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RESEARCH ARTICLE

GROUND SUPPORT DESIGN FOR BAN HOUAYXAI UNDERGROUND EXPLORATION DECLINE IN PEOPLE'S REPUBLIC OF LAOS

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ABSTRACT

The ground support for the Ban Houayxai exploration decline project has been thoughtfully designed, leveraging a wealth of research alongside detailed geological and geotechnical mapping of the underground conditions. While the drilled holes presented some unexpected results in the decline area, our dedicated team has made remarkable strides in collecting valuable data through meticulous underground geotechnical mapping. This essential information has positively influenced our ground support design.Recognizing the complexities of the ground conditions, we are well-equipped to enhance our systems to maintain the safety and stability of our operations. This proactive approach underscores our team's extensive experience and strong observational skills. As we progress through the exploration phase, we are committed to continuously refining our techniques, which will foster greater confidence among our stakeholders regarding the project's potential. The data we gathered will empower us to integrate numerical analysis into our planning, establishing a robust foundation for developing improved strategies and more effective ground support solutions. Our empirical research demonstrates that the safety factor for our design exceeds 1.2, ensuring that our ground support remains stable throughout the mine's operational life. This paper primarily focuses on the rock mass classification of the Q system and the rock mass rating, which are critical elements of our comprehensive analysis.

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INTRODUCTION

The Ban Houayxai (BHX) Gold-Silver Operation serves as a significant asset for PanAust Limited, an Australian company dedicated to the production of copper and gold. This operation not only enhances PanAust's strategic position within the mining sector but also fosters growth and development in the region (PanAust, 2012). Located in the Truong Son Fold Belt, approximately 25 kilometers west of PanAust's Phu Kham Copper-Gold project (as illustrated in Fig. 1), the Ban Houayxai Gold-Silver project is ideally positioned to leverage synergies between the two sites. PanAust manages a 90% stake in BHX Mining, with the Laotian government holding the remaining 10% (PanAust, 2012). This partnership and proximity to other key projects underline the importance of BHX in strengthening the mining sector in northern Laos, contributing to both local and regional economic development in Southeast Asia. The deposit is situated within an early Permian volcano-sedimentary formation, which is part of a volcanic–plutonic sequence that dates to the late Carboniferous to Early Permian period (approximately 310 to 270 million years ago) within the Truong Son Fold Belt (Tate, 2005). The significant mineralization of Gold (Au) and Silver (Ag) at BHX is characterized by hydrothermal veins and breccias linked to a mineral assemblage of carbonate–quartz–sulfides (such as pyrite, sphalerite, galena, and chalcopyrite), along with sericite, chlorite, electrum, native silver, and stephanite (Manaka, 2019). A study of how the land has changed over time shows that the gold and silver deposits at Ban Houayxai formed because of the movement of the Earth's crust (Tate, 2005). Specifically, this happened a long time ago when one piece of the ocean floor moved under another piece of land called the Indochina Terrane during the Early Permian period (Manaka, 2019). The discovery of the ancient epithermal system at Ban Houayxai highlights the significant potential of the Truong Son Fold Belt for hosting deeper magmatic-related mineralization. This region may encompass valuable resources such as porphyry systems and their associated skarn deposits (Khin Zaw et al., 2017). In a groundbreaking exploration effort between 1996 and 1997, Phu Bia Mining Ltd. successfully identified the Ban Houayxai deposit, marking a pivotal moment in mineral discovery and development in the area (Khin Zaw et al., 2007). This breakthrough followed a thorough exploration process that included regional drainage sampling of soil and rock chips and detailed testing through diamond drill hole operations (Khin Zaw et al., 2009). This meticulous approach laid the groundwork for uncovering this valuable mineral resource. Launched in 2012, the Ban Houayxai project is a shining example of a visionary mining strategy (Khin Zaw et al., 2007). It masterfully employs open-pit mining techniques to extract ore for a carbon-in-leach recovery plant with an impressive capacity of four million tonnes (Khin Zaw et al., 2009). This innovative approach achieves the project's operational goals and maximizes recovery efficiency to its fullest potential. Moreover, the BHX project exemplifies a solid commitment to excellence by adhering to the International Cyanide Management Code in every facet—transportation, utilization, and disposal—of the gold production process (Khin Zaw et al., 2007). By embracing these principles, the project is dedicated to operational excellence and environmental stewardship, inspiring a new standard in sustainable mining practices

(Khin Zaw et al., 2007). Since the North Open has become deeper, this method has become uneconomical. However, Phu Bia Mining is committed to the safe and efficient development of an underground mine, specifically utilizing an exploration decline platform that complements a robust infrastructure ((Khin Zaw et al., 2007). The decline in exploration includes a well-designed portal that provides access to underground workings and strategically placed passing and loading bays to facilitate the smooth transfer of materials. Stockpile and Cuddies will be incorporated to store mined resources temporarily, and sumps will be installed for effective underground water management. Also, refuge bays will be constructed as safe havens for emergency personnel. Many of these excavations are engineered for multiple purposes, allowing them to adapt and change in function as mining activities progress and evolve.

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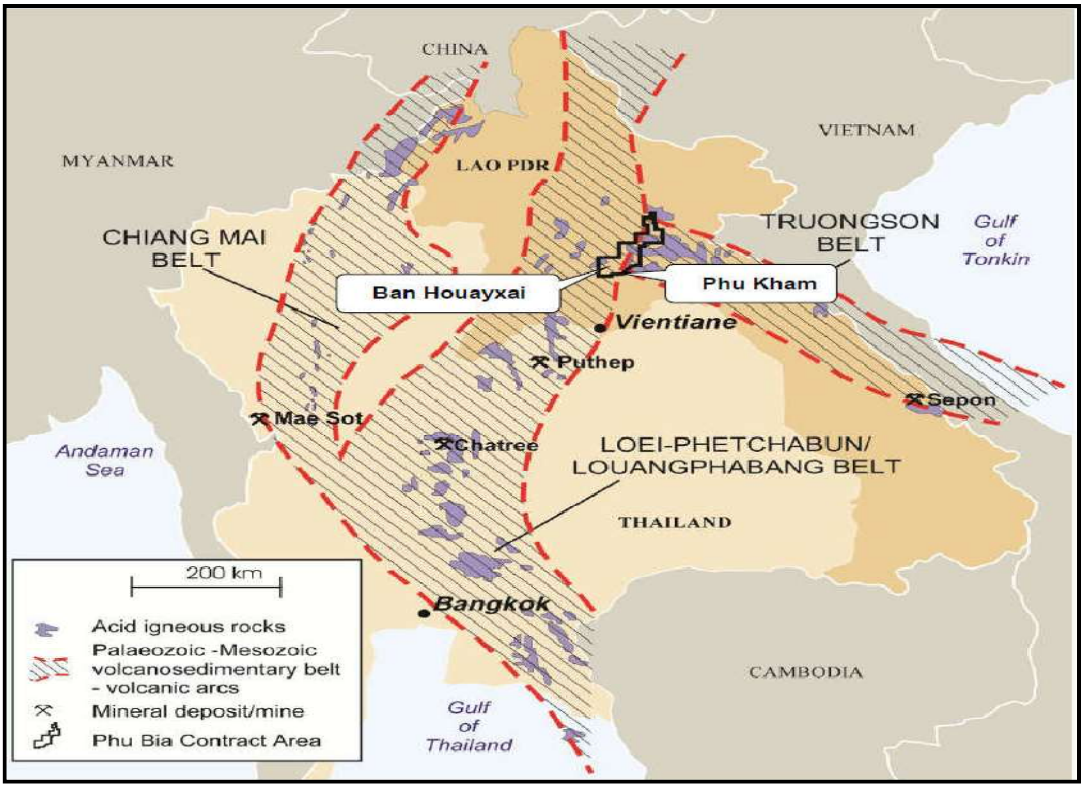

Fig. 1. Location of the Ban Houayxai projection in the Phu Bia Contract Area (Manaka, 2019)

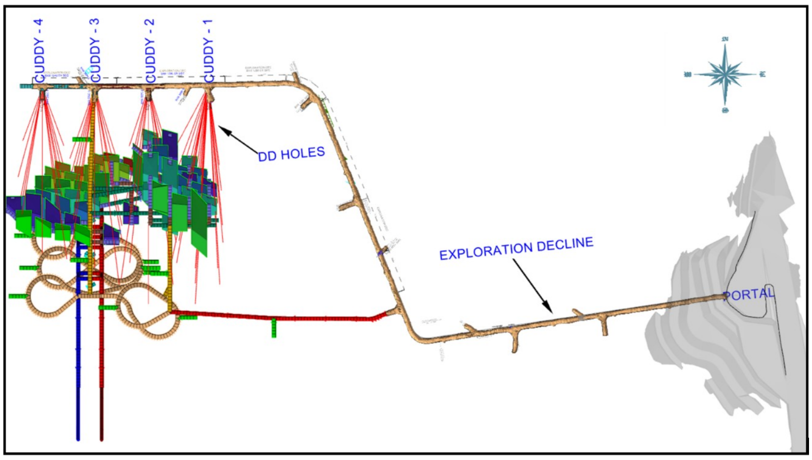

Fig. 2. BHX Underground conceptual design for the exploration decline

This breakthrough followed a thorough exploration process that included regional drainage sampling of soil and rock chips and detailed testing through diamond drill hole operations (Khin Zaw et al., 2009). This meticulous approach laid the groundwork for uncovering this valuable mineral resource. Launched in 2012, the Ban Houayxai project is a shining example of a visionary mining strategy (Khin Zaw et al., 2007). It masterfully employs open-pit mining

platform that complements a robust infrastructure ((Khin Zaw et al., 2007). The decline in exploration includes a well-designed portal that provides access to underground workings and strategically placed passing and loading bays to facilitate the smooth transfer of materials. Stockpile and Cuddies will be incorporated to store mined resources temporarily, and sumps will be installed for effective underground water management. Also, refuge bays will be constructed as safe havens for emergency personnel. Many of these excavations are engineered for multiple purposes, allowing them to adapt and change in function as mining activities progress and evolve.

BHX Underground Conceptual Design: The illustration in Figure 2 below presents an intricate conceptual plan view of the BHX underground, vividly highlighting the significant decline in exploration activities. This decline commences at the primary access portal, a vital entryway that facilitates the movement of personnel and equipment, and stretches all the way to the terminal point at the end of the underground passage. Within this strategic plan, meticulously defined operational areas known as Drill Cuddy 1, Drill Cuddy 2, Drill Cuddy 3, and Drill Cuddy 4 are prominently featured. These specialized drill cuddy areas are carefully positioned at crucial intervals along the exploration decline route, ensuring maximum efficiency in the drilling process. Each cuddy is thoughtfully designed to function as a dedicated platform for advanced drilling rigs, offering generous space for the necessary equipment and skilled personnel, thereby optimizing both safety and productivity in this critical undertaking (PanAust, 2012). The careful positioning of these drilling platforms enhances operational efficiency and improves safety by allowing for a controlled environment where all drilling activities can be conducted. This layout is crucial for maximizing productivity during the exploration phase and ensuring that all objectives are met effectively.

Borehole Logging: Some drill boreholes from the surface intercepted part of the exploration decline during surface exploration drilling. However, some of the boreholes could not intercept the decline in exploration. The logging of these boreholes was explicitly to get data for Rock Quality Designation (RQD) as shown in Fig. 3 (a) and (b), Rock Strength, Joint Spacing, Joint Condition (Aperture, infill, roughness, persistence, weathering), Groundwater and Joint Orientation. Major structures intercepted from the boreholes during the decline development of exploration were also captured during core logging, and they have been identified on the surface as major structures (faults), as shown in Fig. 4 (a) and (b). Critical geological structures were identified during the decline of exploration development, providing valuable insights for future improvements. By implementing adequate ground support measures, we can enhance the decline's stability and ensure a safer operation. Notable faults, such as Fault F2 N Lower and Fault F5 Ec, were detected through surface open pit operations, highlighting areas where we can focus our efforts for better management and safety. However, for the RQD values from the boreholes, the values intercepted were in the range of Fair to Very Good. Suggests that the rock mass in most parts of the decline is intact and sound (Fig. 4 (b)).

Underground Geotechnical Mapping: Underground mapping was carried out utilizing both scanline and window mapping techniques to ensure comprehensive data collection.

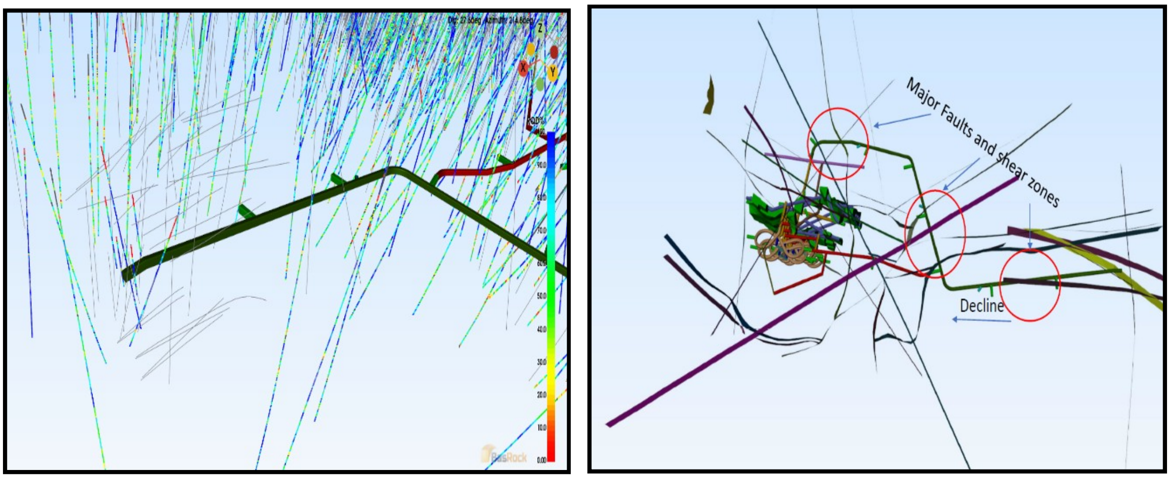

Fig. 3. Surface geological structures (a) intercepted in the borehole identified as Cent-N Pit Fault_F2 (b)

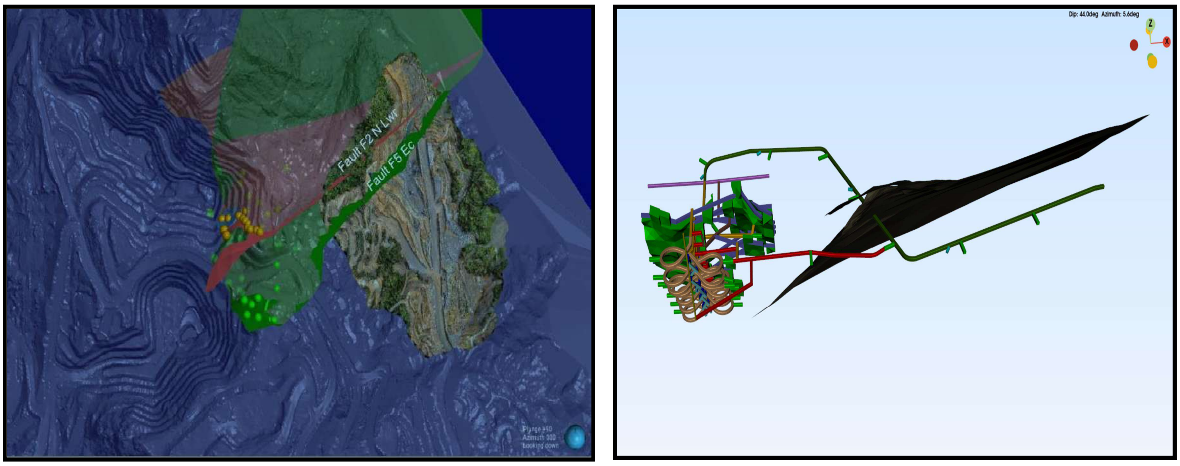

Fig. 4. Surface geological structures (a) intercepted in the borehole identified as Cent-N Pit Fault_F2 (b)

Geotechnical Data Collection: We have diligently collected geotechnical data from three reliable and reputable sources, ensuring a robust foundation for our analysis. This extensive information is vital for our project, providing critical insights that will inform and steer our decision-making process as we progress further.

As the heading advanced through the underground workings, face mapping of the decline development was meticulously conducted. This was essential for capturing critical parameters that inform excavation and ground support design (Fig. 5). During this detailed mapping process, various parameters were recorded, including Rock Quality Designation (RQD), which assesses the quality and integrity of the rock.

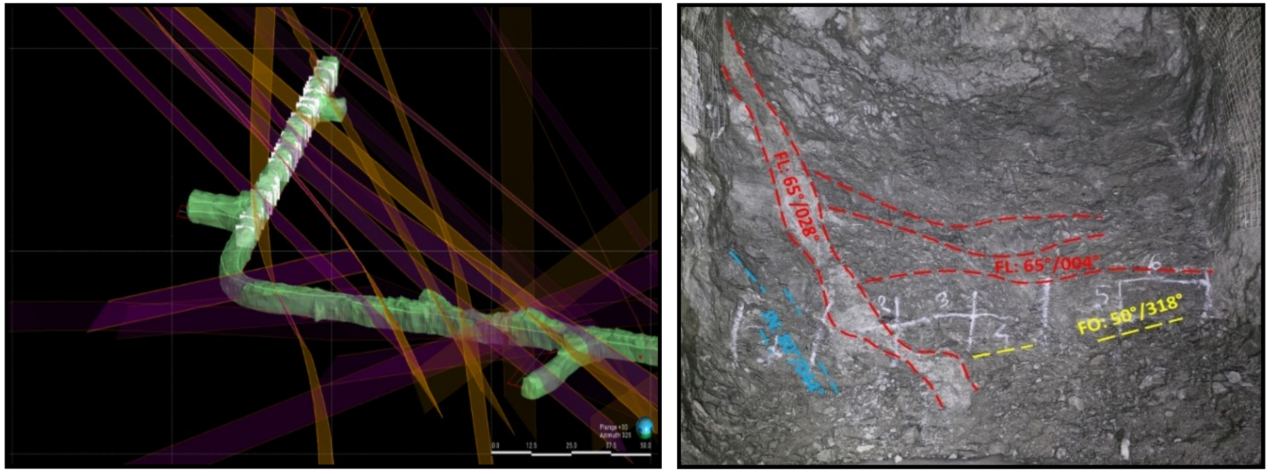

Fig. 5. Major geological structures intercepted in the decline (a) and at the face (b)

Table 1. Geotechnical face mapping important parameters captured

#	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.
Parameters	RQD	Rock hardness	Spacing jt/m	Joint Spacing (cm)	Joint Continuity (m)	Joint-Infill	Joint Alteration	Dominant Joint vs Drift	Joint-Water	Joint Roughness	Joint Set	SRF
Values	86	R 5	0.5	0.2	7.5	Serpentine	unweathered	unfavorable	dry	Undulating-rough	Two joint set plus random	Medium stress: 1

Table 2. BHX underground exploration damage mapping

Height (m)	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9
Occurrence	0	1	4	1	3	5	5	2	3	3	1	2	1	2	0	2	0	2	0	0
Actual (%)	0%	3%	11%	3%	8%	14%	14%	5%	8%	8%	3%	5%	3%	5%	0%	5%	0%	5%	0%	0%
Cum (%)	0%	3%	14%	16%	24%	38%	51%	57%	65%	73%	76%	81%	84%	89%	95%	95%	95%	100%	100%	100%

Table 3. Classification of the exploration decline according to Q-value

Domain	RQD (%)	J_n	J_r	J_a	J_w	SRF	Q-value	Comments
1. Poor	40	9	1	1.5	0.66	1	1.96	(17 - Decline)
2. Fair	70	9	1	1.5	1	1	5.23	(19% - Decline)
3. Good	95	3	1.5	1	1	1	47.50	(64% - Decline)

Measurements of rock strength were taken to evaluate its load-bearing capabilities. Joint spacing and conditions were also documented, examining critical characteristics such as aperture, infill materials, surface roughness, the persistence of the joints, and any signs of weathering (as shown in Fig. 5 and Table 1). Groundwater presence and joint orientation were other vital factors observed, providing insights into potential challenges during excavation. In addition, the mapping captured important details about the dip and dip direction of the joints, along with significant geological structures that could impact the excavation's stability. Notably, any water-logged areas encountered along the way were treated with special attention and handled separately in a designated section of the decline to mitigate potential issues related to water infiltration. This thorough approach ensured a well-informed strategy for safe excavation and robust ground support.

Underground Damage Mapping: Damage mapping was meticulously performed in the decline area, targeting both the sidewalls and the tunnel roof. The primary objective of this mapping was to accurately determine the maximum or 95% fallout height, an essential parameter in the design of support resistance systems. This measurement plays a critical role in ensuring the tunnel's structural integrity during operations. The following is a comprehensive summary of the findings from the damage mapping (Table 2).

Rock Mass Classification: In this design approach for the decline of exploration, we focus on the rock mass classifications known as the RMR (Rock Mass Rating) and the Q-system. These empirical methodologies are invaluable for categorizing the decline into various geotechnical domains, helping us understand the different characteristics and stability of the rock formations in our area of interest (Barton and Grimstad, 1996). By analyzing the data obtained from core logging and detailed mapping, we will summarize the findings for both the Q-system and RMR.

This summarized information will be crucial in designing an appropriate ground support system tailored for the exploration phase. The Drilling Cuddies are among the critical components of this design for ground support, which ensures safety and operational efficiency during the exploration process.

NGI – Q system: The Q-value is a valuable metric for assessing the stability of rock masses surrounding underground openings, particularly in jointed rock formations (Barton et al., 1996). By evaluating six key parameters, the Q-value provides insight into the rock mass quality, ranging from very poor to excellent. The Q-value is expressed in Equation (1), and the parameters used in this assessment include: -

$$Q = \frac{RQD}{J_n} \, x \, \frac{J_r}{J_a} \, x \, \frac{J_w}{SRF} \qquad (1)$$

These six parameters used in this assessment include:

RQD = Rock Quality Designation
J_n = Number of joint sets
J_r = Joint roughness number
J_a = Joint alteration number
J_w = Joint water reduction factor
SRF = Stress reduction factor

When evaluated collectively, these parameters contribute to a comprehensive understanding of the rock mass's integrity and stability, a depth of knowledge that is facilitated by the Q-value and invaluable in engineering and geological applications (Baron et al., 1996).

Rock Mass Rating : A valuable empirical relationship exists between the RMR_{89} (Rock Mass Rating) and the Q-system, which significantly streamlines the process of calculating either Q-value or RMR values. This connection is thoughtfully illustrated in Fig. 6, as outlined in the research by Potvin (1997). Their study provides compelling evidence supporting this relationship, enhancing our understanding and application in practical contexts. Furthermore, Equation (2) offers a clear formula that illustrates how to relate the Q-value to the RMR, contributing to more effective analyses in the field (Hutchinson and Diederichs, 1996).

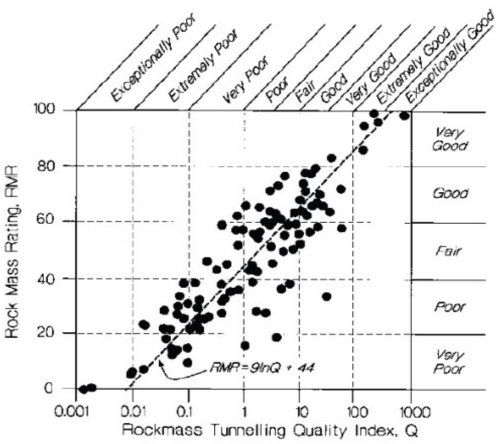

Fig. 6. Relationship between Q-value and RMR (Hutchinson & Diederichs, 1996)

Below is the expression in equation (2) relating Q-value and RMR: -

$$RMR = 9 \, In \, Q + 44 \qquad (2)$$

The ground support for the BHX exploration project is meticulously designed, drawing upon extensive research and detailed data obtained from geological maps. Although the drilled holes did not precisely target the decline area we anticipated, our team gathered a wealth of information through advanced scanning techniques and extensive mapping efforts. This information has proven instrumental in shaping our ground support design. Our support system is primarily based on the initial analysis, and our findings suggest that we may encounter various geological challenges during the project. However, we have confidence in our robust support structure, which is engineered to mitigate any issues that may arise effectively. In instances where ground conditions are suboptimal, we proactively reinforce our support systems to ensure the safety and stability of the operation. This comprehensive study relies heavily on our team's experience and keen observation skills. Nevertheless, as we continue to collect more data throughout the exploration process, we are committed to improving our techniques. With an influx of new information, we can incorporate numerical analysis into our planning, paving the way for enhanced strategies and more effective ground support solutions.

Table 4. Summary of RMR89 Values for the BHX decline

Domain	RQD (%)	UCS (MPa)	Joint Spacing (cm)	RMR_{89}-value	Comments
1. Fair	55	70	10-20	50	Fair rock mass
2. Fair	70	70	21-50	59	Fair rock mass
3. Good	90	120	>50	79	Good Rock Mass

Ground Support Designs: The empirical designs for ground support are thoughtfully developed using the Q system, which effectively addresses key factors such as ground support, stand-up time, and support density. These elements are outlined below, providing a comprehensive understanding of the approach.

Excavation Support Ratio and Q-value : The excavation support ratio (ESR) is an empirical approach Barton et al. (1996) developed for the ground support selection of the Q-value as shown in Fig. 7. From the empirical point of view, every excavation has its ESR according to its purpose. The decline in exploration, in this case, is categorized as permanent access to the mine; henceforth, the ESR for this tunnel is 1.6, according to the empirical chart (Barton et al., 1996). A lower ESR value will indicate the need for a high level of safety. In comparison, a higher ESR value means a lower level of protection that should be accepted in the design approach. Therefore, the ESR is defined in relationship with the span (or wall height) and is expressed as: -It's our responsibility to accept this and design accordingly.

$$D_e = \frac{Span \; or \; Height \; (m)}{ESR} \qquad \ldots\ldots\ldots\ldots\ldots\ldots(3)$$

Table 5. Equivalent dimension of the exploration decline

No.	Excavation	Tunnel Size or Span (m)	ESR	D_e
1).	Decline	6	1.6	3.1
2).	Sump	5	1.6	3.1
3).	Stockpile	7	1.6	4.4
4).	Cuddy	7	1.6	4.4

Following the analysis, it is essential to prioritize category 3 in our ground support design, as it addresses key structural needs effectively. Furthermore, in instances where ground conditions are exceptionally poor, we should be ready to implement the specialized strategies outlined in exceptional category 4. This proactive approach will enhance the safety and stability of our support systems under challenging conditions.

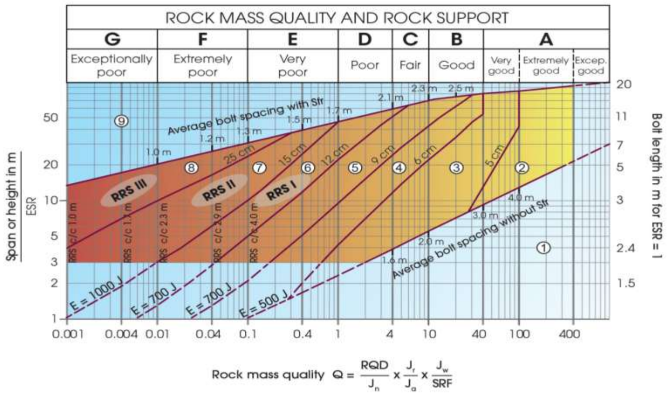

Fig. 7. Ground support estimates using equivalent dimension and Q-value after Barton and Grimstad (1996)

Table 6. Ground support estimates according to Q-value and equivalent dimension after Barton et al. (1996)

Number	Support Category
[1]	Unsupported or Spot Bolting
[2]	Spot Bolting, SB
[3]	Systematic bolting, fibre reinforce sprayed concrete, 5-6 cm, B + Sfr
[4]	Fibre reinforced sprayed concrete and bolting, 6-9 cm, Sfr (E500) + B
[5]	Fibre reinforced sprayed concrete and bolting, 9-12 cm, Sfr (E700) + B

Bolt Length of the Decline: To guarantee a robust and secure excavation for the 5.0 m x 5.0 m decline, it is essential to precisely determine the optimal length of the primary support bolts. By utilizing the formula established by Barton et al. (1996), as detailed in Equation (4) below, we can effectively assess the necessary specifications for these crucial supports. This well-researched method not only ensures the structural integrity of the excavation but also enhances safety measures, forming a critical component of our comprehensive risk management strategy. With these calculations, we can foster confidence in the stability of our excavation site and protect the integrity of the surrounding environment.

$$L = 2 + \frac{0.15\ x\ Span\ (m)}{ESR} \quad \text{……………..(4)}$$

To enhance our understanding, let's define L as the bolt length in meters. For the tunnel under consideration, which spans 5 meters, we will utilize an Excavation Support Ratio (ESR) of 1.6. This framework will help us assess structural integrity effectively. Therefore, the average estimated bolt length for the tunnel is between 2.4 mto 2.5 m.

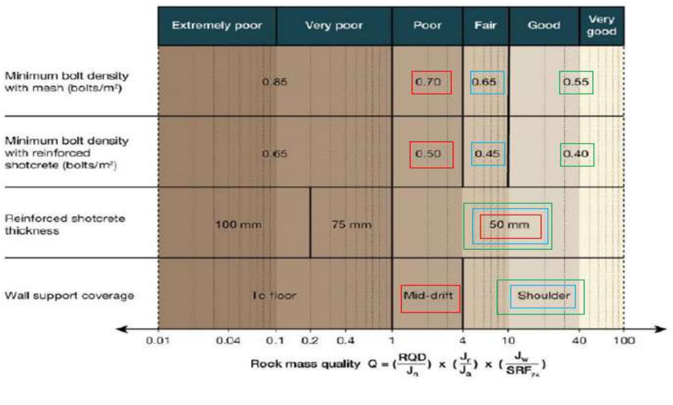

Fig. 8. Ground support estimate for the bolt density using Potvin and Hadjigeorhious (2016)

Support Density Estimates using Q-value: Support density can also be estimated using empirical, analytical, and numerical design approaches. It's worth noting that Potvin and Hadjigeorhiou (2016)'s estimate, one of the earliest adopted support density estimates, has a rich history in this field. Empirical design concept follows the support guidelines for the Q-system by considering four categories: (1) minimum bolt density with mesh, which determines the number of bolts required for a given area; (2) minimum bolt density with reinforced shotcrete, which calculates the minimum number of bolts needed for a specific area with reinforced shotcrete; (3) reinforced shotcrete thickness, which measures the thickness of the shotcrete required for support; and (4) wall support coverage, which evaluates the extent of support needed for a wall. The adaptability of support density estimate results is a key feature, allowing for adjustments according to the specific geotechnical domains as shown in Fig. 8. To provide a more precise overview, the support plots and estimates for the decline in underground exploration highlight essential results and assumptions we can use to enhance our empirical design concept moving forward by considering Potvin and Hadjigeorhiou (2016).

Table 7. Calculated bolt density based on the defined geotechnical domains

Domain	Unit	Bolt density mesh (without shotcrete)-Option 1	Bolt density (with reinforced shotcrete-50 mm)-Option 2	Wall support coverage
1). Poor	Bolts/m^2	0.75	0.50	Bolt up to mid of the drive
	(m x m)	(1.1 m x 1.1 m)	(1.4 m x 1.4 m)	
2). Fair	Bolts/m^2	0.65	0.45	Bolt up to shoulder
	(m x m)	(1.2 m x 1.2 m)	(1.5 m x 1.5 m)	
3). Good	Bolts/m^2	0.55	0.40	Bolt up to shoulder
	(m x m)	(1.3 m x 1.3 m)	(1.6 m x 1.6 m)	

Stand-Up Time Estimates: Before the need for additional support and the drilling process, the maximum allowable span for the decline face can be determined or estimated by applying the formula below (Grimstad and Barton, 1996). This calculation is essential for ensuring the stability and safety of the mine structure during operations. The expression in equation (5) is used to estimate the maximum unsupported span as follows:

$$Maximum\ unsupported\ span\ (m) = 2.0\ x\ ESR\ x\ Q^{0.4} \quad (5)$$

The logging and mapping data summary indicate that an ESR of 1.6 was selected for the calculated Q-values under poor, fair, and good rock mass conditions. This choice provides a solid foundation for understanding the corresponding maximum unsupported spans, detailed in Table 8 below. This approach will enhance our analysis and decision-making process moving forward. This is extended to Fig. 9 to determine the stand-up time for unsupported for the decline tunnel.

Table 8. Calculated maximum unsupported span

Number	Domain	Q-value	Maximum unsupported span
1	1—Poor	1.96	4.16
2	2—Fair	5.25	6.08
3	3—Good	47.50	15.04

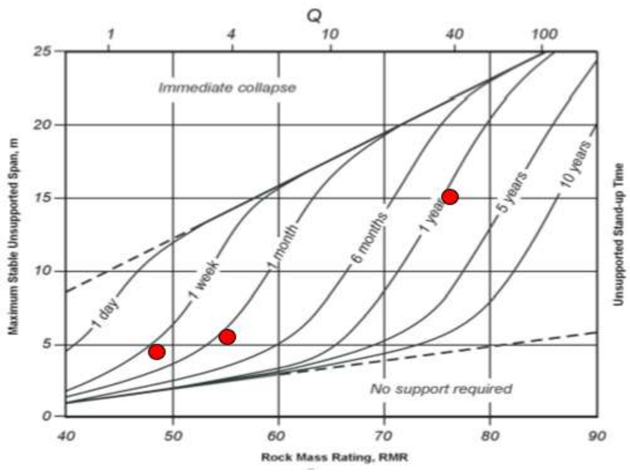

Fig. 9. Stand-up time for the maximum unsupported spans without support for poor, fair and good rock mass

Equally, the factor of safety for each unsupported span is determined empirically using Q-value and RMR. According to the results obtained for the poor zone, it is between 0.9 and 1.0, Fair rock mass is between 1.0 and 1.1, and good rock mass is between 1.1 and 1.2, respectively, as presented in Fig. 10.

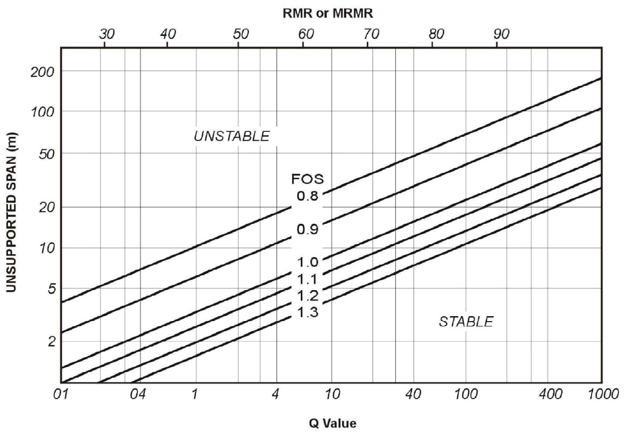

Fig. 10. Factor of Safety for each geotechnical domain for the stand-up time

Support Resistance: In addition to establishing the fallout height, the damage mapping approach was instrumental in calculating the factor of safety (FoS) for the designed bolt spacing (presented in section 3.3). By analyzing the extent and type of damage observed in the tunnel, we could make informed decisions regarding the adequacy of the support system and identify any necessary adjustments to enhance safety. Therefore, the 95% value captured in the damage mapping is at 1.68 m as shown in Fig. 11.

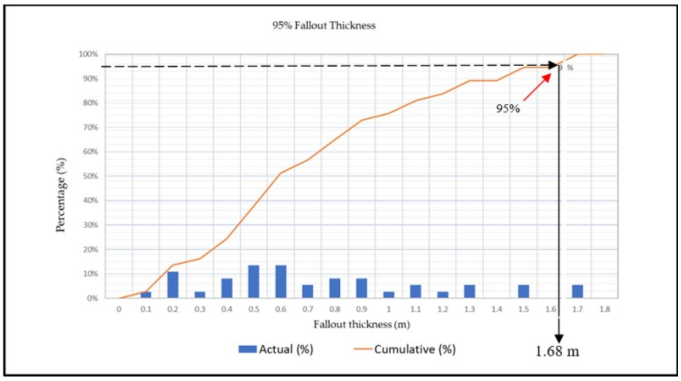

Fig. 11. Damage mapping of the decline to record a 95% fallout thickness

The process of calculating support resistance to evaluate the factor of safety for a decline involves several detailed steps. These steps are essential for ensuring structural integrity and preventing potential failures in the system. Here's a breakdown of the procedure: -

1) Step 1 is to determine the Fallout height (m)
Bolt must be at least 200 mm long than the fallout thickness.
100 mm protruding
300 mm great
1.68 m + 0.3 m = 1.98 m ≠2.0 m

2) Step 2 is to consider the Rule of Thumb (Kgm^3/)
0.33 x span or height (m)
0.33 x 5.8 m = 1.914 m ~1.9 m
1.9 m + 0.2 m = 2.1 m
Density of VLT = 2700Kg/m^3

3) Step 3 is to evaluate theCurrent Bolt Capacity
15 tonne Strength (from the pull test)
15 tonne x 9.81 m/s^2= 147.15kN
Bolt Spacing = 1.2 m x 1.3 m = 1.56 m^2/bolt

4) Step 3 is to consider the Current 2.4 m Long Bolt (kN/m^2)
Support thickness = 2.1 m (excluding 0.2 m critical bond length and 0.1 m stick out)

$$Support\ Demand = Density\ x\ Gravity\ x\ Fall\ out\ height \quad (6)$$

Support Demand = 2700 Kg/m^3 x 9.81 m/s^2 x 2.1 m = 55.62 kN/m^2

5) Step 4 is to calculate the Support Resistance (SR)

$$(SR) = \frac{Tensile\ Strength}{Tributary\ Area} = \frac{147.15kN}{1.56\ \ ^2} = 94.33kN/m^2 \quad (7)$$

6) Step 5 is to calculate the Factor of Safety

$$F.o.S = \frac{Capacity}{Demand} = \frac{94.33kN/m^2}{55.62kN/m^2} = 1.70 \quad (8)$$

7) Step 6 is to calculate Support Demand
Support Thickness = 1.68 m + 0.1 m + 0.2 m = 1.98 ~ 2.0 m(damage mapping)
Support Demand = 2.0 m x 2700 kg/m^3 x 9.81 m/s^2= 52.97 kN/m^2

8) Step 7 is to calculate the actual Factor of Safety

$$F.o.S = \frac{Capacity}{Demand} = \frac{94.33kN/m^2}{52.97kN/m^2} = 1.8$$

Table 9 below provides a comprehensive summary of the safety factors associated with bolt spacing. The calculations follow established steps, and it's important to note that the area differs depending on the specific bolting spacing employed. This clarification will help ensure accurate implementation and enhance overall safety.

Table 9. Summary of the calculated of factor of safety based on support resistance

Scenarios	Bolt Spacing	Capacity (kN/m^2)	Demand (kN/m^2)	Factor of Safety
1	1.5 m x 1.5 m	65.40	52.97	1.2
2	1.2 m x 1.3 m	94.33	52.97	1.8
3	1.1 m x 1.1 m	121.61	52.97	2.3
4	1.0 m x 1.0 m	147.15	52.97	2.8

Mode of Failure: The behavior of the rock mass in decline is characterized as isotropic and occurs under low-stress conditions, with jointed to heavily jointed features. This presents us with an opportunity for positive development. We anticipate constructive outcomes, particularly gravity wedge shakedown in the roof and sidewalls, as well as unraveling shakedown in the sidewalls (refer to Fig. 12). By gaining a deeper understanding of these mechanisms, we can create effective strategies to enhance rock stability and ensure safety in the area.

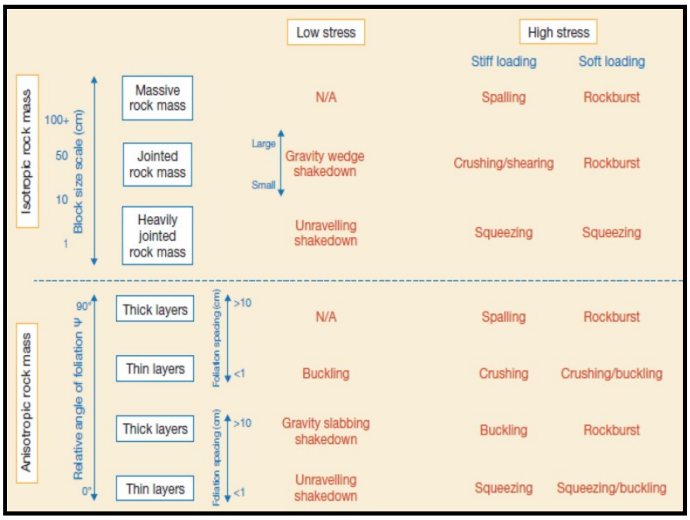

Fig. 12. Rock mass behaviour and failure mechanism matrix (after Potvin, 2017)

Intersection Cable Bolt design: Considering a safety factor of 1.5 for the solid rock mass, the analysis conducted using the parabolic equation indicates that installing just nine cable bolts is adequate to ensure stability and safety. This finding is illustrated in Figure 13, which shows the effective configuration. This approach not only meets the required safety standards but also optimizes resource use, demonstrating a careful balance between safety and efficiency (Potvin, 2017).

where: -
v = volume of the paraboloid(m^3)
d = diameter of the paraboloid (m)
h = height of paraboloid (m)
B = number of Cable Bolts required
c= Capacity of the cable bolt (t)for twin cables used at BHX Underground

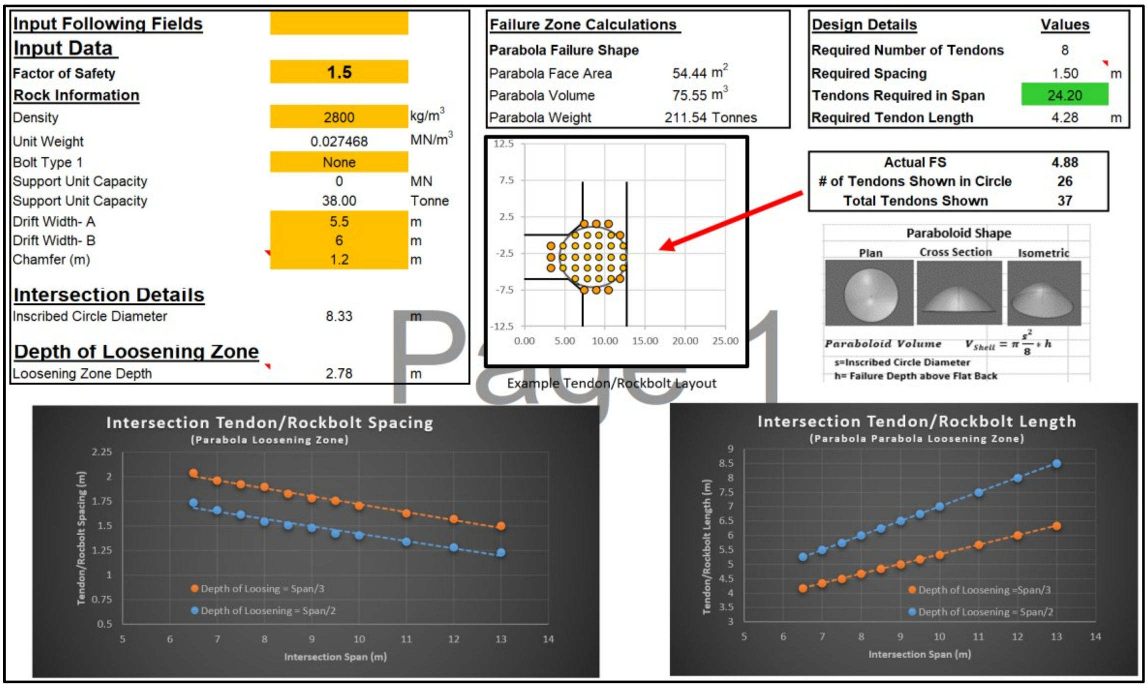

Fig. 13. Intersection Cable Bolt design for the Ban Houayxai decline

Table 10. Empirical cable bolt design using the parabolic method

#	Design	Junction	Diameter of inscribed circle	Height of paraboloid	Minimum cable bolt length	Number of cable bolts	FS limit
1).	5.0 x 5.0 m	Tee	8.3	2.8	5.1	6	4
2).	6.0 x 6.0 m	Tee	8.7	2.9	5.2	7	5
3).	5.0 x 5.0 m	Cross	10.6	3.5	5.7	13	9
4).	5.0 x 5.0 m	Elbow	7.3	2.4	4.8	4	3

The requirements for cable bolts can be effectively determined by applying the parabolic dome concept, a crucial framework in underground construction and stability analysis (Hills et al., 2015). This approach allows us to install an adequate support system that can safely withstand the weight of the rock dome situated above the intersection, thereby preventing any potential collapses (Pender and Mattner, 1963).To optimize the design of this support system, we focus on the area of the dome's base, specifically the largest circle that can be inscribed on the back wall of the intersection (Hills et al., 2015). This inscribed circle serves as a critical reference point, representing the maximum footprint for support installation. Furthermore, to enhance the stability and structural integrity of the dome, it is advisable to define its height as one-third of its diameter (Hills et al., 2015). This proportion helps balance the vertical and horizontal forces acting on the structure. The mathematical expression that characterizes this relationship and supports our calculations is as follows:

$$v = \frac{(\pi \; x \; d^3)}{24} \tag{9}$$

$$m = v \; x \; \rho \tag{10}$$

$$h = \frac{d}{3} \tag{11}$$

$$B = \left(\frac{m}{c}\right) x \; 1.5 \tag{12}$$

To effectively utilize the calculations provided, it's essential to ensure that the length of the cable bolt surpasses the height of the paraboloid by a sufficient margin for optimal anchorage. Hutchinson and Diederichs (1996) recommend incorporating an additional 2.0 meters into your measurements. They also suggest the following equation (13) to help estimate the appropriate length for the cable bolt:

$$Length = 0.7 \; x \; span^{0.7} + 2.0 \; m \tag{13}$$

This methodology has been effectively implemented in the BHX underground standard design, utilizing Garford bulb cable bolts. We ensure robust structural integrity by employing a rock mass density of 2.8 t/m³ and a factor of safety (FS) of 1.5. Table 10 illustrates the compelling results, highlighting the strength and reliability of the theoretical designs.

DISCUSSION

The geotechnical data obtained from thorough core logging and meticulous mapping has unveiled a range of significant geotechnical parameters. Notably, most decline is characterized by high-quality rock mass, reflected by a Q-value exceeding 47 and a Rock Mass Rating (RMR) greater than 70. An empirical analysis plotting the Q-value against the equivalent dimensions indicates that the appropriate ground support classifications are predominantly 3 and 4, with category 2 being a less frequent occurrence. In terms of support recommendations, the analysis advocates for implementing systematic bolting combined with the application of fibre-reinforced concrete, with a recommended thickness of between 50 and 60 millimeters. Support density calculation within most of the decline has been recorded at approximately 0.55, correlating a bolt spacing configuration of 1.3 meters by 1.3 meters. In scenarios where shotcrete is not employed, mesh is advised as an alternative. This recommendation not only enhances safety measures but also supports the mine's overall operational sustainability objectives, ensuring a reliable approach to maintaining structural integrity and worker safety. In regions characterized by competent rock formations, we will employ a safety factor of 1.5 in the design of cable bolt support systems. This approach will involve installing approximately 6 cable bolts, maintaining 2 to 3 meters spacing between each bolt. This strategy aims to maximize safety and stability within these intense rock environments. In this context, the primary expected failure mode is the gravity drive system, a mechanism frequently utilized in shallow mining operations. This system relies on the natural force of gravity to transport materials, making it critical in such environments. However, its vulnerability to failure poses significant risks that must be addressed to ensure operational safety and efficiency.

CONCLUSION

The current ground support design effectively utilizes empirical analysis based on the Q system and Rock Mass Rating (RMR) values, providing a solid understanding of geotechnical and geological conditions. To further enhance this foundation, the integration of numerical analysis in future phases presents an exciting opportunity for improvement. This addition will not only refine the design process but also significantly boost overall performance by offering deeper insights into the rock mass behavior of the decline. Embracing these advancements will lead to more effective and sustainable outcomes.

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