Engineering Geological and Geotechnical Challenges of Lin Ma Hang Mine Revitalization – A Unique Community-based Educational Mining Heritage Project

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ABSTRACT

The revitalization of the 19th-century Lin Ma Hang Lead Mine cavern and surrounds provides a unique demonstration of innovative geotechnical investigation and design for conservation and educational purposes in country park. The restoration of the cavern complex and nearby area aimed to improve the safety of the old heritage mining complex for the public, whilst enhancing the recreational value of the newly designated Robin's Nest Country Park. The project is a unique example of historical and scientific preservation and safety-based enhancement for the public and community. From the outset, assessment of the engineering geological and geotechnical conditions of the natural terrain, drainage, anthropogenic influences and the rock mass related to the ore body were key for prioritizing the geotechnical works. Insights gained from the challenges encountered during the background study, investigations, design and construction phases will contribute valuable experience for future projects with similar sensitivity in Hong Kong and elsewhere.

The design balanced safety and stakeholder issues with the goal of promoting the outstanding mining heritage and associated scientific value as a unique user-based educational facility showcasing the splendour of the remote environment, the outstanding mine geology and geomorphological setting within a palimpsestic framework of old anthropogenic activity ranging from several phases of mine activity, war intervention, and cycles of land management over many centuries. Technical challenges included: (1) methodology for assessment with limited access to the rock face; and (2) balancing robust geotechnical works with resultant visual impact. The NGI Q-system was utilized for rock stabilization along with analytical design through kinematic analysis. Enhanced access afforded by the construction stage refined geotechnical works for rock pillars and blocks formed as part of the historical and geological context of the mine, potentially blast-induced open apertures, a fault zone, and a galena vein found in association with highly decomposed materials.

Construction challenges were numerous due to the remoteness of the site. Advanced techniques such as 3D point cloud model from laser scanning of the cavern complex helped develop an authentic record of the mining heritage in parallel with the works. Comprehensive planning was important to ensure timely project delivery with helicopter-lifts as the major means of material and machinery delivery. To ensure safety during drilling works, tensioned safety nets were used to protect workers from potential rock fall. Grouting the mostly vertical rock dowels in highly jointed / fractured rock required a multi-stage approach with control of grout viscosity. Coring was utilised to reduce vibration and noise impacts to minimize disturbance to the Site of Special Scientific Interest (SSSI) bat roosts nearby. Artificial rock cladding was employed for pillar buttresses and waste rock features, together with heritage-style brown finishes for dowel heads and wire meshes. All essential elements in helping establish a balance between making "safe for purpose" without compromising the integrity of the heritage and scientific character of the site. From an industrial mining perspective, the finished cavern works resemble features commonly associated with active mine environments and some original rusted steel structures.

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1 INTRODUCTION

The revitalization for the Lin Ma Hang Lead Mine was completed and open to the public on 31 December 2024. It provides a unique demonstration of innovative geotechnical investigation and design for conservation and educational purposes. The restoration was aimed at upgrading the cavern for public access by providing a safe environment through engineering geological and geotechnical assessment. The cavern now serves as a focus to enhance the recreational value of the new Robin's Nest Country Park.

For some context, other successful cavern examples for tourism purposes in the world, include The Mammoth Cave System in Kentucky, USA (Palmer, 2016), and other karstic caves in Jenolan Caves in NSW, Vietnam and Guizhou, China. Many of the cavern examples are formed in carbonate rock due to natural dissolution of the rock with some later human influence. While for the underground city in Cappodocia in Central Anatolia of Turkey, caverns were developed in soft pumice of volcanic tuff through carving with simple hand tools (Erguvanli & Yüzer, 1978). The host rock in Lin Ma Hang Lead Mine cavern is mainly ash tuff, which shares some similarities with Cappodocia despite the mineralogical differences. The tuffs in Cappodocia, in spite of having lower UCS (5-13 MPa, vs 80 MPa in Lin Ma Hang), modelled with Finite Element Modelling (FEM) method, shows that the rock mass is self-supporting while kinematically driven rockfall risk is sufficiently mitigated by light protective measures including bolts, mesh and scaling (Sari, 2022). As with all heritage sites, protective measures need to maintain aesthetic appearance and zonation may be considered an alternative method (Tunusluoglu & Zorlu, 2008). The balance between heritage protection and geotechnical safety is paramount for such sites globally, and was a significant driver for the cavern revitalization works at Lin Ma Hang.

The Project Team was appointed by the Civil Engineering and Development Department (CEDD) of the Government of the Hong Kong Special Administrative Region (HKSAR) to provide professional services to revitalize the existing Lin Ma Hang Lead Mine cavern and turning into an open museum as proposed by the Agriculture, Fisheries and Conservation Department and complete natural terrain hazard studies to make the accessible area safer for the public. This included revitalization works for the main cavern and nearby adits, as well as provision of recreational space for scenic points, covering geotechnical, civil & structure, drainage, electrical and mechanical, landscape among other disciplines. Table 1 details the key items under the Project scope. This paper summarizes some of the challenges associated with the engineering geological and geotechnical aspects of project delivery and documents the strategies to ensure the successful completion of this unique community-based educational mining heritage project.

Table 1: Major items - Project Scope of Lin Ma Hang Lead Mine Revitalisation

Location	Typical Measures
Main Cavern	• Rock Dowels, Wire Mesh, Buttress • Additional gravel layers on cavern floor • Concrete structures covered by Artificial Rock Claddings
Adit A6B	• Shotcreting, Dentition, Wire Mesh • Additional Lighting
Slope at the Atrium	• Rock Dowels, Shotcreting, Wire Mesh
Shafts	• Fencing off with chain link fence
Scenic Point	• Viewing point with a pavilion and footpath with handrailing

2 SITE DESCRIPTION & GEOLOGY

The Lin Ma Hang Lead Mine is an abandoned mine site operated intermittently from the 1860s until 1962 (Mellor, 2021). Uncovered after the retreat of the frontier closed area in 2016, it remains an important and intact cultural heritage contributing to the mining history of Hong Kong. Galena, and the associated lead and silver, was the major targeted mineral of the mine operation (Chu & Chan, 2015;

Williams, 1991). The mine had produced an estimated 16,000 tonnes of lead metal and 360,000 ounces of silver over its life. The mineralization is associated with an NW-SE striking fissure vein deposit which dips between 15° and 60° (Davis & Snelgrove, 1956 & 1964). From an engineering geological perspective, these mineralization veins often occur along weak zones that could contribute to crown instability, posing geotechnical risks of rockfall to visitors. Therefore, unlike other underground engineering projects, the revitalization of this site requires more in-depth engineering geological understanding before analysis on the rock mass and kinematic conditions. The rock is dark grey to brownish grey, strong to moderately strong, slightly to moderately weathered, Grade II/III, coarse ash tuff, associated with localized white quartz veins up to 20-60mm thick and light grey galena occurring in patches up to 100mm in thickness (GEO, 1991; GEO, 1996; Unpublished Site Observation). Locally, a highly to moderately decomposed tuff belt striking 020-200 was observed at the crown in association with veining in the southern portion of the cavern. The rock in proximity is highly fractured moderately decomposed tuff. In general, the rock mass is PW90/100 at the crown around the cavern. Joints are persistent (up to >10m), medium- to very widely-spaced, tight to narrow with surface roughness ranging from rough undulating to slickensided planar. The joints are generally clean and occasionally stained with iron oxide. Persistent seepage and groundwater flow from the cavern crown was observed during inspections in January 2024 (dry season) which implies that infiltration along the rock mass discontinuities occurs throughout the year. It also indicates that the rock mass is likely drained with little development of water pressure.

3 PROJECT DELIVERY

The Project commenced in early 2021 with a literature review of the history of Lin Ma Hang Lead Mine, together with desk study and site reconnaissance to gain understanding of extent of development. The project team adopted various innovative approaches for site inspection and analysis. Firstly, a hand-held LiDAR scanner was used to acquire point cloud data during site reconnaissance, enabling a fast and efficient means to form models for 2D and 3D engineering geological assessments of rock pillars and cavern crown and adits (Leung et al., 2022). Preliminary kinematic assessment was also made through use of the point cloud data by CloudCompare for joint facet dip and dip orientation (Dewez et al., 2016; Idrees & Pradhan, 2018). For natural terrain hazard assessment, aerial photograph interpretation (API) integrated with digital classification of anthropogenic features was applied using ArcGIS to assess the Quasi-natural Heritage Landscape of the Lin Ma Hang Lead Mine area by utilizing territory-wide LiDAR data (Lai et al, 2012; Styles & Law, 2012; Lee et al., 2022; Wong, 2021). These approaches were implemented to overcome technical challenges due to the remote location of the mine and to ultimately accelerate the Design Stage. Construction commenced in November 2023. Scaffolding platforms erected during construction allowed closer verification of joint conditions as well as verification of rock mass classification data. Rock dowel locations and wire mesh extent inside the cavern were finalized in February 2024. Buttress extents were confirmed in August 2024 and effectively communicated with the Contractor to preserve and maintain the landscape and authenticity of the site. By November 2024, all major geotechnical items were completed. The Lin Ma Hang Lead Mine was officially opened to the public on 31 December 2024.

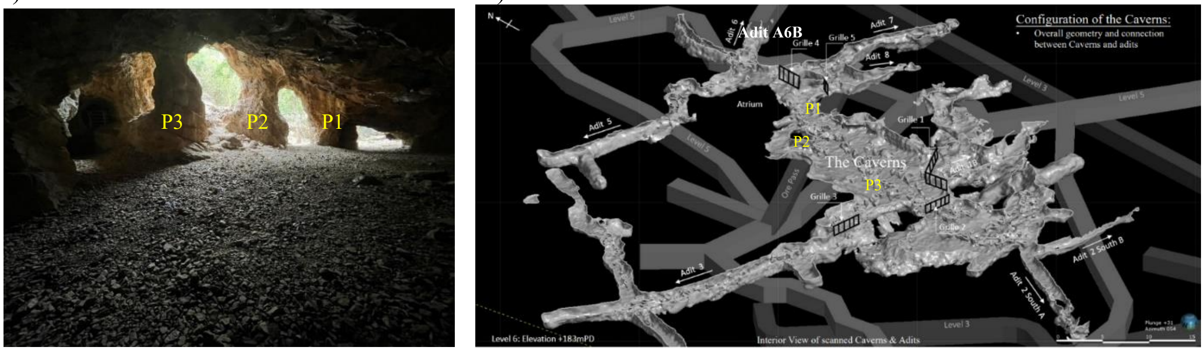
a)
b)

Figure 1: (a) The main cavern after completion; (b) 3D configuration of the cavern, atrium and Adit A6B, the main scope of the rehabilitation works - the atrium was formed during the mine operation before 1924; three major pillars in the main cavern are labelled as P1, P2 & P3.

4 DESIGN

4.1 Commitment

The team was committed to provide geotechnical design balancing safety issues and other stakeholder issues on maintaining the authenticity of the mining heritage. The design approach of the main cavern roof (Figure 1b for the configuration) was to use the room and pillar concept and rock pillar strength to model the crown stability and reduce concrete reinforcement from adversely affecting the natural heritage / appearance of the cavern. The design approach demonstrated that the dominant failure mode within the cavern was governed by structurally controlled instability due to the relatively low overburden (average 4.5m) with stress induced spalling identified as a localized risk. The overburden pressure was assumed to be distributed proportionally over the rock pillars. Figure 2 shows the main cavern during the rock dowel installation and works to the atrium.

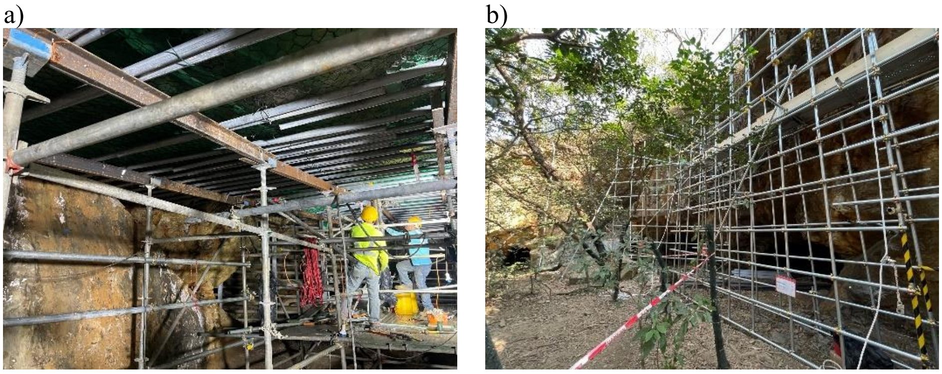

Figure 2: (a) Works in the main cavern; (b) Works in the atrium area

4.2 Technical Challenges

Two key technical challenges were encountered during design: (1) methodology for assessment with limited access to the rock face; and (2) balancing robust geotechnical works with resultant visual impact. The main cavern is about 8m high and 19m wide with limited access to rock face during initial investigations, and therefore initial assessments were from ground level. To maintain the authenticity of the mine appearance, it was decided that the site should be dealt with as a rare case with neither concrete or shotcrete lining to be utilized. Minor rock fall was considered the residual risk due to the rock mass discontinuities. Empirical and observational methods were adopted for initial rock mass assessment for tendering purposes by using the NGI Q System (NGI, 2022), with spot dowel verification during construction to cater for local instability. The innovative use of hand-held laser scanner technology was particularly well suited in capturing the geometry required for stability assessment by empirical means together with analytical methods including limit equilibrium method and kinematic analysis. A coloured point cloud model enabled better visualization of the main cavern and facilitated early development of design options for holistic stabilization measures, for example, the colour requirements for dowel heads and artificial cladding for concrete surfacing works.

4.3 Design Stage - Initial Geotechnical Assessment

i. Crown Stability

Vertical stress above the main cavern was based on average overburden of soil and rock. The ground cover ranged from 9m in the southern part of the gallery, to 4m at the rock arch entrance, implying vertical stress above the cavern between 91.25 kN/m^2 and 166 kN/m^2. This geometry was confirmed in

3D models of the surface LiDAR and the geo-rectified scanning data from inside the cavern. Given this low confining stress environment, stability issues were governed by adverse joint controlled failure or gravity driven fallout of wedges and blocks from the roof. Evidence of instability, such as roof collapse and fallen blocks were identified in some of the nearby adits but not within the main cavern.

ii. *Rock Mass Assessment – the Main Cavern*

Discontinuity mapping and rock mass survey of RMR_{89} / GSI / Q-system were completed for the main cavern roof and pillars. The four major joint sets are presented in **Table 2**. The lead mineralization containing Galena occurred in veins oriented similar to Major Joint Set J2, which gave insight on the multiple lineated ore distribution, in spite of minor striking variations in lower working levels northward to the main cavern.

Table 2: Major Joint Sets in the Main Cavern

Major Joint Set	**Manual Discontinuity Survey**	
	Dip Angle	Dip Direction
J1	43	117
J2	76	023
J3	42	044
J4	79	183

The following Q and RMR parameters are typical. (**Tables 3 & 4**)

Table 3: Q-system Rock Mass Classification - Estimated Q-value range: 0.32 – 2.67

Parameter	**Wall (East)**	**Wall (South)**	**Roof**
RQD	75	75	80
Jn	9	12	9
Jr	1.5	0.5	1.5
Ja	2	4	2
Jw	0.66	1	1
SRF	2.5	2.5	2.5
Calculated Q	1.65	0.32	2.67

Table 4: Rock Mass Rating - Estimated RMR_{89}: 58

Parameter	**Value**	**Rating**
UCS	Estimated 50 MPa	7
RQD	50 – 75%	13
Joint Spacing	0.6 – 2m	15
Joint Condition - Persistence	Most joints are 3 – 10m long	2
Joint Condition – Separation	Most joints have 1 – 5mm aperture	1
Joint Condition – Roughness	Most joints have slightly rough to smooth surface	1
Joint Condition – Infilling	Most joints are clean	6
Joint Condition – Weathering	Most joints are moderately weathered with stained surface	3
Groundwater	Damp	10

The estimated GSI range indicates the rock is moderately weathered with interlocked undisturbed blocky rock mass with two intersecting joint sets. GSI values ranging from 50 to 60 are estimated for the rock mass based on the empirical relationship between Bieniawski Rock Mass Rating (RMR89) and GSI. FEM software RS2 was used to develop a numerical model and three rows of pattern dowels were proposed based on the cavern geometry and the above parameters utilizing the Q-system for systematic support spacing.

iii. *Rock Mass Assessment – Adit A6B*

Adit A6B stability assessment was also examined by empirical Q-system rock mass quality and rock support chart. A Q-vale of 1.25 is assigned to the rock mass within the adit based on the mapped parameters shown in **Table 5**:

Table 5: Q-system Rock Mass Classification of Adit A6B

Parameter	**Value**
RQD	50
Jn	12
Jr	1.5
Ja	2
Jw	1
SRF	2.5
Calculated Q	1.25

Dentition was proposed to support a localized rock block on the western wall of the adit to mitigate risk of structural controlled minor rock block failure. For a 12m portion, 100mm shotcrete with 2 layers of A252 mesh (Figure 3) was proposed to mitigate the stress due to shallow rock cover and localized fractured rock.

Figure 3: Paving wire mesh prior to shotcreting in Adit A6B (Left);
Lighting on the shotcrete lining added after works (Right)

iv. *Pillar Stability*

Adverse joints were identified at rock pillar P1 and P3 with the risk of structurally controlled failure at these pillars necessitating stabilization measures. The fractured southern face at rock pillar P1 may undermine the remaining portion of the pillar, while open sub-horizontal joints were identified near Pillar 3 and the adjacent crown. Therefore, two concrete buttress, B1 & B2, were proposed as a measure to maintain roof stability caused by the potentially sliding rock block exerted. Checking of the buttress against sliding, overturning and bearing capacity utilized the point cloud geometric data and the results are summarized in Table 6.

Table 6: Factor-of-Safety for Concrete Buttresses

Concrete Buttress	**Sliding**		**Overturning**		**Bearing Pressure**	
	Required FoS	**Designed FoS**	**Required FoS**	**Designed FoS**	**Required FoS**	**Designed FoS**
B1 (for Pillar P1)	1.5	1.88	1.5	1.72	3	14
B2 (for Pillar P3)	1.5	4.81	1.5	1.55	3	20.69

Limit Equilibrium analysis adopted rock joint shear strength derived from Barton-Bandis empirical criteria to check structurally controlled failure induced by adverse joints at rock pillar P2 (Matin & Maybee, 2000). No stabilization works were required at this pillar. Conventional concrete surfacing of buttresses is totally different from the exposed rock in the cavern. To integrate this structure with the environment, artificial rock-like cladding was adopted to address the aesthetic requirement of mine heritage.

4.3 Design Verification

The initial geotechnical assessment was based on visual inspection during site reconnaissance and point cloud data obtained from handheld laser scanning. The permanent nature of the works and the lack of a concrete lining meant that verification of the design was required for confirmation of the geological model and groundwater conditions. The assumptions made on rock weathering grade, joint conditions, seepage and instability was reviewed and assessed. Construction commenced in November 2023, with verification works conducted in January 2024, followed by design amendments regarding localized instability identified on site. Open joints were observed during inspection at heights that were previously obscured during mapping from the cavern floor. These open joints presented potential rockfall hazards and either related to fractures resulting from blasting of the cavern during mining or stress release of the major joint sets after excavation. A locally persistent joint was observed near the southern portion of the main cavern in which no rock wall contact was recorded, and infill was >50mm in thickness. To address these issues spot dowels and wire mesh were recommended as part of design amendments to mitigate the local risk of instability.

4.4 Design Outcomes

The cavern provided unique engineering geological, geotechnical and technical challenges that were overcome through adopting innovative technology and collaborative union of all the stakeholder. The use of hand-held laser scanning was particularly useful in developing point cloud data of the geometry for analysis, accelerating the design programme and works progress, as well as providing early insight of the design from an aesthetic perspective.

5 CONSTRUCTION CHALLENGES

5.1 Logistical Difficulties

The remote and undeveloped nature of the site resulted in logistical challenges. The site is at +181mPD with access limited to a hiking trail of "998 steps" without vehicular access. This posed enormous difficulties for manual lifting methods as a means to transport material to the site. Therefore, material delivery was limited to airlift, requiring advanced planning and coordination between the site supervision team and the contractor (Figure 4).

Figure 4: Helicopter Lift in Operation

5.2 Dowel Installation in SSSI

i. Coring for Rock Dowels

The majority of the geotechnical works are confined to the main cavern and atrium area, situated in proximity to a SSSI for one of the most important bat roosts in Hong Kong (Wong et al., 2004). The Site Team planned and conducted works to minimize disturbance to bats, particularly during the breeding season, through control of work procedures and programming of work fronts. Typical coring works present noise and dust issues. Therefore, an electrical coring machine with water flushing was utilized within the operational area enclosed by tarpaulin sheeting to reduce noise reflection and spread of dust. Noise enclosure was used at the front of the coring machine to reduce dust emission. As the main cavern remained unsupported during construction, a safety net and lifting jet were deployed to prevent rock falling triggered by the coring works. Handheld tools were used to scale loose material and unstable rock fragments to reduce the risk of falls. Figure 5 illustrates the set up during the coring works.

ii. Grouting for Rock Dowels

The challenges of grouting works for rock dowels were revealed during Construction Stage due to presence of interconnected joint networks and blast-induced open apertures. Grout leakage led to requirement of more stringent grouting procedures.

Figure 5: Coring Works - Scaffolding platform with safety net to prevent rockfall

Innovative method using multi-stage grouting was preferred by first developing a grout fan above the crown, utilizing more diluted grout because of better penetration capability in the rock mass. As the cracks and joints were sealed, more viscous grout was used to fully grout the dowels. Figure 6 illustrates the setup for grouting. All the grouting works utilized the cored hole for the rock dowels and any leakage was immediately cleaned to avoid damage to the adjacent mine area. To check integrity of the grout inside the drillhole, the set up illustrated in Figure 6 was used. When the dowel was fully grouted, the grout pressure would drive the grout up along the pipe and reach the end for verification. Grouting terminated only when the inflow rate was equivalent to the outflow rate of the grout, allowing grout leakage to be checked indirectly.

Figure 6: Details of grouting works (Left); Site photos of grouting of dowels (Right)

5.3 Finishing and Landscaping for Heritage Preservation

i. Natural Finishing

From an industrial mining perspective, suitably rock coloured pigments were applied to dowel heads and PVC coating of wire meshes, so that the finish resembled original rusted steel structures consistent with the mine heritage.

ii. Artificial Rock Cladding

To integrate concrete structures within the mine context, artificial rock cladding resembling the weathered tuff was applied to the concrete surface. The cladding is cement, sand and ST-C01, mixed with water. ST-C01 is dry packed proprietary pre-mix and polymerized cementitious plaster, commonly adopted as a topcoat on relatively coarse exterior environments. Table 7 summarizes product performance from the product catalogue. Resistant to alkali and acid attack, and along with its strength performance, the cladding was as a durable material that requires reduced maintenance and routine inspection. This is a benefit given the remoteness of the site.

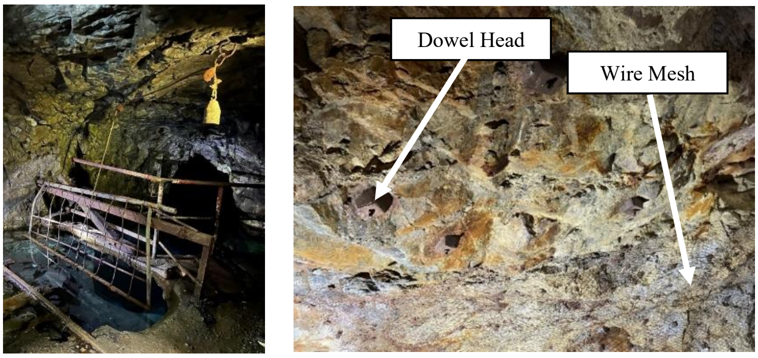

Figure 7: An example of a rusted steel structure in Ma On Shan Iron Mine (from online source) (Left); Dowel heads and wire mesh recently installed for the main cavern during the works (Right)

Table 7: Properties of ST-C01, a dry packed proprietary pre-mix and polymerized cementitious plaster

Colour	Grey/White
Density	Dry: $1650 \pm 200 kg/m^3$ Wet: $1750 \pm 200 kg/m^3$
Compressive Strength (at 28 days)	$\geq 6MPa$
Flexural Strength (at 28 days)	$\geq 3MPa$

The cladding was sculpted and coloured on site. As illustrated in Figure 8, the cladding is fixed to a steel frame and mesh. An initial scratch coat made of cement, sand and water is applied. The carve coat is established on top of the scratch coat and allows for decorative and sacrificial surfacing and can be easily profiled to achieve the required appearance. To blend in the mine heritage environment, the coat was carved to assimilate natural block shape of rock mass with joint traces, then coloured with brush, sponge and airless spray.

a) b)

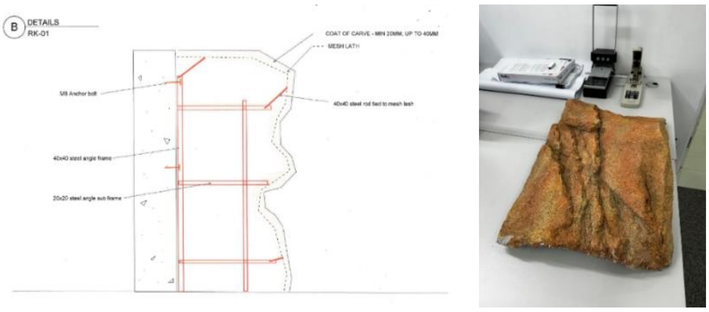

Figure 8: (a) Details of artificial rock cladding – interior consists of steel frame, with mesh lath paving as supporting material for the carving, which forms the final decorative surface covering the buttresses; (b) Sample of a piece of rock cladding

Figure 9a-9c shows a buttress before and after cladding. This is a unique example in Hong Kong demonstrating integration of mitigation measures to mimic the original landscape with a goal of heritage preservation and geotechnical safety both achieved.

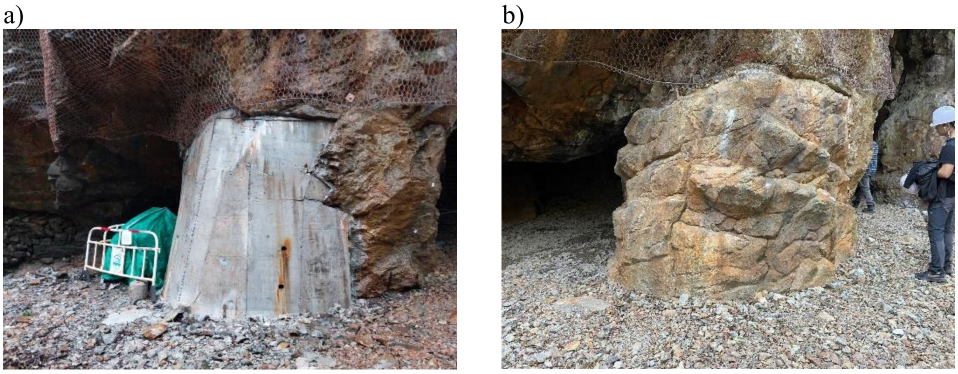
a) b)

Figure 9a: Buttress B1 - (a) before artificial rock cladding fixed on concrete surface; (b) after artificial rock cladding over concrete surface

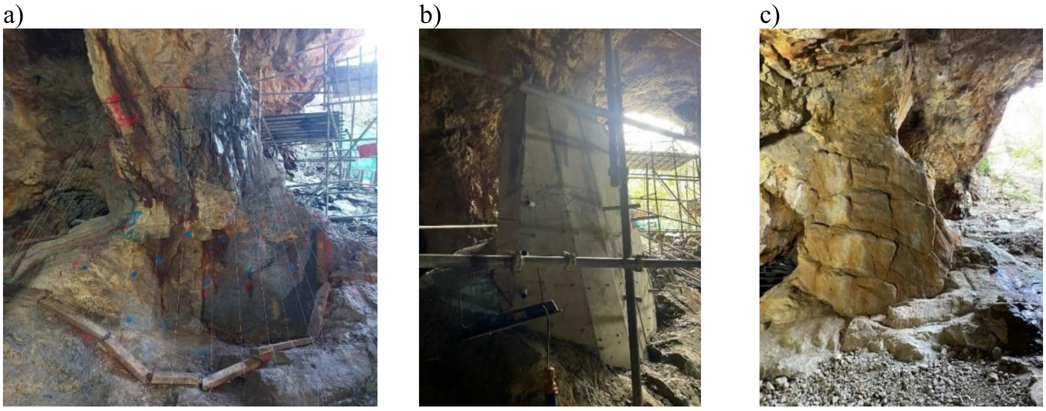
a) b) c)

Figure 9b: Buttress B2 (Pillar P3) – (a) rock spalling as recorded during setting out the buttress extent; (b) before artificial rock cladding fixed on concrete surface; (c) after artificial rock cladding

a) b)

Figure 9c: Buttress B3 - (a) before artificial rock cladding fixed on concrete surface; (b) after artificial rock cladding

iii. Preservation of Geological Features of Special Interest – Mylonite Zone

The eastern end of the atrium at the entrance to Adit A6B exhibits a unique example of a geological feature of special interest – mylonitized fault zone striking into the atrium and main cavern. Whilst it was necessary to apply some protection measures to the fault zone, the design tried to retain the unique nature of the original geological feature without full shotcreting or wire meshing that a section of the mylonitized fault breccia was preserved without facing (Figure 10a & 10b).

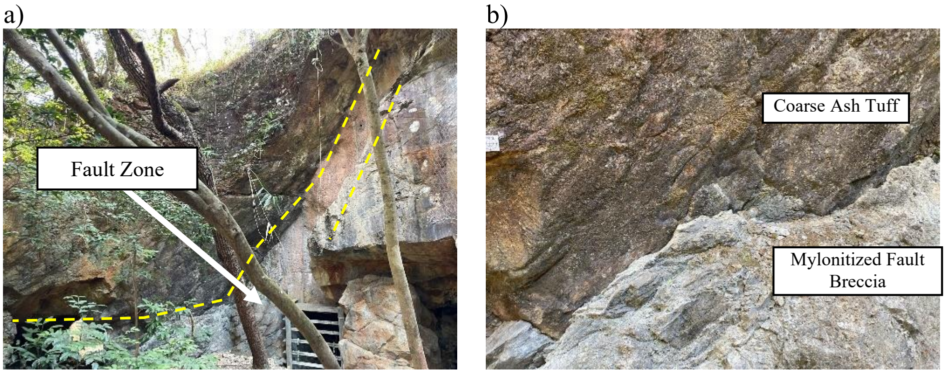

Figure 10: Geological Features of Special Interest in the atrium - (a) Fault Zone exposed in the atrium; (b) mylonitized fault breccia preserved at Entrance to Adit A6B as a geological feature of special interest showing results of crushing in a fault zone

6 CONCLUSIONS

As a community-based educational mining heritage site, it was essential to consider the final finish from the country park users' perspective. As demonstrated, a balance between preserving authenticity of the mine heritage while maintaining geotechnical safety, through utilizing analytical methods to model rock pillar strength as supporting the cavern, resulted in reduced use of concrete reinforcement.

To achieve the stakeholder shared revitalization "vision", the project team overcame various technical challenges to validate the design, including (1) methodology for assessment with limited access to the rock face; and (2) balancing robust geotechnical works with resultant visual impact. Adoption of innovative technology, such as the hand-held LiDAR scanner, was a part of achieving success in design due to the accuracy in obtaining geometry and kinematic data and ability to model. The construction team encountered multiple challenges caused by the unique nature of the site: (1) logistical difficulties in remote terrain, (2) dowel installation near SSSI, and (3) finishing and landscaping to preserve the geological and mining heritage. These challenges were addressed through efforts of site supervision team, the Contractor and other stakeholders. With the revitalization works completed and open to the public since end December 2024, we hope the experience in delivering this project will contribute valuable insight for future projects with similar sensitivity in Hong Kong and elsewhere.

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