. XR technology has seen a continuously expanding array of applications that serve both the mining and civil engineering industries (Strzałkowski et al 2024).

Most XR applications are constructed using OpenXR, a high-performance open-source application programming interface (API) that provides the foundation for development and aims to streamline development (Khronos Group 2024). This API prevents developers from being constrained to a single hardware or software ecosystem, fostering both innovation and collaboration. This standardised foundation simplifies adoption to future hardware and permits synchronous communication between MR, VR, and the conventional desktop. One example is the mine mapping application EasyMineXR where all three platforms can be used (SRK 2024).

VR and MR have already demonstrated significant capabilities in mine safety though virtual training (Scorgie et al. 2023; Zoleykani et al. 2024), assessment of hazardous/inaccessible regions (Isleyen & Duzgun 2019), and visualisation of complex 3D mine models (Onsel et al. 2019). This paper demonstrates how VR and MR resources can advance deep mining through three different XR applications developed by the first author. Finally, a brief overview of other XR applications undertaken in underground mining is provided.

2 Development specifications

Most applications presented here were developed for the Microsoft HoloLens 1 and 2 (Microsoft 2024a). Development is now being undertaken using the Meta Quest 3 (Meta 2024). The main VR headset used previously was the HP Mixed Reality headset (HP Development Company 2024). All applications are constructed in Unity, a comprehensive game-engine that allows development of interactive 3D environments and supports various data types from complex 3D mesh files to point files (Unity Technologies 2024). C# is Unity’s primary scripting language, allowing robust frameworks for constructing complex behaviours, mechanics, and facilitates rapid prototype iterations in VR and MR devices.

Mixed reality toolkit (MRTK), an open-source collection of scripts, was used to accelerate XR development in Unity. MRTK, developed by Microsoft (2024b), features an OpenXR architecture, enabling integration and adoption across various devices (Khronos Group 2024; Microsoft 2024b).

Due to the storage and processing power limitations of current XR hardware, several preprocessing operations are required (Onsel et al 2019). Some of these procedures are automated through in-house Python scripting to ensure rapid iterations between different projects. Preprocessing is an essential step in XR methodology as exceeding the limits of XR hardware causes frame rate drops as information must be compiled in real-time. Low framerates are an undesired trait within applications as it leads to nauseating effects, loss of immersion continuity, and generates undesired artifacts (Zielinski et al. 2016; Kroma et al. 2021). This dependency is pivotal for XR, yet it must be executed meticulously to ensure information is not compromised.

The preprocessing requirements for MR headsets tend to be greater due to hardware specification. VR platforms, however, requires less preprocessing and are better at handling complex 3D models, because they either have higher specifications or rely on the processing power of the computer to which the headset is tethered. Despite these benefits, VR poses other limitations, such as occlusion of the real world, eyestrain, and disorientation (Chang 2021). Additionally, pixel density and lens type of VR headsets significantly influence the resolution and the focal point. These characteristics, along with design and hardware capabilities, are the key differentiators among various VR headsets (Apple 2024; Meta 2024; Varjo 2024; Pimax 2024).

The distinction between VR and MR enables developed applications in MR to be translatable to VR, but not vice versa. The type of XR hardware used for each application was determined by the nature of the data handled.

3 Results of XR mine visualisation

3.1 Virtual core investigation

Core logging is a fundamental operation in mining; however, it has been suggested that more than 70% of core analysis is unreliable (McPhee et al. 2015). Incorrect data can result from poor core laboratory procedures, human errors, inadequate reporting, and unrepresentative testing. These errors become more prominent when observations are based on visual observations alone. Many tools are available to retrieve reliable core information, including assay results and hyperspectral analysis (Tavakoli 2018). Each procedure has its benefits and limitations, and thus, using a combination of assessments is optimum (McPhee et al. 2015). However, this results in a multi-parameter array of complex data that are rarely consolidated, even though they may aid in noise reduction and correlation of information.

The virtual paradigm was seen as a platform that could host all the core data in an intuitive manner. An in-house 3D core scanner has been constructed that can derive 3D virtual core samples. The resulting high-resolution output from the scanner is a highly detailed mesh that allows automated quantification of geotechnical and geological parameters (Figure 2). The scanned model can capture minerals and textures at a submillimetre granularity scale (Figure 3). Although the visualised model resolution is reduced to facilitate effective import into the virtual paradigm, all quantitative data are calculated prior to mesh reduction to ensure the collection of fully representative data.

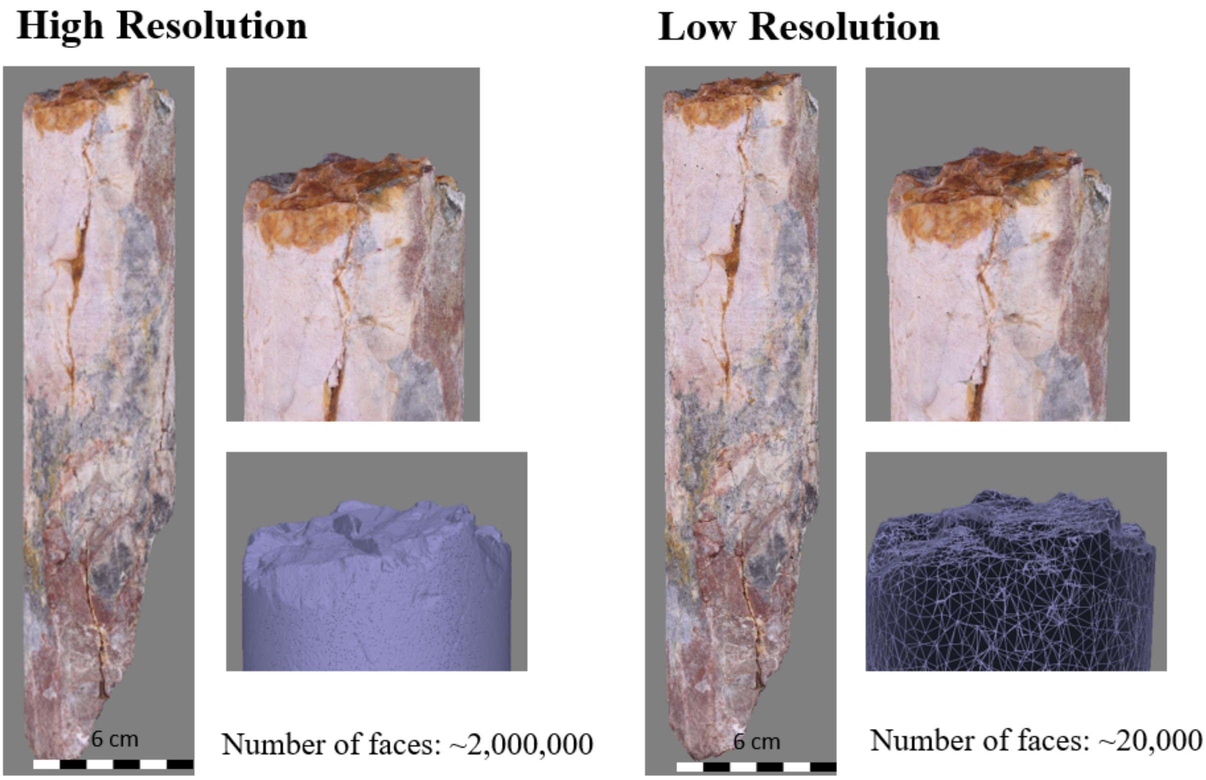


Figure 2 Results and complexity of derived mesh from the in-house core scanner. Mesh required simplification to host multiple core samples within desired extended reality platforms (Chang 2021)

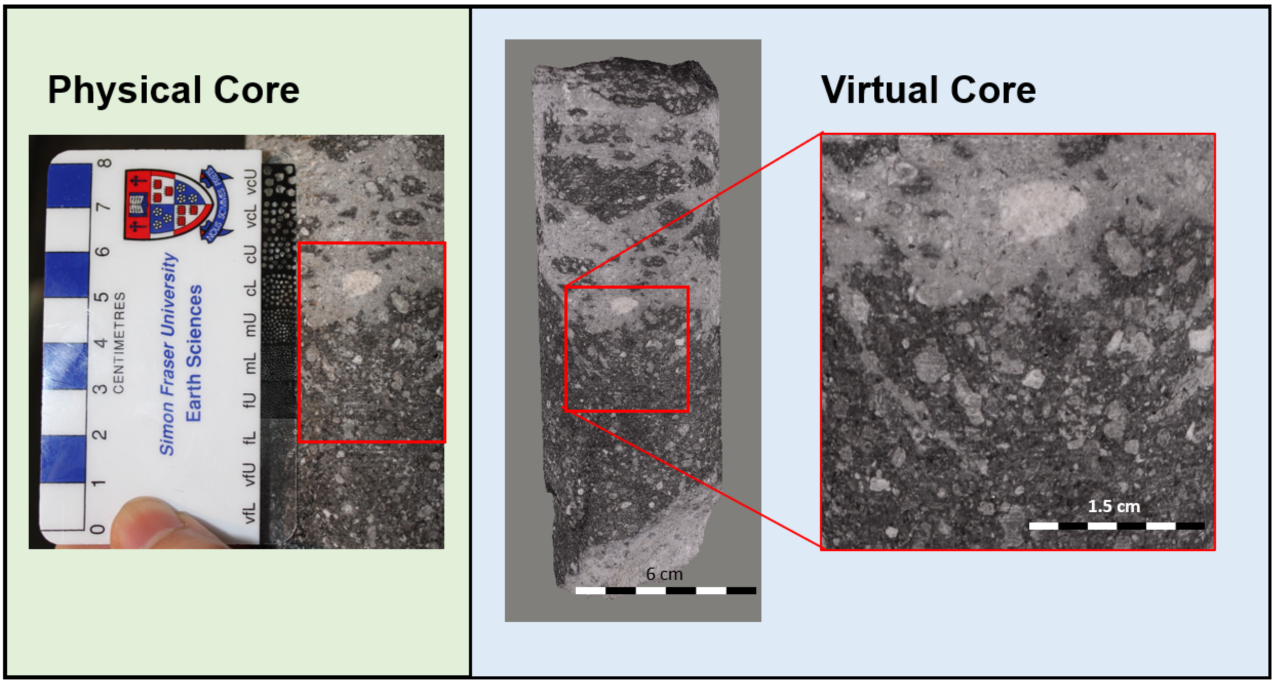


Figure 3 Resolution comparison of physical core versus virtual core sample (Chang 2021)

Once processed, a variety of user-defined supplementary information can be superimposed on the resulting virtual core. Some parameters that have been tested include thermal data, thermal imagery, and hyperspectral information. Virtual pigments are also manipulated, via image processing to highlight features and emphasise mineralisation. A thin section from the scanned core was also captured at 15˚ intervals allowing a virtual petrographic assessment (Figure 4).

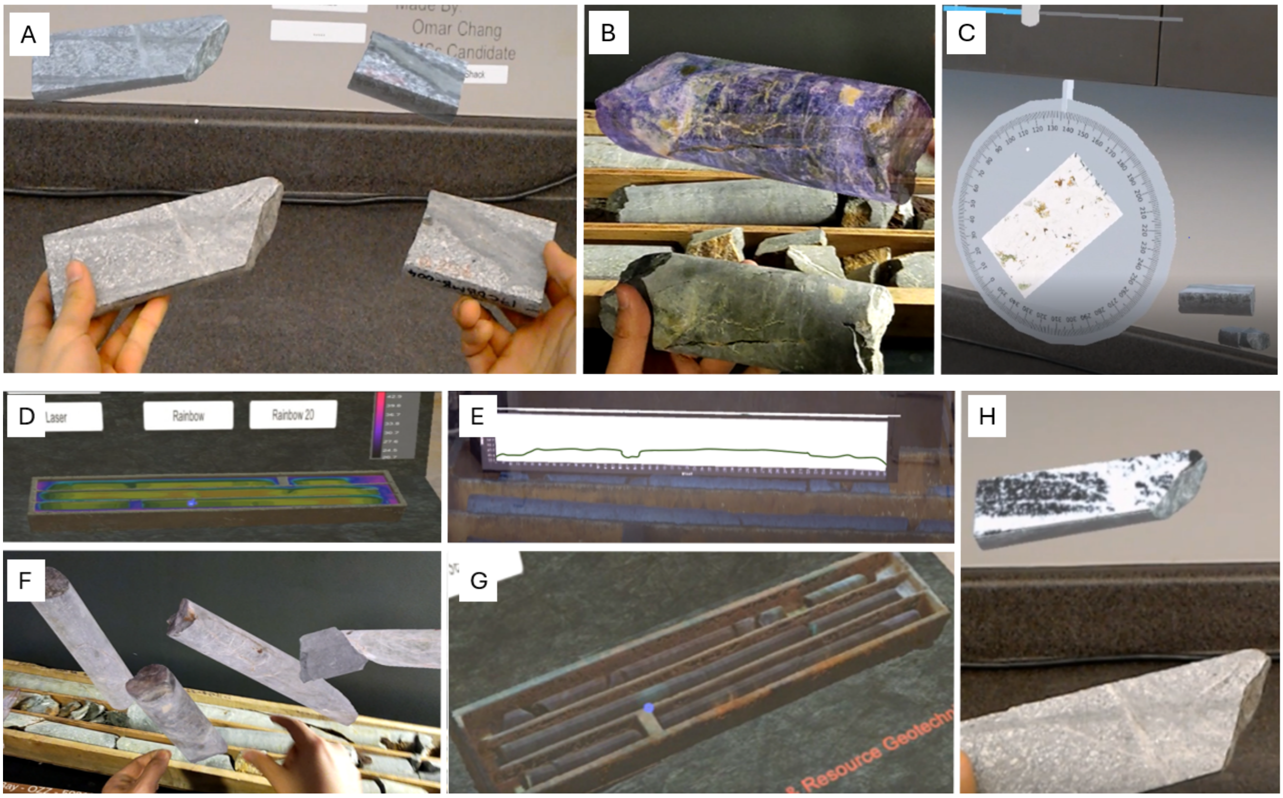


Figure 4 **Various data sets applied to virtual core samples. (a) Observing virtual core and physical core congruently. The contrast of the virtual core was enhanced to depict textures more easily; (b) Colour manipulation applied to virtual core sample to highlight mineralisation; (c) Virtual plane polarised light thin section that can be converted to polarised and rotated at user's discretion every 15°; (d) Thermal imagery overlaid on core samples; (e) 2D thermal cooling graph juxtaposed on respective region; (f) Multiple virtual core samples that can be moved and scaled freely; (g) Hyperspectral imagery overlaid on the virtual core; (h) Grayscale imagery overlaid on the virtual core (top) compared to the physical core (below) (Chang 2021)**

All pieces of the core in the box were scanned and stored virtually. Demonstrating the potential for establishing virtual core shacks comprised of virtual core samples. This innovation would allow remote core evaluation, facilitate backlog core sample referrals, expedite geologist core logging, and computational quantification of multiple parameters. Centralising all relevant core data for each specific core run on a unified platform would enhance core comprehension and correlation. Moreover, it improves quality control/assurance by facilitating simultaneous multi-disciplinary remote logging of the virtual core by various experts. Revolutionising and advancing current methodologies (CoreScan 2024; GeologicAI 2024; INGEN 2024; DMT 2024) of storing core information and visualisation.

Borehole wall imagery obtained by formation micro-imager (FMI) was also used to demonstrate the capability of VR to travel down virtual boreholes and examine specific features, thereby allowing an innovative approach for geological mapping and assessment of borehole imagery. The virtual core sample can be placed adjacent to the borehole, allowing further improvement in core evaluation (Figure 5). For instance, this can determine whether open fractures along the physical core correspond to induced fractures along weak veins or other planes of weakness.

The synergy between drill cores and the virtual paradigm has major potential for subsurface characterisation and exploration. As interpreting drill cores constitutes a critical component of mining projects, both structurally and lithologically, there are multiple through which this new technology can be leveraged in mineral exploration, mining engineering, and geotechnical assessment.

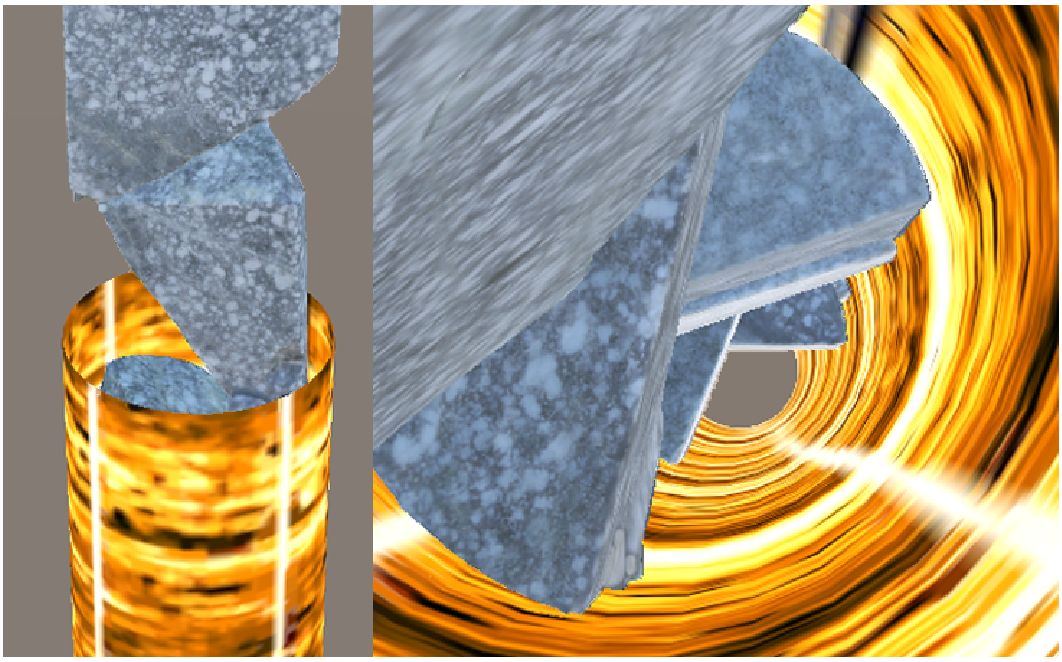


Figure 5 **Formation micro-imager data adjacent to the virtual core. Demonstrating borehole imagery can be observed in extended reality platform (Chang 2021)**

3.2 MR application for discrete fracture network

Discontinuity data from the Middleton room and pillar mine, United Kingdom, was used to compile a DFN using FracMan 7.80 (Elmo & Stead 2009). The resulting model was then exported as a text file and a PLY file.

A MR application was developed to facilitate the import of discontinuity set files, providing a MR DFN model that allows intuitive discontinuity set manipulation. A dynamic user interface (UI) was created to automatically generate an interactive legend and interface solely from the raw PLY file. The UI allows toggling, isolation, and manipulation of each joint set (Figure 6). This application demonstrates how MR capabilities can overcome the limitations of conventional 2D screen displays of 3D models. That results in a pseudo-three-dimensional model, causing complicated navigation and user interaction.

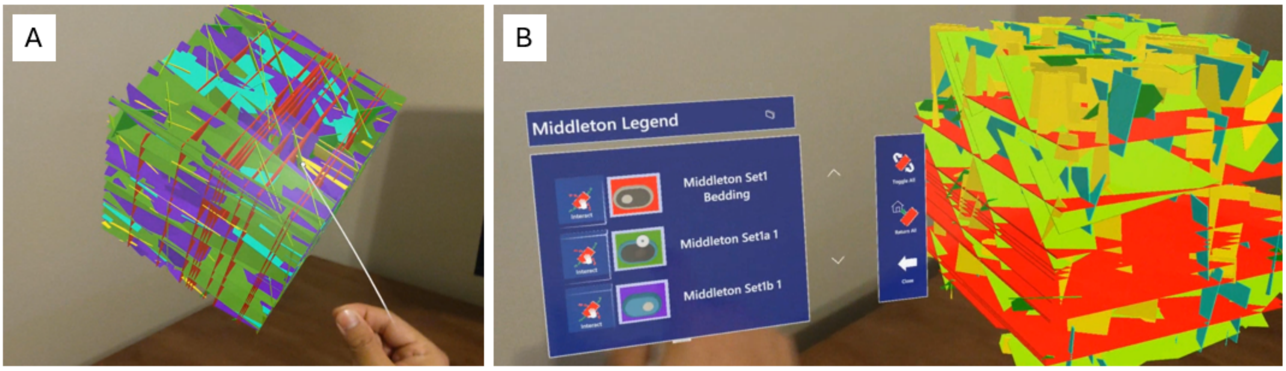


Figure 6 **Discrete fracture networks (DFN) model observed in mixed reality. (a) DFN model can be manipulated freely by the user; (b) DFN joint sets can be toggled on and off**

The developed MR DFN model also makes every joint set interactable and can be controlled by the dynamic UI. The model can also be broken apart easily, aiding in debugging of the numerical model. By pressing a button, all joint sets are returned to their origin, helping the user experience (UX) (Figure 7). The ability to visualise every fracture independently helps visualise the spacing, fracture intensity, connectivity, and rock bridge distribution in an intuitive manner. Errors within the fracture network model can also be easily observed as they are not occluded as when observed on a conventional fixed display screen.

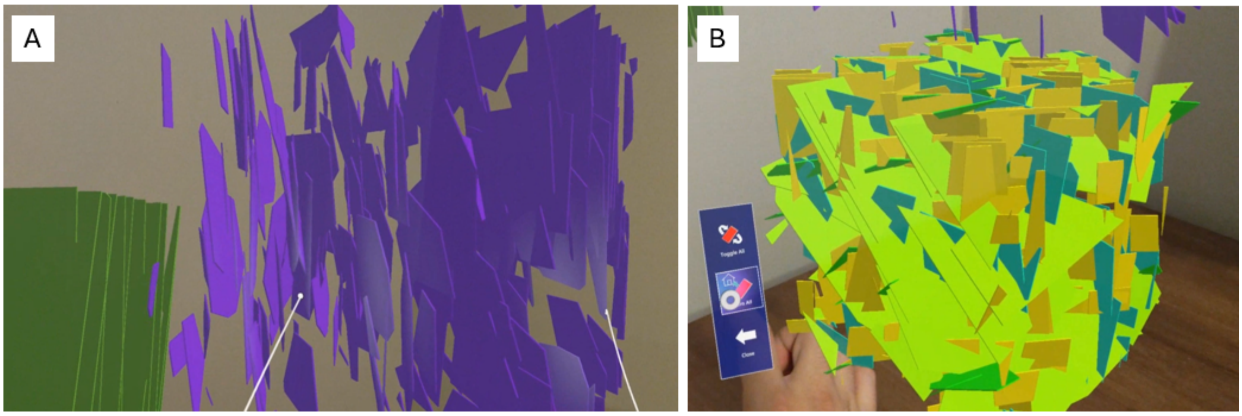


Figure 7 **Discrete fracture networks model user experience for individual joint sets. (a) The user has interacted with Middleton Set 1b and can freely manipulate it to their will; (b) Major joint sets have been removed and emplaced around the room for further investigation. Simply clicking a button will return all joints to the original model**

Virtual boreholes can also easily be ‘drilled’ into the DFN. The representative drillholes are then derived, hosting the intersecting representative fractures along the virtual borehole with their assigned identification colour (Figure 8). This part of the DFN module can also be used to compare virtual joints intersecting the virtual DFN core against physical drillcore runs, improving the interpretation of the rock mass.

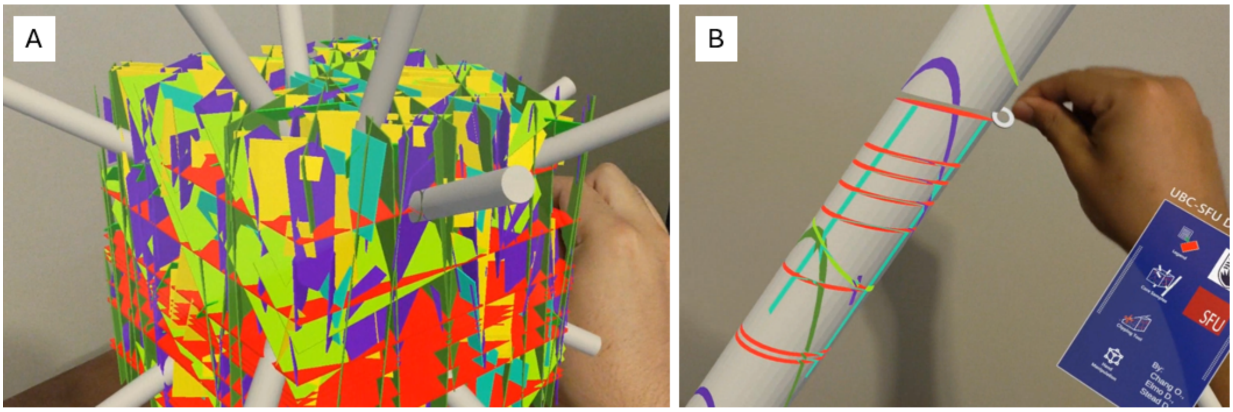


Figure 8 **Mixed reality discrete fracture networks (DFN) with virtual core samples drilled into it. (a) Virtual cores are ‘drilled’ at different localities and rotations showing the effect of sampling bias; (b) Core samples can be extracted from the DFN model with respective discontinuities set denoted along it**

Each virtual DFN core piece formed by adjacent virtual discontinuities is interactive, allowing independent analysis of the core samples at the user’s discretion. Multiple layers of interaction had to be constructed to ensure that undesired movement did not occur between the DFN model, virtual boreholes, and individual core pieces (Figure 9).

The virtual boreholes within the DFN demonstrate the large effect sampling bias can have on rock mass characterisation. Structures parallel or subparallel to the borehole will be under sampled, while perpendicular structures intersect more frequently, and thus are oversampled (Terzaghi 1965; Palmström 1995).

Orientation bias can profoundly impact mine design when incorrectly considering instability on graph methods or numerical modelling design. Through the virtual DFN model orientation bias is immediately visible. This application can help define the optimum borehole drilling angle and location to help investigate the rock mass. By optimising the drillhole spatial attributes, a more representative model of DFN can be constructed. This has important implications for a wide range of mine design issues, including kinematic block stability assessment, stability graph stope design, rock mass strength, numerical design, groundwater flow and conductivity.

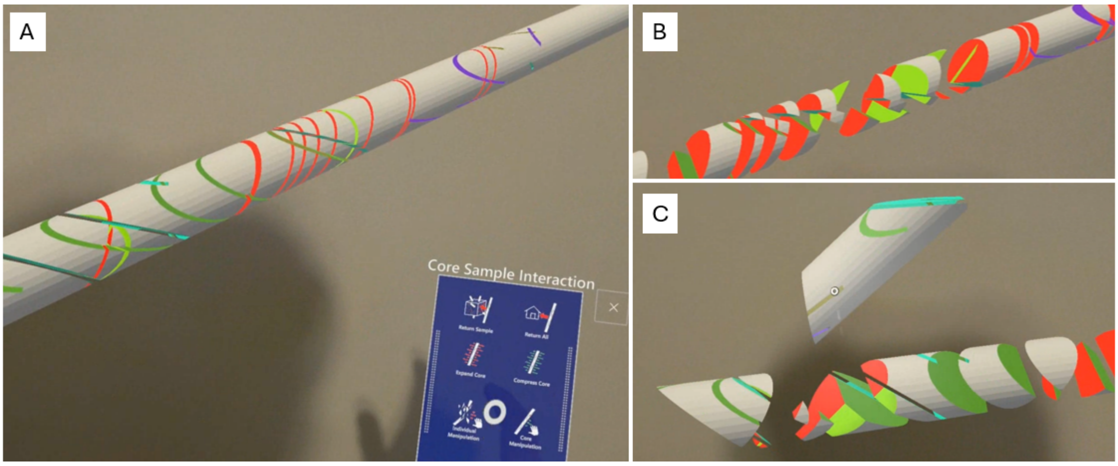


Figure 9 **All virtual discrete fracture networks (DFN) borehole samples are interactive, allowing the user to control each sample individually. (a) A random virtual borehole was removed from the virtual DFN for detailed examination; (b) DFN borehole sample can be expanded through a user interface button, allowing the user to grab individual samples easily; (c) Random individual core sample removed from borehole to perform detailed analysis (including core end conditions)**

Two clipping tools were developed, the first consists of a plane with the ability to create real-time cross sections along the virtual DFN model (i.e. showing the fracture traces on a specific orientation of excavation face). The second DFN clipping tool consists of a cylindrical body that can be moved, scaled, and rotated freely to simulate the excavation of a tunnel, raise or shaft through the DFN model. The shape of the tunnel could be changed to irregular dimensions as desired; however, for simplicity the tunnel was kept cylindrical. Both these approaches improve the evaluation of the kinematics stability of excavations, of any orientation within the simulated MR DFN model (Figure 10).

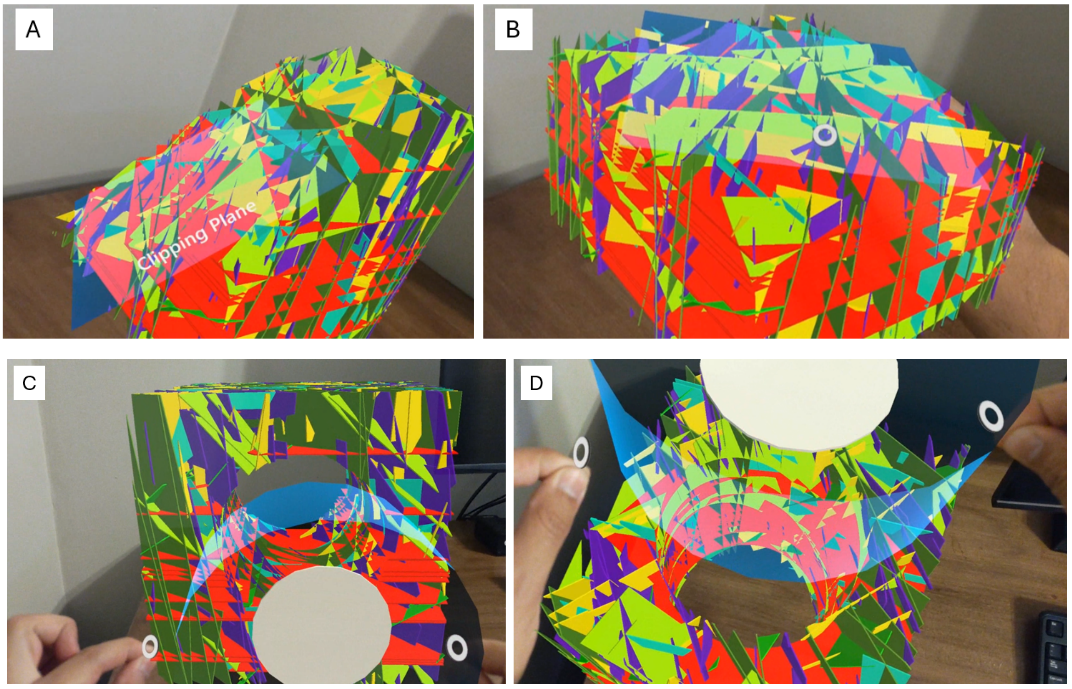


Figure 10 **Example of the use of clipping tool within the discrete fracture networks mixed reality application. (a) The user placed the clipping plane at an angle allowing investigation of fracture traces along the chosen plane orientation; (b) Clipping plane being moved along the Z-axis, allowing the user to observe how discontinuity traces changes along the Z-axis within the DFN; (c) Clipping cylinder representing a tunnel/raise/shaft observed along the DFN model; (d) Clipping cylinder is placed along the Z-axis to observe DFN**

This module demonstrates MR's capability of providing a dynamic and intuitive approach for assessing complex 3D numerical models such as DFNs in mining. By leveraging enhanced visualisation, quality assurance of computationally constructed models can be attained.

The control that the user has over the model, ranges from individual core pieces to the entire model, allowing major improvements in our understanding of the DFN models and their implications for deep mining including cave fragmentation, discontinuity-controlled instability, support, and mine design.

3.3 Underground tunnel evaluation

A ~3.5 km long section of the Ape Cave lava tube (Washington, USA) is used to show the applicability of MR/VR for evaluating changes in underground excavation geometry. The lava tube was formed from multiple flows and shows significant variations in tunnel geometry (Muñoz 2024).

The tube was scanned using a GeoSlam ZEB Horizon at a resolution of 6 mm (FARO 2024; Muñoz 2024). The resulting model consisted of more than 42 million points and was subsequently down sampled to a 5 cm mesh. The extent and complexity of this model precluded importation into MR holographic platforms effectively, unless only small sections were investigated. All the operations were handled within a desktop setting in preparation for import into VR platforms or future MR platforms.

A Python tool was developed capable of generating perpendicular cross-sectional views at a user-defined interval. The interval would be excepted on regions requiring compression (e.g. sharp bends) to accommodate for the curvature. The meandering nature of the lava tube required such a trait (Figure 11). Python scripts were then used to automatically derive values such as specific location/angle of cross-section, total area, total perimeter length, width, and height (Figure 12). The derived cross-section was composed of multiple faces due to lava tube diversions and/or splitting of the lava tube, the segment was treated both as a group and individually (Figure 12d).

Despite being based on a lava tube, the module can be readily applied to assess underground mine tunnel spalling, or regions damaged by blasting (Mitelman & Elmo 2015). This module is still under development, but preliminary results show promising potential for rock mechanics and geological assessment.

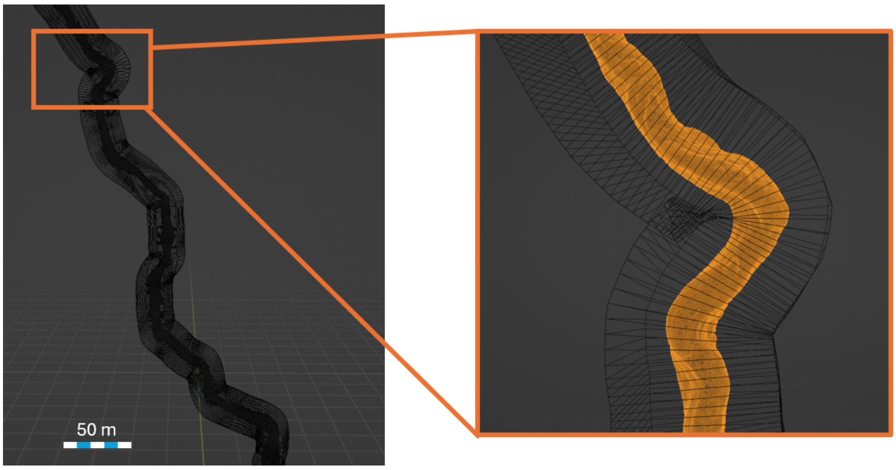
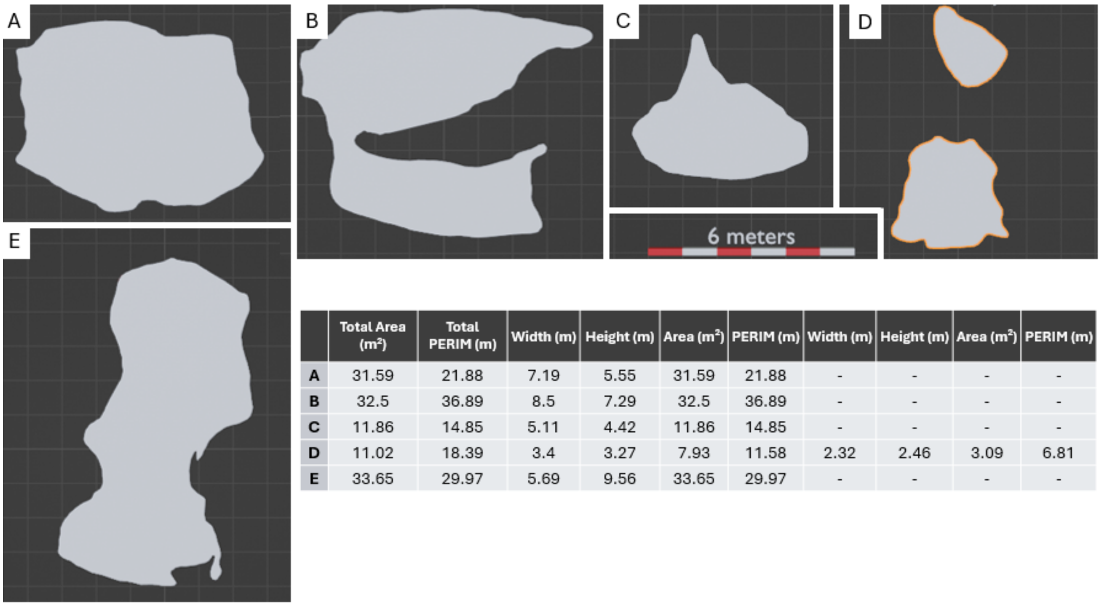


Figure 11 Tunnel segmented in ~1 m intervals to derive perpendicular cross sections. Segmentation is not consistent due to meandering of the lava tube. Certain areas had to be compressed to ensure the cross-section was centred and perpendicular to the tunnel along sharp bends

There is significant potential in visualisation of underground excavations both overbreak and deformation/spalling of tunnels/drillholes and characterisation of raises or mine stopes. Furthermore, the user can travel along the virtual model of the excavation and observe the changes in excavation geometry, structures, and changes over time in excavation profile. These results can also be compared against numerical models, which offer significant advantages in understanding and correlating ground performance with rock mass characteristics.



	Total Area (m²)	Total PERIM (m)	Width (m)	Height (m)	Area (m²)	PERIM (m)	Width (m)	Height (m)	Area (m²)	PERIM (m)
A	31.59	21.88	7.19	5.55	31.59	21.88	-	-	-	-
B	32.5	36.89	8.5	7.29	32.5	36.89	-	-	-	-
C	11.86	14.85	5.11	4.42	11.86	14.85	-	-	-	-
D	11.02	18.39	3.4	3.27	7.93	11.58	2.32	2.46	3.09	6.81
E	33.65	29.97	5.69	9.56	33.65	29.97	-	-	-	-

Figure 12 Irregular shaped cross-sectional profiles observed throughout the lava tube trajectory. Primary parameters shown on adjacent table

4 Other VR/MR applications related to deep mining

Various other MR/VR applications have been developed at Simon Fraser University that have significant synergies with deep mining. These include MR/VR visualisation of ground subsidence data (GPS, InSAR) micro-seismicity, block cave propagations, underground excavation mapping, and numerical modelling mine design (Table 1).

Table 1 Other XR applications that can serve underground mining

Simulation	Description
Surficial deformation formed from sublevel caving	Surficial information such as GPS, InSAR, and structural information was superimposed on LKAB Kiruna, Sweden sublevel caving mine with the potential for improved understanding of cave induced subsidence (Chang 2021)
Block caving	Geovisualisation of Palabora open pit, South Africa. Block caving propagation of underground mine beneath open pit can be visualised, along with InSAR and numerical modelling data (Figure 13) (Onsel et al. 2019)
Micro-seismicity	Microseismic information can be visualised adjacent to underground layout and be observed relative to surficial information. Supplementary data such as lithological and structural information would help delineate the source of seismicity. The user can control seismic range and time range for specified analysis (Chang 2021)
Underground and stope mapping	EasyMineXR is a collaborative mapping software developed by Simon Fraser University and SRK Vancouver (Onsel et al. 2019; SRK 2024). It enables multi-platform mapping of outcrops. Collective visualisation promotes collaboration and improves quality assurance and control

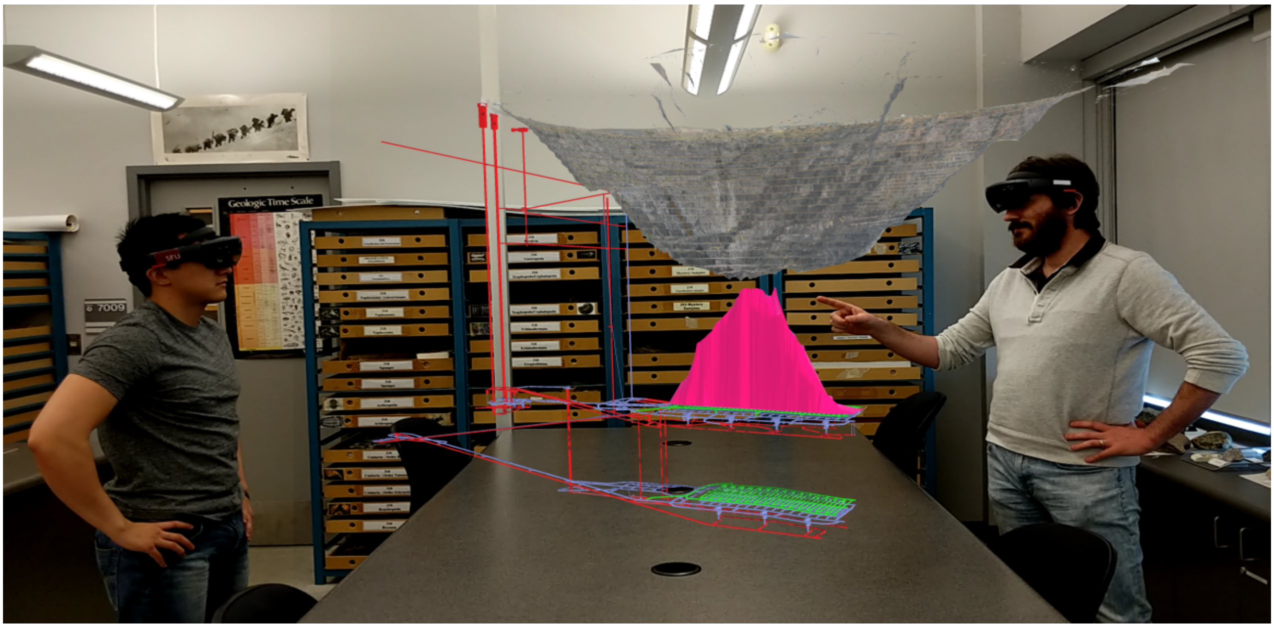


Figure 13 Palabora Mine, South Africa being observed in mixed reality by students at Simon Fraser University. Block cave propagation from the underground mine towards the open pit mine is evident (Onsel et al. 2019)

5 Conclusion

The major benefits and innovative advancement that XR platforms can provide to the mining industry have been demonstrated by the previous examples of data visualisation. A large variety of complex 3D numerical software is currently available to the mining industry. While traditional 2D screens have served as a primary data visualisation and analysis tool, they inherently lack the depth and spatial context to effectively display complex mine models. In contrast, XR platforms offer a paradigm shift that immerses the user in a virtual or augmented environment, providing unparalleled visualisation and manipulation. Mining professionals can improve their understanding of geological, geotechnical, and mine engineering design in three dimensions. XR also transcends physical space limitations enabling remote collaboration (SRK 2024) and assessment of datasets ranging from drill core data to complex numerical models.

Exploring XR applications within underground mining demonstrates a wide array of benefits that can support and enhance future mining operations. The immersive and interactive experience offered by XR can streamline workflow, efficiency, and boost productivity in mining. It aids in improved decision-making, stability assessment, optimisation of mine operations, accuracy and understanding of complex geological/engineering information. By investing in XR – infrastructure, expertise, and integration strategies – mining companies can position themselves to harness future XR technology with continuously improving hardware specifications.

The virtual paradigm demonstrates major potential in reshaping perception, comprehension, and engagement with geological and engineering challenges. As mining transcends away from shallow, low stress environments, new mediums must be investigated. various empirical procedures, logging, and indexes were initially developed for shallower contexts. The synergy that XR brings to mining presents substantial opportunities for adoption to address the challenges encountered in deep mining; which involves more complex geological, geotechnical, and engineering environments.

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