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The sustainability of collapse for tunnel advance excavation in the rock around the mine Tenggarong Subdistrict, Kutai Kartanegara District, east Kalimantan

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Abstract: This study aims to assess the lithological conditions and geological structures of the research area, evaluate collapse characteristics in mining excavations using the advanced tunneling method, and examine the sustainability of mining management to prevent rock collapse. Groundwater data were obtained through falling-head tests, while lithological and structural data were collected from geological mapping. Ecological, economic, social, legal–institutional, and technological data were derived from field observations and expert questionnaires. Based on Rock Mass Rating (RMR) classification, the direct roof has a score of 53.00 and the main roof 58.50. Without support, the average stand-up time for the L layer with a 4 m tunnel advance is approximately 6 days and 16 hours before collapse. The current sustainability status across five dimensions, ecological, economic, social, legal–institutional, and technological, achieved a score of 48.74%, categorized as sufficient. By improving sensitive attributes, this score could increase to 81.74%, representing good sustainability. Accordingly, this study recommends the application of appropriate tunnel support systems, particularly self-advancing supports, and targeted improvements across all sustainability dimensions to ensure safe, stable, and sustainable mining operations.
Keywords: *Multidimensional scaling, Rock collapse, Tunnel.*

1. Introduction

Surface mining is one of the mines that damages the environment, such as research from Sujiman [1] that the impact of mining on the environment around Kutai Kartanegara Regency, East Kalimantan, the Fe quality of the wastewater increased to 62.30 mg/ltr. After management, the quality decreased to 0.07 mg/ltr to 3.16 mg/ltr.

Tunnels are one option in underground mining. The design and construction of underground structures carry certain potential risks due to the nature and characteristics of rock mass behavior, its spatial variations, and technology [2]. Failure during construction can be caused by sudden changes in rock mass strength, deformation of surrounding strata, blasting, tunnel lining, groundwater, and delays in installing supports [3]. While the majority of tunnel construction projects have been carried out safely, several incidents, such as collapses, have occurred [4]. Tunnel failures and collapses can occur due to the lack of comprehensive soil investigation and analysis from a geological and geotechnical perspective before excavation [5]. Tunnel failures sometimes occur during construction or due to a lack of proper management and careless mistakes during excavation. This can cost time, money, and even result in injury and death [4, 6, 7]. Therefore, it is necessary to conduct a careful and in-depth analysis to determine the strength of the tunnel supports to avoid collapse.

Proper tunnel support construction requires considering rock properties. Investigation and analysis of rock properties can be conducted using several engineering classifications, including the rock mass rating (RMR), the rock mass quality Q-system (Q), the rock mass index (RMi), and the

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geological strength index (GSI), and others [8]. Rock mass rating is one method frequently used to determine rock properties [9-11]. Furthermore, research on the relationship between engineering geological characteristics, specifically Rock Mass Rating (RMR) and Geological Strength Index (GSI) in the Sigli–Aceh Toll Road Tunnel shows a strong correlation between these two parameters [12]. The same finding was also demonstrated by research conducted in a tunnel in Guizhou Province, China [8]. This underscores the importance of rock property assessment methods, including RMR. RMR is a classic rock mass classification method that is simple to use. The parameters used for analysis can be obtained from both borehole data and geotechnical mapping of underground structures. The rock mass classification is divided into five classes, ranging from weakest to strongest. However, in reality, the RMR rock classification value will be around the middle range [13].

The Deep Mill Level Zone (DMLZ) underground mine is located more than 1,500 meters below the surface, beneath the Deep Ore Zone (DOZ) underground mine [14]. Due to its depth, this type of mining is considered high-risk. Block caving mining is common in the DMLZ. This method involves disseminating large blocks containing valuable minerals, making it suitable for mining. Block caving is a mass mining technique in which the bottom of an ore block is excavated, allowing the overlying rock to collapse due to the structure and nature of the rock mass. Due to the risky nature of this method, a thorough drilling process is carried out before blasting. Rock samples are taken and analyzed to understand their characteristics and strength. This information is crucial for optimizing the blasting process and minimizing potential hazards [15]. A study conducted in Zambia found that the most appropriate underground mining methods, in order of suitability based on rock conditions, are vertical crater retreat, sublevel open stope, chamber and pillar, sublevel backfill, cut and fill, shrinkage stope, and finally, block caving [16].

For underground mining in areas with complex geological structures, the stope and pillar method are often applied, with standard dimensions of 6 x 5 meters and interspersed with 10-meter-thick pillars [17]. Integrating data-driven and theory-driven approaches in pillar design using the RMR classification system supports safe, sustainable, and economically viable mining operations [18].

In China, underground coal mining has caused significant land subsidence. Environmentally friendly and sustainable mining practices emphasize fully mechanized methods with post-mining backfill to minimize surface impacts [19]. East Kalimantan Province, Indonesia, has substantial coal resources estimated at 36,922.57 billion tons, with total reserves of 10,951.37 billion metric tons. This resource is planned to be mined through open-pit and underground mining methods [20]. Specifically, Tenggarong District in Kutai Kartanegara Regency has sufficient coal reserves for deep underground mining.

Understanding mine collapse is inherently interdisciplinary. Therefore, research on the environmental sustainability of underground mine collapse prevention, integrating geological, mining, social, economic, technological, and environmental perspectives, is crucial to supporting Kutai Kartanegara's long-term development as a sustainable mining region.

Deep mining is susceptible to collapse, which often results in serious accidents. Tunnel failures in rock commonly occur during construction. Therefore, the risk of failure must be minimized by implementing measures to prevent and mitigate tunnel failures and collapses from the early stages of tunnel design [21]. Furthermore, in tropical regions with unpredictable environmental conditions around tunnels, such as high rainfall, pore water pressure, and seismic activity, the vulnerability to collapse can also exacerbate the risk. Economic factors and limitations of the technology used in mining projects often limit the choice of safe and effective support methods.

2. Materials and Methods

2.1. Study Area and Data Collection

This research was conducted in the Tenggarong District, Kutai Kartanegara Regency, East Kalimantan. Lithological data were obtained from geological mapping and from core samples collected at one geotechnical drilling site using a full coring system. Each lithological layer was sampled to represent the field conditions and subsequently analyzed using uniaxial compressive strength (UCS) testing.

Groundwater data were collected through falling-head tests, while lithological and structural data were derived from geological mapping. Ecological information was obtained from field observations and expert questionnaires. Social, economic, legal, and technological data were gathered from questionnaires distributed to 11 expert respondents, who provided weighting values for each attribute across five dimensions: ecology, society, economy, legal–institutional, and technology. This study was conducted in accordance with the Declaration of Helsinki and approved by the Institutional Review Board (Ethics Committee) of the Institute of Research and Community Development, Kutai Kartanegara University.

2.2. Data Analysis

Lithological data were analyzed using tabulation and descriptive methods. Geological structures were examined using dip measurements. The collapse analysis incorporated groundwater conditions, rock compressive strength, Rock Quality Designation (RQD), fracture spacing, and fracture characteristics, assessed through the Rock Mass Rating (RMR) system. Sustainability aspects were evaluated using the Multidimensional Scaling (MDS) method.

3. Results

3.1. Stratigraphy

The stratigraphy of the study area consists of several lithological units:

3.1.1. Claystone Unit

This unit is composed of mudstone, siltstone, and shale, interbedded with coal and sandstone. The claystone is typically dark grey, of medium hardness, and occasionally carbonaceous. Mudstone, which is more abundant than other rock types, is dark to brownish grey, moderately hard, well sorted, sometimes showing cross-bedding, and relatively compact. Shale is generally dark grey, carbonaceous, and moderately hard, and is often found interbedded with coal seams (Fig. 1).

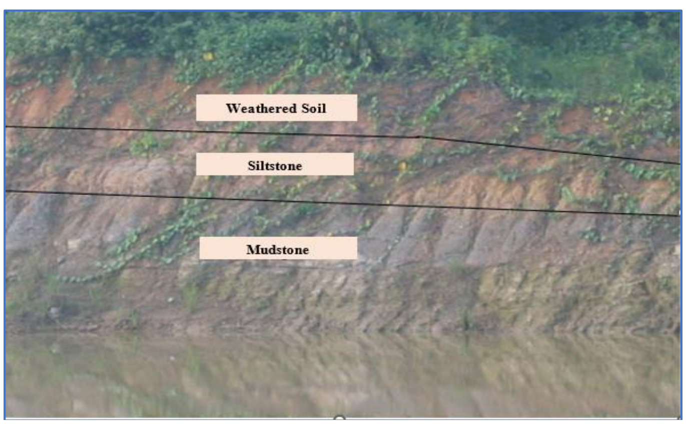

Figure 1.
The mudstone is light gray to dark gray and contains siltstone inserts.

3.1.2. Sandstone Unit

This rock unit is located in the eastern part, occupying approximately 60% of the study area. The sandstone is brownish grey, containing fragments of quartz, feldspar, mafic minerals, and heavy minerals. These fragments are angular to rounded, hard, and compact. The sandstone exhibits a cross-bedding structure, sometimes laminated. It also contains siltstone, claystone, and coal inserts (Fig. 2).

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Figure 2.
Sandstone units, which contain many joints, are exposed at the research location.

3.1.3. Siltstone Unit

The siltstone unit is characterized by grey mudstone that is well sorted, rounded, and exhibits close packing with a layered structure. It has poor porosity, is compact, and primarily composed of quartz and feldspar minerals. Groundwater is present in a moist condition. Fracture spacing ranges from 0.6 to 2 m, with rather coarse fracture conditions, apertures of less than 1 mm, and layer slopes of 0°–10°. Grain size ranges from very fine silt (1/16–1/8 mm) to clay-sized particles (<1/256 mm). This unit also includes interbedded claystone, sandstone, and coal.

3.2. Geological Structure

The dip of the syncline wing layers in this area ranges between 4° and 10° with a NE–SW orientation. Brittle structures identified in the field include shear joints, release joints, and extension joints. These structures exhibit spacing of 0.1–0.25 m, lengths of 0.85–1.2 m, and apertures of 2–4 mm. Surface roughness is fine to slightly coarse with striations of less than 5 mm. The brittle structures are generally filled with clay and display a moderate degree of weathering.

3.3. Aquifer Productivity

The study area comprises rock units with varying grain sizes, resulting in differences in porosity and groundwater content. Generally, sandstone exhibits higher porosity than siltstone, leading to variations in aquifer productivity. Two aquifer types are identified as follows. Medium-productivity aquifer – This category includes sandstone and alluvial deposits, which are widespread across the study area. These aquifers form part of a granular system where water flows through pore spaces between grains. Permeability varies, and sorting is moderate. Medium-productivity aquifers in the study area are located within weathered soil layers from 0 to 13.95 m depth (thickness: 13.95 m) and within sandstone layers at depths of 73.25–74.82 m (thickness: 1.57 m). The productivity of these aquifers is detailed in *Table 1*.

Low-productivity aquifer – This aquifer type occurs in fissured or nested systems with limited productivity. Permeability is generally very low, and shallow groundwater is only locally available in valleys or weathered zones. The associated rocks are compact and moderately hard. In the study area, low-productivity aquifers are found within siltstone layers at depths of 65.95–69.15 m (thickness: 3.20 m). Details of these aquifers are also provided in Table 1.

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Table 1.
Aquifer types in the study area.

Drill Point	Lithology type	Depth (m)	Thick (m)	Lithology description	Aquifer productivity
GT 01	Material dumping overburden	0.00 – 7.70	7.70	Overburden dumping material, mine waste material.	Medium
	weathered soil	7.70 – 13.95	6.25	weathered soil, consisting of loose material, sandstone to claystone.	Medium
	Siltstone, sandstone, and claystone	65.95 – 74.82	3.20	Dark gray color, moderately sorted, rounded closed packing, poor porosity, compact, mineral composition quartz and feldspar, fracture separation (0.6 - 2 m), fracture condition rather coarse, fracture < 1 mm, moist groundwater, layer slope 10 - 20°.	Low - medium

3.4. Rock Strength

Based on RQD, the lowest layer has poor to excellent strength, but above the coal layer, the strength ranges from good to very good and slightly poor. Subsequently, the higher the strength of the rock, the same pattern applies, namely from very poor to very good. The lithology type and RQD of the location can be seen in Table 2.

Table 2.
Lithology type and RQD of GT 01 Drilling.

Depth (m)		Thick (m)	Lithology	RQD (%)	Rock quality
Form	To				
0	17.3	17.3	Disposal, mudstone, coal	0	Very bad
17.3	37.13	19.83	Sandstone, siltstone	92-100	Very good
37.13	37.75	0.62	Siltstone, siltstone	75	Good
37.75	38.76	1.01	Coal	43	Bad
38.76	137.1	98.24	Siltstone, sandstone, claystone	95	Very good

Rock strength conditions based on the results of rock mechanics laboratory analysis, obtained specific gravity between 2.39 and 2.66. The results of direct shear test analysis of cohesion range from 0.621 to 1.369 kg/cm^2, with the inner shear angle at peak cohesion ranging from 11.56 to 22.49 degrees. The analysis of uniaxial compressive strength of the rock yielded values from 0.23 MPa to 0.54 MPa. Poisson's ratio was found to be between 0.16 and 0.22, and the elastic modulus ranged from 7.24 MPa to 35.23 MPa. The rock strength conditions at the drill points are detailed in Table 3.

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Table 3.
Lithology type and RQD of GT 01 Drilling.

No. Lab			1	2	3	4
Drill Holes			01	01	01	01
Rock sample code			R26	R29	R32	R50
WEIGHT-VOLUME CHARACTERISTICS						
Original sample weight (Wn)	gr		235.80	226.20	160.10	356.20
Dry sample weight (Wo)	gr		214.40	211.20	144.80	320.20
Saturated sample weight (Ww)	gr		252.30	239.70	171.80	377.40
Saturated sample weight suspended in water	gr		133.70	128.30	89.80	186.20
Original moisture content	W	%	9.98	7.10	10.57	11.24
Saturated water content	W	%	17.68	13.49	18.65	17.86
Specific Weight	Gs	-	2.66	2.55	2.63	2.39
Original content weight	ɣ	g/cm³	1.99	2.03	1.95	1.86
Dry weight	ɣd	g/cm³	1.81	1.90	1.77	1.67
Saturated weight	ɣsat	g/cm³	2.13	2.15	2.10	1.97
Porosity	N	%	31.95	25.58	32.93	29.92
Pore count	e	-	0.47	0.34	0.49	0.43
Saturation degree	Sr	%	56.46	52.63	56.67	62.94
Uniaxial test						
Uniaxial compressive strength		MPa	0.23	0.54	0.23	0.48
Poisson Ratio		-	0.16	0.20	0.22	0.17
Elasticity modulus		MPa	14.47	35.23	7.24	20.53
Direct shear test						
Cohesion	cr	kg/cm²	0.6217	1.3697	0.7842	0.6644
Inner shear angle	Ør	°	20.98	22.49	21.87	11.56

Characterization of coal-bearing rock layers. Rock mass characterization is the quantitative description of significant properties of rock masses for the purpose of analysis, design, and construction of an excavation in a geological medium.

3.5. Characteristics of Coal Roof and Floor Rocks

Based on the lithological study of the boreholes in this research location area, it can be seen in Table 4.

Table 4.
Direct roof rock type and main roof and floor.

Drill Holes	**Thick coal (m)**	**Main Roof**		**Immediate Roof**		**Floor**	
		Rock Name	**Thick (m)**	**Rock Name**	**Thick (m)**	**Rock Name**	**Thick (m)**
GT01	1.32	Sandstone, siltstone, claystone and coal	14.18	Claystone	5.13	Claystone	0.54

Immediate roof: The layer of rock directly above the coal seam. Main roof: The layer of rock above the immediate roof that is still affected by the buckling effect. The condition of the coal floor rock layer from the mine site is mudstone with a thickness of 0.54 meters and a percentage of 100%. The roof directly is also mudstone with a thickness of 5.13 meters and a percentage of 100%. Meanwhile, the main roof of the mining location is mudstone 9.97 meters thick with a percentage of 70.31%. Below that, there is siltstone 3.39 meters thick with a percentage of 23.91%. Below that is sandstone 0.60 meters thick with a percentage of 4.23%, and finally, there is a coal layer 0.22 meters thick with a percentage of 1.55%. The percentage of floor rock, direct roof, and main roof of the coal is shown in mining (Table 5).

Table 5.
Percentage of direct and main roof rocks in Coal Mined.

Drill Holes	Lithology Type	Coal Mined (m)			Coal Mined (%)		
		Floor	Direct Roof	Main Roof	Floor	Direct Roof	Main Roof
GT01	Claystone	0.54	5.13	9.97	100%	100%	70.31 %
	Siltstone	-	-	3.39	-	-	23.91 %
	Sandstone	-	-	0.60	-	-	4.23 %
	Coal	-	-	0.22	-	-	1.55 %
Total		0.54	5.13	14.18	100%	100%	100%

Description: Immediate roof: The layer of rock directly above the coal seam. Main Roof: The layer of rock above the immediate roof that is still affected by the buckling effect.

3.6. Geological Structure Characteristics

The structural characteristics observed and measured were length, spacing, opening width, surface roughness, fill material, and groundwater, as well as strike and dip orientation and pair continuity.

In the measurement of brinks found in the field, they generally have a direction of Southwest - Northeast, and some have a Southeast - Northwest direction, with a relatively large slope. At observation station 1 (one), located at Northing 9954718 and Easting 487233, the general position of the bridle dip direction is N216°E with a dip of 85, or N126°E/85, and a dip direction of N37°E with a dip of 89, or N307°E/89. A bridle spacing of 0.2 meters, a bridle length of 0.9 meters, and an opening width of 2 millimeters were obtained. The roughness level is rather coarse to very coarse, with a stretch smaller than 1 millimeter, composed of clay fill material, with good weathering and lithology of sandstone and siltstone. Photographs of joints in sandstone, siltstone, and claystone in the investigation area can be seen in Figure 3 and Figure 4. The results of joint measurements in the field are presented in Table 6.

Figure 3.
Brittle sandstone with spacing between 10 centimeters to 80 centimeters.

These bruises are filled with clay material, have moderate surface roughness, are under moderate weathering conditions, are paired, and have an opening width of 2-5 centimeters.

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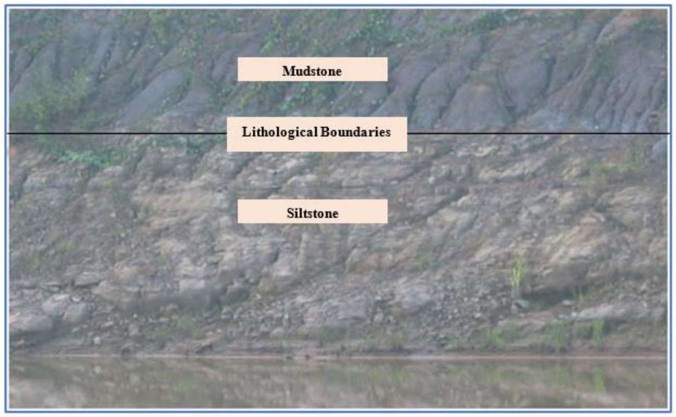

Figure 4.
Brittle siltstone, which has a spacing of 5 centimeters to 90 centimeters.

The fracture data from field measurements were then analyzed using pole net, showing that the pole projections of the data were almost all in the north and northeast, as seen in Figure 5.

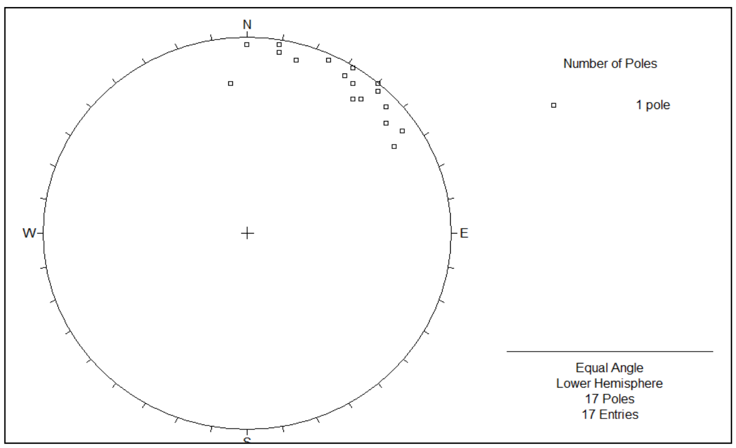

Figure 5.
The projection of the bristle pole at Northing 9954718 and Easting 487233, with the pole spreading in the Northeast.

The percentage value of the pole net of the fracture that has been measured in the field is the largest between 32% and 36%, which is around N 38° E/5°. The percentage value of the fracture pole projection at the research location can be seen in Figure 6.

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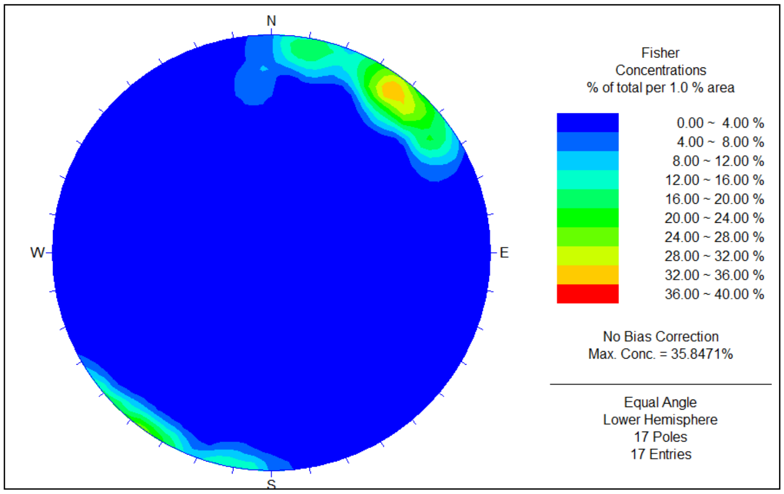

Figure 6.
The percentage value of the projection of the joint poles at Northeast 9954718 and East 487233, with concentration points in the Northeast and Southwest.

The results of the fan diagram analysis of the existing fracture measurements show that the general fracture position is N 136° E (Figure 7).

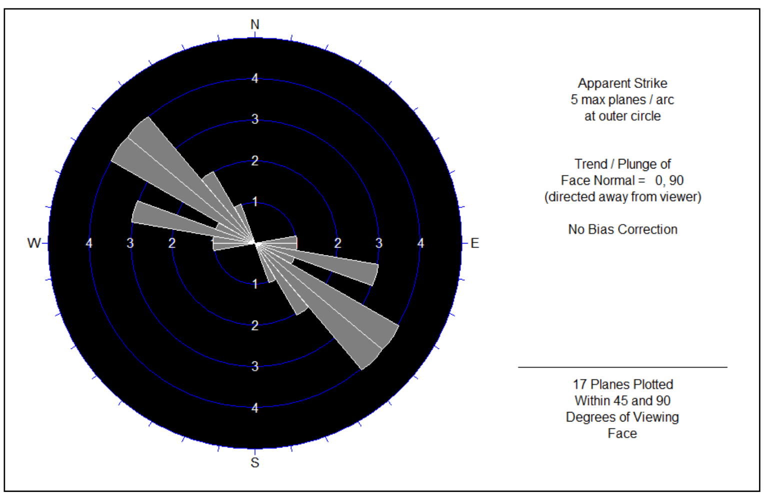

Figure 7.
Stereographic projection of alignment values from measurements of bristles at Station 1 location (one) North 9954718 and East 487233.

In general, the results of the stereographic projection of fracture measurements in the field show the fracture dip direction between N 37° E and N 216° E, with a fracture dip of 85° to 89°. The stereographic projection of the general value and fracture slope from the measurements at the research location can be seen in Figure 8.

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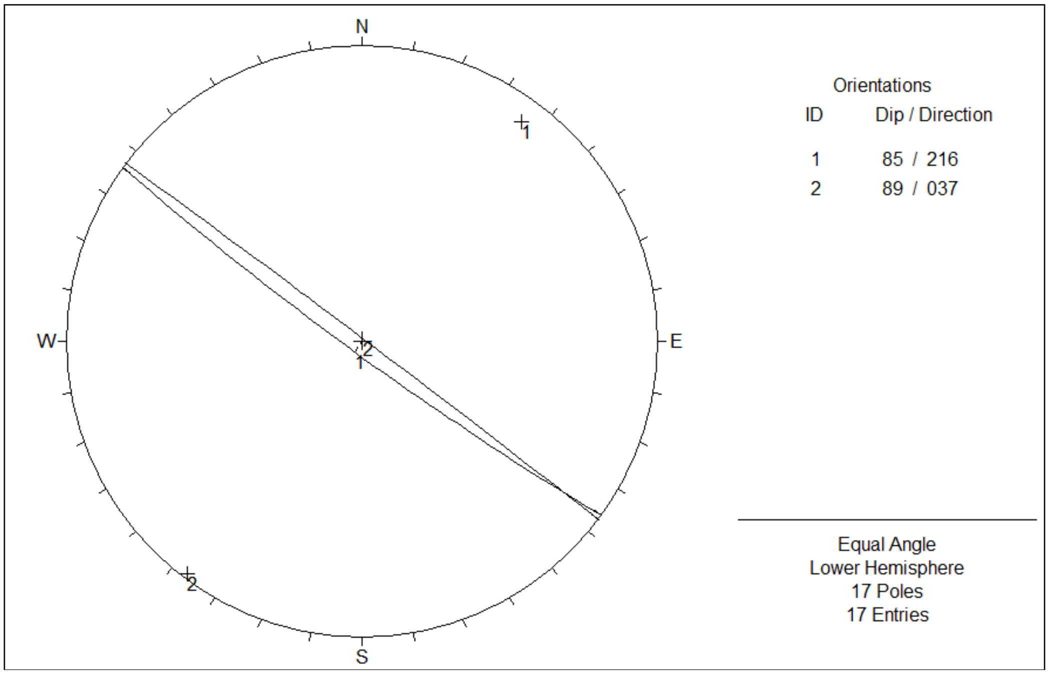

Figure 8.
Stereographic projection of generalized strike and dip values from brittle measurements at Station 1 location (one) Northing 9954718 and Easting 487233.

Table 6.
Observation of joint at ground level in the study area.

No.	Observation	Station 1	Station 2
1	General position	N 268 E / 66 N 208 E / 80	N 210 E / 76 N 270 E / 77
2	Space (m)	0.2	0.15
3	Length (m)	0.9	1.2
4	Opening width (m)	2	2
5	Roughness	Somewhat coarse to very coarse, stretch < 1 mm	Somewhat coarse to very coarse, stretch < 1 mm
6	Filler	Clay	Clay
7	Weathering	Good enough	Good enough
8	Lithology	Sandstone and siltstone	Sandstone and siltstone

3.7. Rock Mass Classification

The classification of rock masses is organized based on the Rock Mass Rating (RMR) system as follows:

Uniaxial Compressive Strength (c) rock mass classification analysis is prioritized based on the thickness of the direct roof and main roof, with a thickness of three times the collapse height. This approach is due to the safety factor at the collapse height. The results of laboratory analysis tests conducted at the research site by the Mining Department Laboratory of the Faculty of Mineral Technology indicate that all existing lithologies have strengths below 25 MPa, as shown in Table 7 and 8.

Table 7.
Compressive strength test analysis results and main roof weighting values.

No	Main Roof		Depth		Shear strength test		Compressive strength test	
Drill	Rock name	Thick (m)	from (m)	to (m)	Cohesion (kg/cm²)	Ø (..º)	Elastic Modulus (MPa)	Compressive strength (MPa)
GT 01	Claystone	1.55	129.35	130.90	0.87	26.64	-	-
	Sandstone	3.05	96.10	99.15	0.66	11.56	36.23	0.54
	Siltstone	3.05	67.05	70.10	0.62	20.98	7.24	0.23

Table 8.
Compressive strength test analysis results and direct roof weighting values.

No Drill	Main Roof		Depth		Shear strength test		Compressive strength test		Weighting Value
	Rock name	Thick (m)	from (m)	to (m)	Weighting Value	Ø (..º)	Elastic Modulus (MPa)	compressive strength (MPa)	
GT 01	Claystone	2.50	82.25	84.75	0.78	21.87	20.53	0.48	2
	Claystone	3.10	73.25	76.35	1.36	22.49	14.47	0.23	2

Rock Quality Designation (RQD)

Rock Quality Designation (RQD) can be calculated with the following formula:

$$RQD = \frac{X}{L} X\ 100\ \%$$

Description: RQD: Rock Quality Designation

X: core drill results longer than 10 centimeters

L: Overall length of core drill results.

Based on the formula above, the Rock Quality Designation (RQD) of the research area was calculated for both the main roof layer and the direct roof layer using drilling data. The results indicate that the main roof layer has an RQD ranging from 86% to 98%, which falls into the category of good rock quality, while the direct roof layer has an RQD of 57%, classified as fair to medium quality. The weighted RQD value for both the main and direct roof layers is interpreted as 13. A summary of the RQD calculations and weighted values for the study area is presented in Table 9.

Table 9.
The calculation results of rock quality designation and weighting values of the study area.

Drill holes	Coal thickness (m)	Main Roof		RQD (%)	Weighting	Immediate Roof		RQD (%)	Weighting
		Rock name	Thick (m)			Rock name	Thick (m)		
GT 01	1.32	Sandstone, siltstone, claystone	9.02	86-94	17	Claystone	5.13	57	13

3.8. Discontinuous Field Space

The results of the fracture spacing measurements for the direct roof and main roof layers at the research location are: spacing on the direct roof of 0.6 meters to 2 meters, and the main roof of between 0.05 meters to more than 2 meters. Based on the Rock Mass Rating classification, the weight value of the fracture spacing is included in the weight rating 8. The results of the measurement of the fracture structure spacing at the research location can be seen in Table 10.

Table 10.
Weighted spacing of bristle structures at the study site.

Drill holes	Main Roof		Joint Spacing(m)	Weighting	Immediate Roof		Joint Spacing (m)	Weighting
	Rock name	Thick (m)			Rock name	Thick (m)		
GT 01	Sandstone, siltstone, claystone	9.02	0.6-2	12.5	Clay-stone	5.13	0.2-2	9

3.8. Joint Spacing

A joint is a type of rock structure in the form of a fracture plane that divides the rock mass into separate blocks. These fractures serve as pathways or cavities that allow external fluids such as water, gas, and other elements to migrate through the rock. At the study site, the fractures are slightly rough with apertures of less than 1 mm. This condition corresponds to a weighting value of 20, which places it in the *moderate* category of the geomechanical rock mass classification. Details of the observed fracture conditions are presented in Table 11.

Table 11.
Observation of the fracture condition of the Study Area.

No Drill	Coal Seam	Joint Spacing	Weighting
GT 01	Main roof	Slightly rough fracture condition, strain <1 mm	20
	Intermediate roof	Slightly rough fracture condition, strain <1 mm	20

3.9. Groundwater Conditions

High-permeability rock formations facilitate the infiltration of rainwater into deeper layers. However, land-use changes such as urban development, industrial expansion, and uncontrolled logging can significantly reduce infiltration capacity, particularly in recharge zones. In the study area, groundwater conditions vary across layers. The main roof is classified as a wet aquifer, with a rating value of 7, while the direct roof above the coal seam to be mined is classified as humid, with a rating value of 10. This indicates that groundwater availability in these layers is minimal. The weighting values for groundwater conditions are presented in Table 12.

Table 12.
Groundwater conditions and weighting values of the Study Area.

No Drill	Coal Seam	Groundwater conditions	Weighting
GT 01	Main roof	Wet	7
	Intermediate roof	Moist	10

3.10. Classification of Rock Mass Condition

Based on the rock mass classification of the RMR of the research area in the coal seam, at the GT 01 drill site, the direct roof and main roof at the research site can be seen in Table 13. The results showed that the direct roof layer has an assessment weight of 53, while the main roof is worth 58.50. Both data are grouped in class III with medium rock mass.

Table 13.
Rock mass classification based on the RMR system in Kutai Kartanegara Regency at Drill Hole GT 01.

Coal Seam	Thick (m)	Weighting Based on RMR					Total	Class
		Uniaxial Strength	RQD	Fracture Spacing	Fracture Condition	Ground water	RMR	
Direct Roof	5.13	2	13	8	20	10	53.00	III
Main roof	14.18	2	17	12.5	20	7	58.50	III

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3.10.1. Average Stand Up Time

The results of determining the RMR system and the average stand-up time in the Kutai Kartanegara Regency research area were based on rock mass classification data in Table 13. The application of forward excavation of this rock may trigger roof collapse within 400 hours or 6 days, 16 hours along 4 meters (Figure 9).

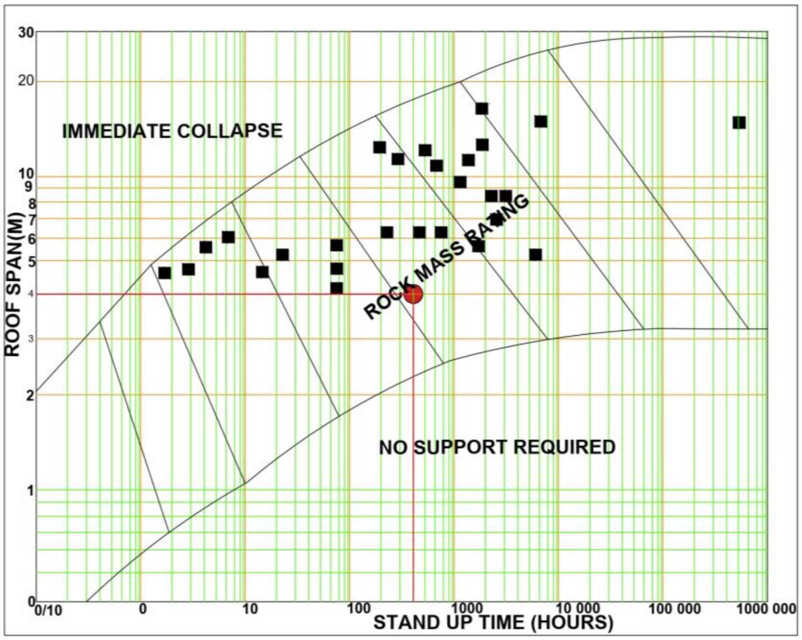

Figure 9.
Determination of the average stand-up time in the area around the study site. If the excavation is advanced by 4 meters and no support is provided, it will collapse in 6 days and 16 hours.

3.11. Sustainability of Deep Mine Fills Environment
3.11.1. Ecological Dimension

Ecological Dimension. The sustainability level of the ecological dimension is influenced by 13 key attributes, namely: 1) brittleness of the rock mass, 2) joint condition, 3) surface water conditions above the underground mine, 4) geohydrological conditions in deep mines, 5) spring conditions within underground mines, 6) surface vegetation cover, 7) rock cohesion around the underground mine, 8) ground surface conditions, 9) occurrence of collapses in the underground mine, 10) roof rock strength, 11) roof rock loading conditions, 12) fault spacing, and the condition of the mined coal. These attributes are illustrated in Figures 10 and 11.

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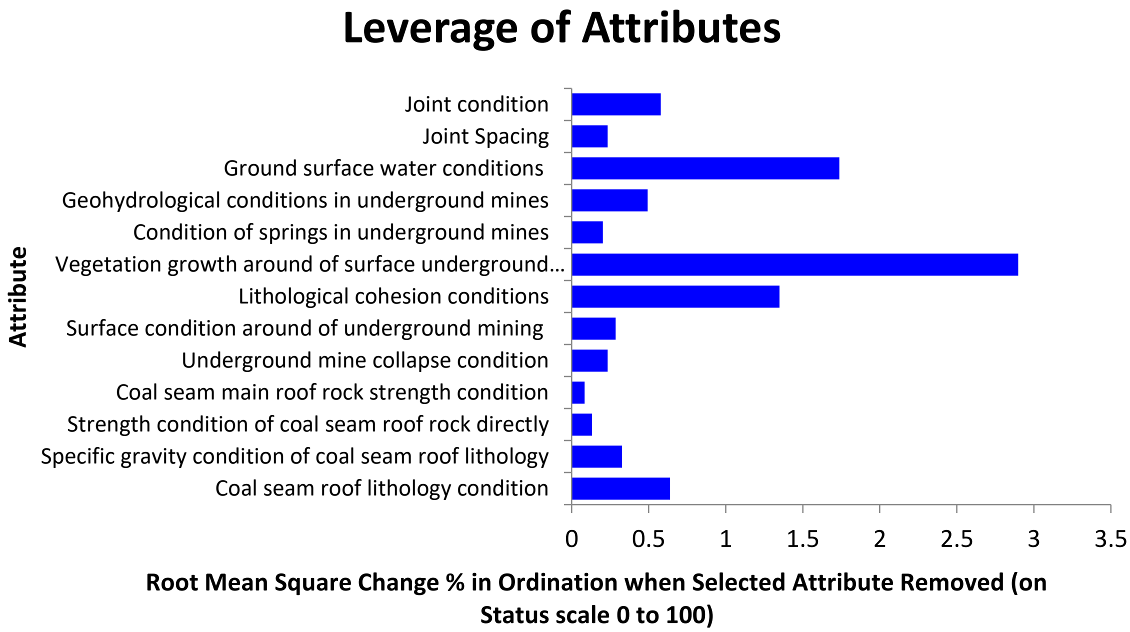

Figure 10.
Leverage Attributes of Ecological Dimensions of Underground Mine Avalanches at the Study Site.

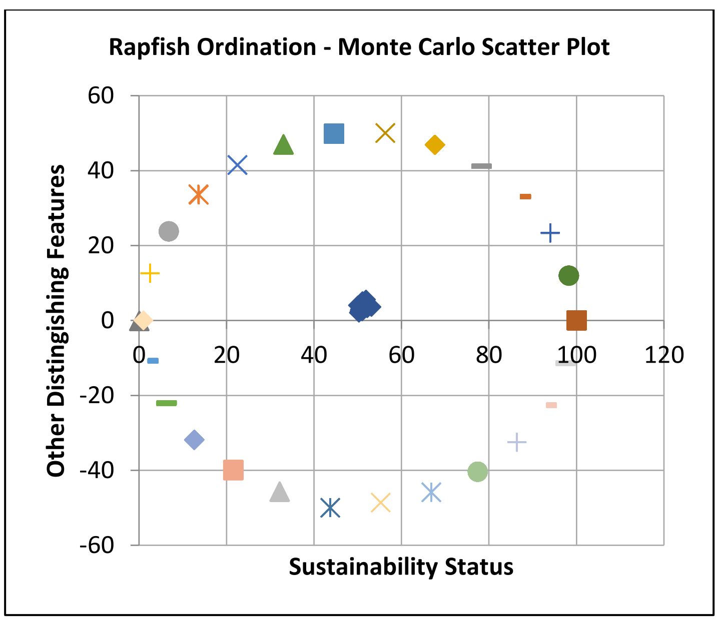

Figure 11.
The Sustainability Index of the Ecological Dimension of the Current Mine at the Re-search Site is 47.78%.

Based on the analysis results from MDS, the ecological sustainability index is 47.78%, indicating a moderately sustainable index.

3.11.2. Economic Dimension

The economic dimensions used for leverage are: 1) Employment rate for underground mining, 2) Increased local revenue from underground mining, 3) SME business of local residents from underground mining, 4) GRDP (Gross Regional Domestic Product) from underground mining, 5) Residents' income from underground mining, 6) Village institutional income from underground mining. The leverage index of the sustainability of the economic dimension of underground mining in the research area is shown in Figures 12 and 13.

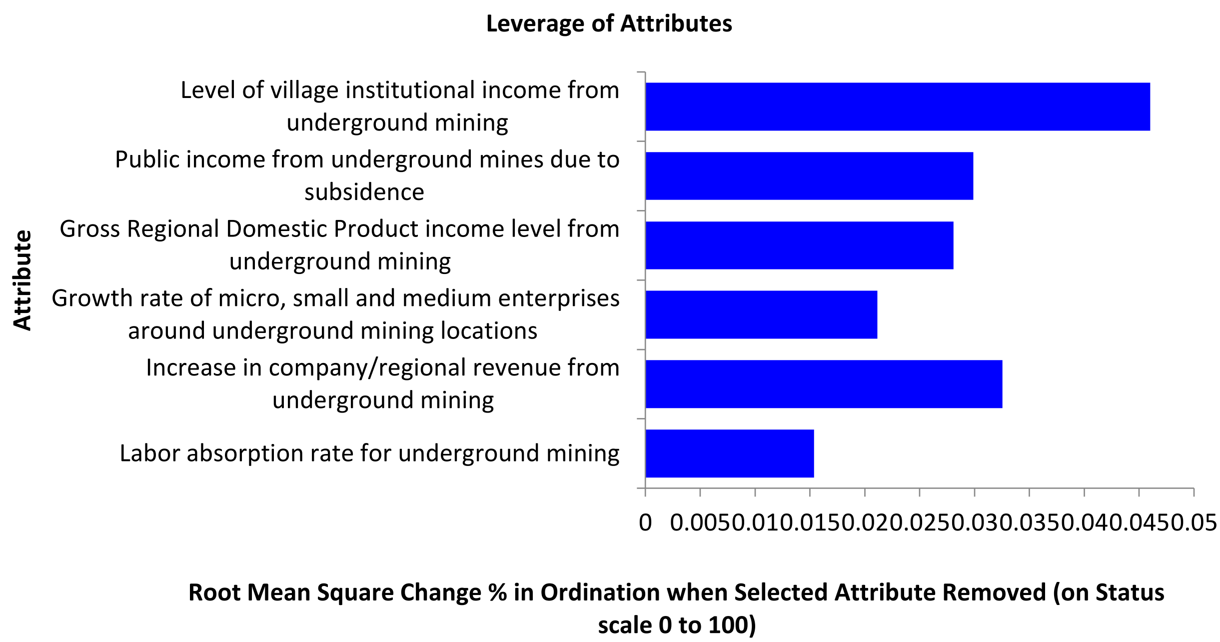

Figure 12.
Leverage Attributes of the Economic Dimension of Underground Mine Avalanches at the Study Site.

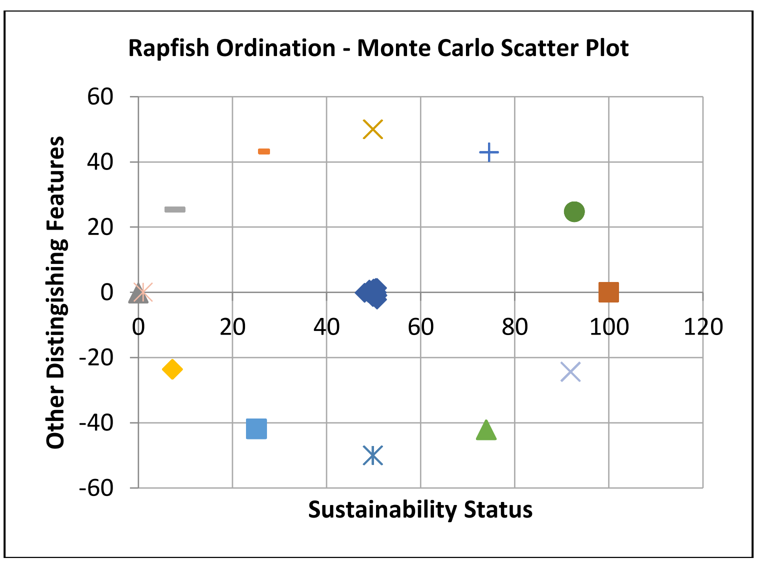

Figure 13.
The Sustainability Index of the Economic Dimension of the Current Underground Mine Avalanche is 50.36 %.

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3.11.3. Social Dimensions

The social dimensions that influence the level of sustainability are: 1) the relationship between underground mining companies and residents around the mine site, 2) the role of community leaders regarding underground mine collapse, 3) community knowledge of underground mining, 4) the influence of underground mine collapse on social aspects, 5) the availability of NGOs at the underground mine site, 6) community perception of the presence of underground mine collapse, 7) NGO supervision if there is an underground mine collapse, 8) the role of stakeholders in underground mine collapse, 9) the role of company leaders in underground mine collapse, as shown in Figures 14 and 15.

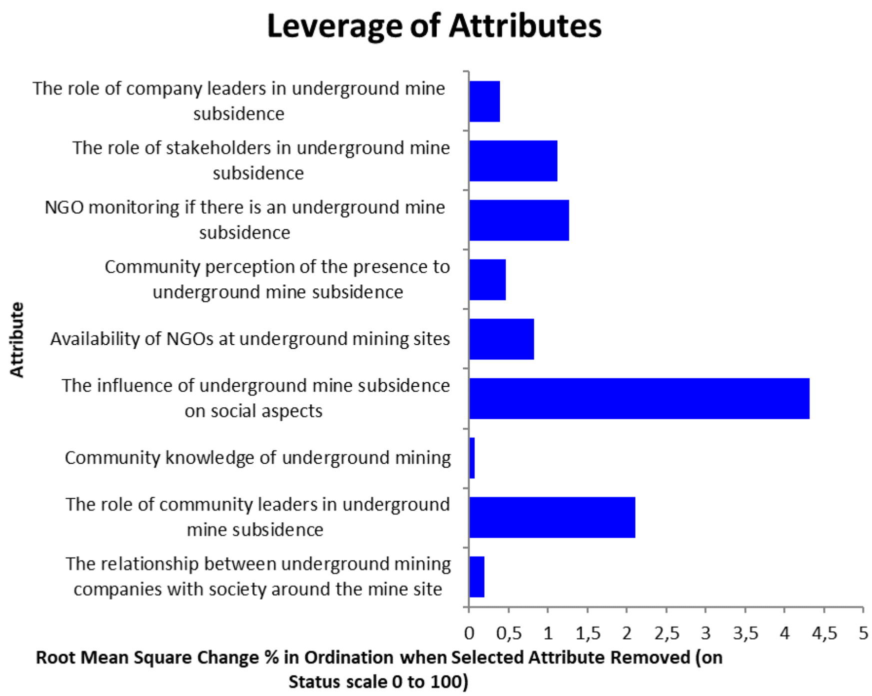

Figure 14.
Leverage of Social Dimension Attributes of Underground Mine Fills in the Study Area.

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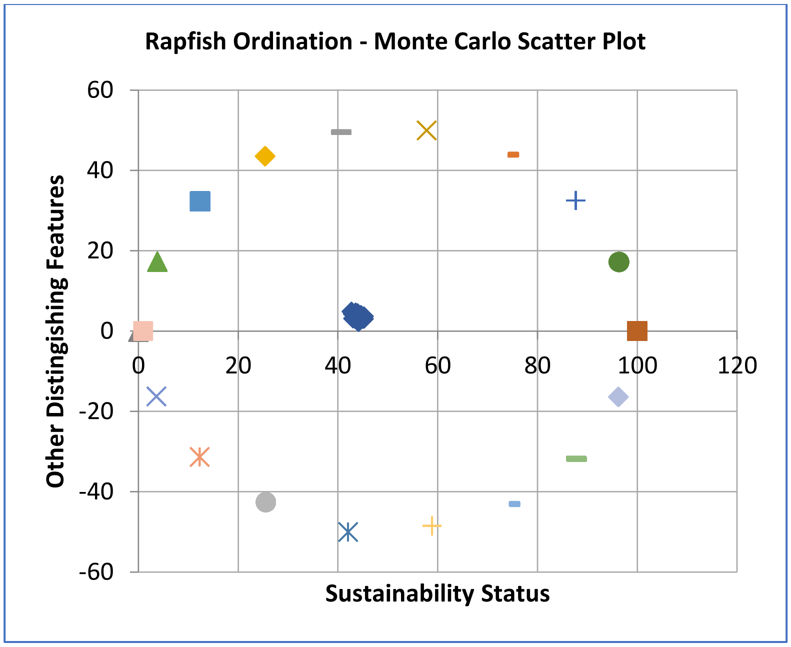

Figure 15.
The Sustainability Index of the Current Underground Mine Collapse in the Social Dimension Research Area is 41.02 %.

3.11.4. The legal and institutional dimensions

The legal and institutional dimensions that can influence the level of sustainability are as follows: 1) The existence of regulations concerning underground mine collapses, 2) The concern of legal personnel regarding underground mine collapses, 3) The compliance of underground coal mining entrepreneurs with applicable laws, 4) The efforts of legal personnel to socialize information about underground mine collapses to the public, 5) The presence of a legal supervisory department overseeing underground mine collapses, 6) The enforcement of laws related to underground mine collapses, 7) The adherence to safety conditions in underground mining operations, 8) The awareness of stakeholders in monitoring underground mine collapses, 9) The utilization of digital tools in monitoring underground mine collapses, 10) The supervision by government agencies in monitoring mine collapses, 11) The existence of local legal institutions involved in underground mine collapse cases, 12) The responsibility of mine owners in cases of underground mine collapses, as shown in Figures 16 and 17.

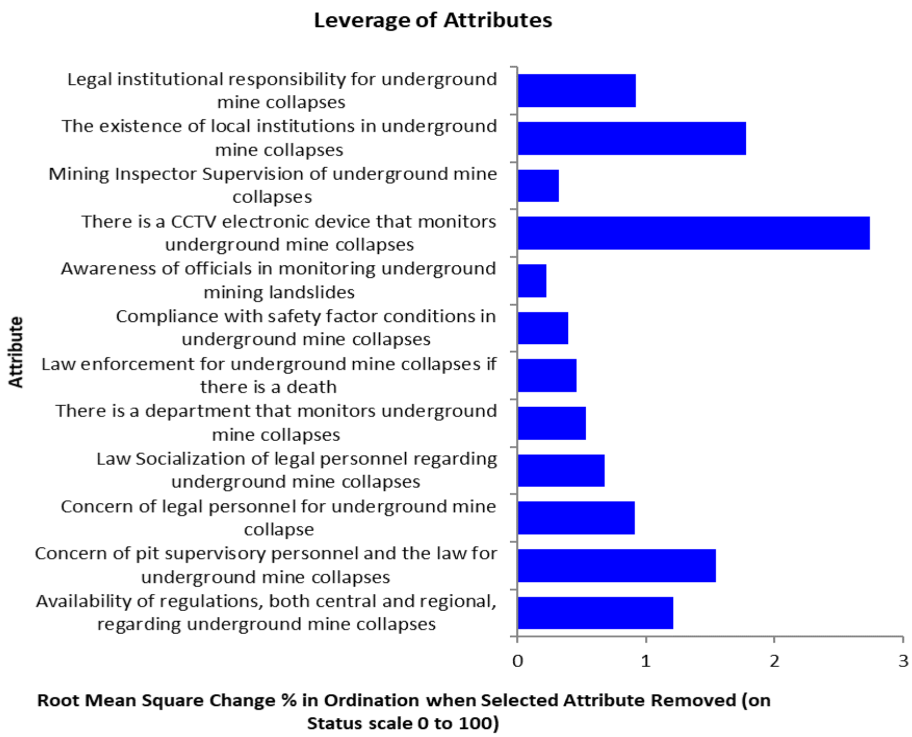

Figure 16.
Leverage of Legal and Institutional Dimensions of Underground Mine Fills at Research Sites.

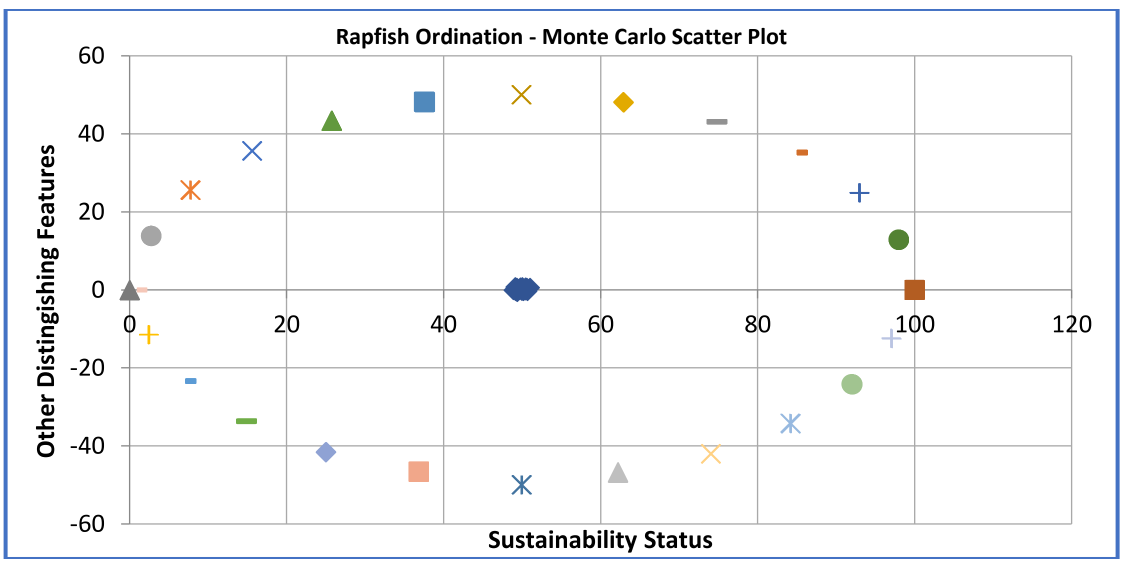

Figure 17.
The Sustainability Index of the Legal and Institutional Dimensions of Underground Mining Ambush at the Research Site is 49.85 %.

3.11.5. The Technology dimension

The Technology dimension that can influence the level of sustainability has 8 attributes, namely:

1) Calculation of underground mine collapse determination, 2) The existence of maintenance in the event of an underground mine collapse, 3) The existence of monitoring technology in the event of an underground mine collapse, 4) The strength of underground mine support, 5) Underground mine water pumping technology, 6) Water handling technology at the mine site, 7) Mastery of deep mine collapse technology, 8) Existence of technology in repairing the site in case of underground mine collapse, as shown in Figures 18 and 19.

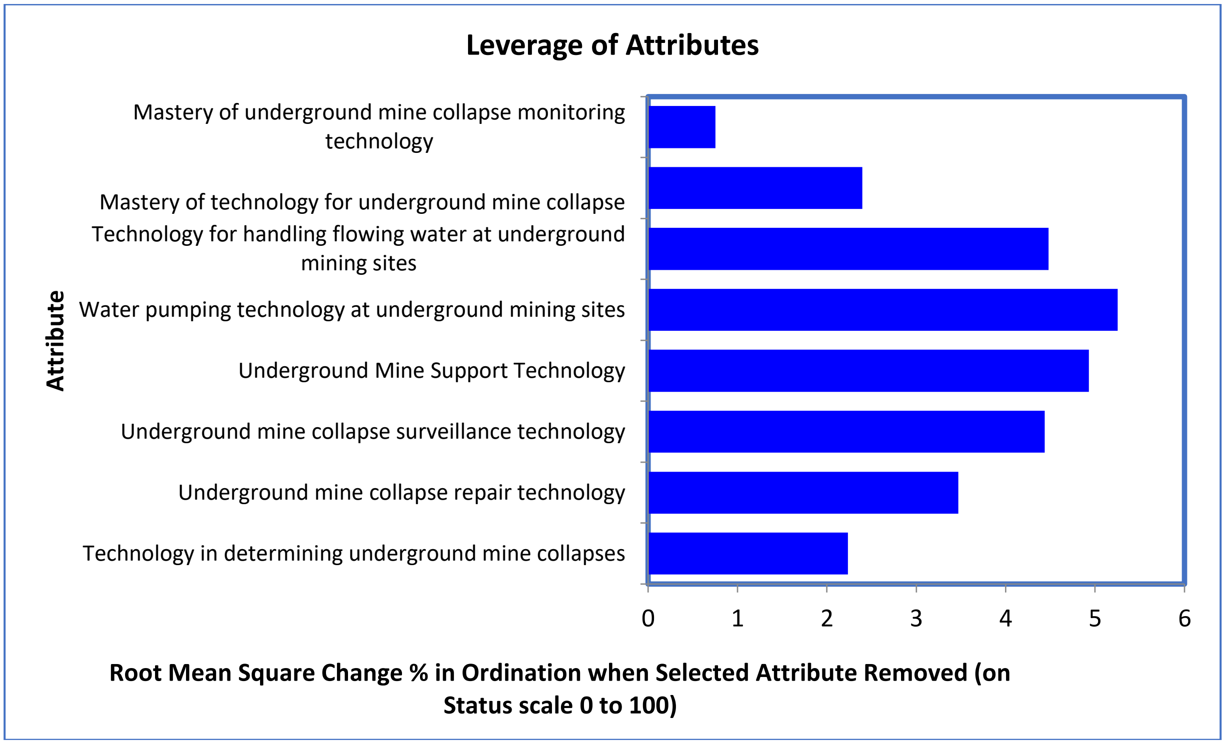

Figure 18.
Leverage of Technological and Institutional Dimensions of Underground Mine Fills at Research Sites.

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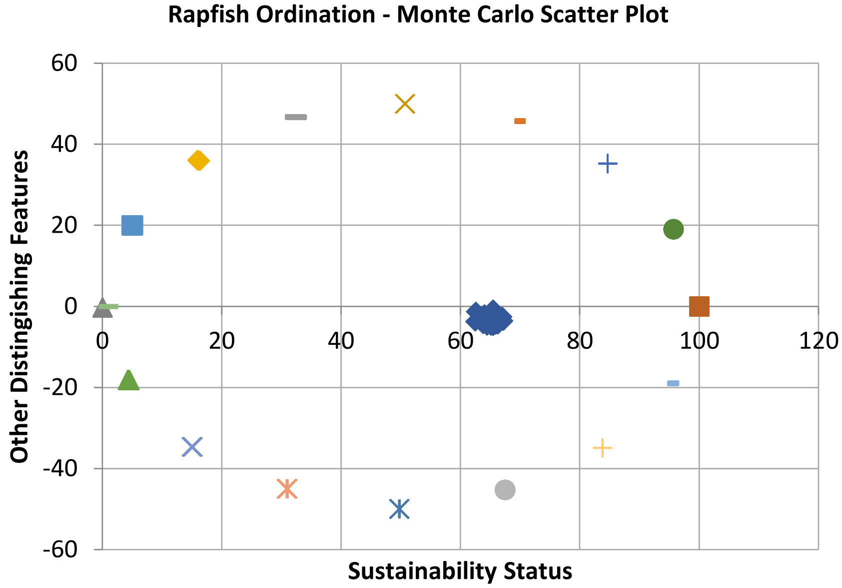

Figure 19.
The Sustainability Index of the current condition of the underground mine spoil at the research site in the technological and institutional dimension is 52.55%.

3.11.6. Current Status of Multidimensional Sustainability

The results of the analysis of the multidimensional sustainability of underground mining collapses in Kutai Kartanegara Regency in the current condition indicate a sustainability index value of 48.74%, which is classified as sufficient. This value is derived from the assessment of five dimensions. The results of the multidimensional scaling analysis of the sustainability of underground mine collapses in Kutai Kartanegara Regency can be seen in Figure 20.

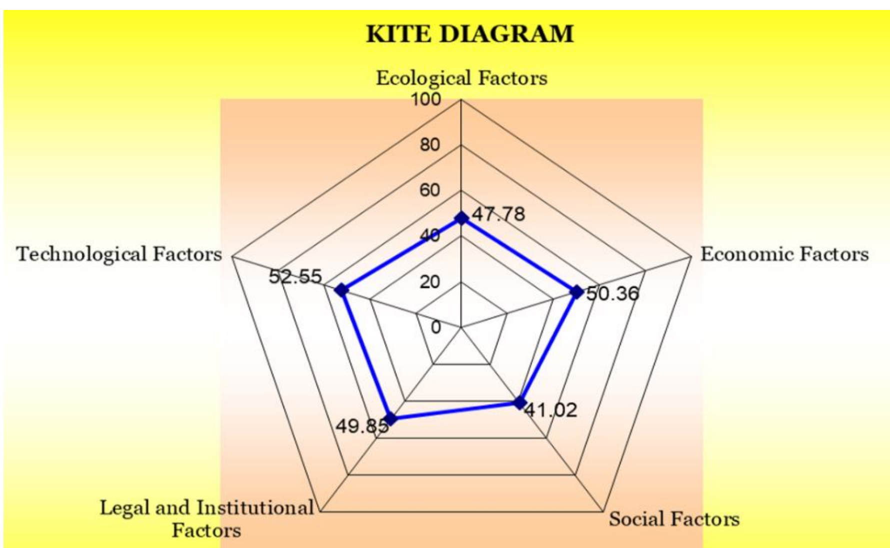

Figure 20.
Kite diagram of the sustainability status of the present condition underground mine collapse in the Kutai Kartanegara district.

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3.11.7. Multidimensional Sustainability Status Future Mass Expectations

The expected sustainability status is to make modest improvements to the attributes of the five sensitive dimensions in order to become better. The results of the multidimensional analysis of the sustainability of underground mine collapses, based on future mass expectations in the Kutai Kartanegara district, amounted to 81.74%, which indicates good sustainability. This can be seen in Figure 21.

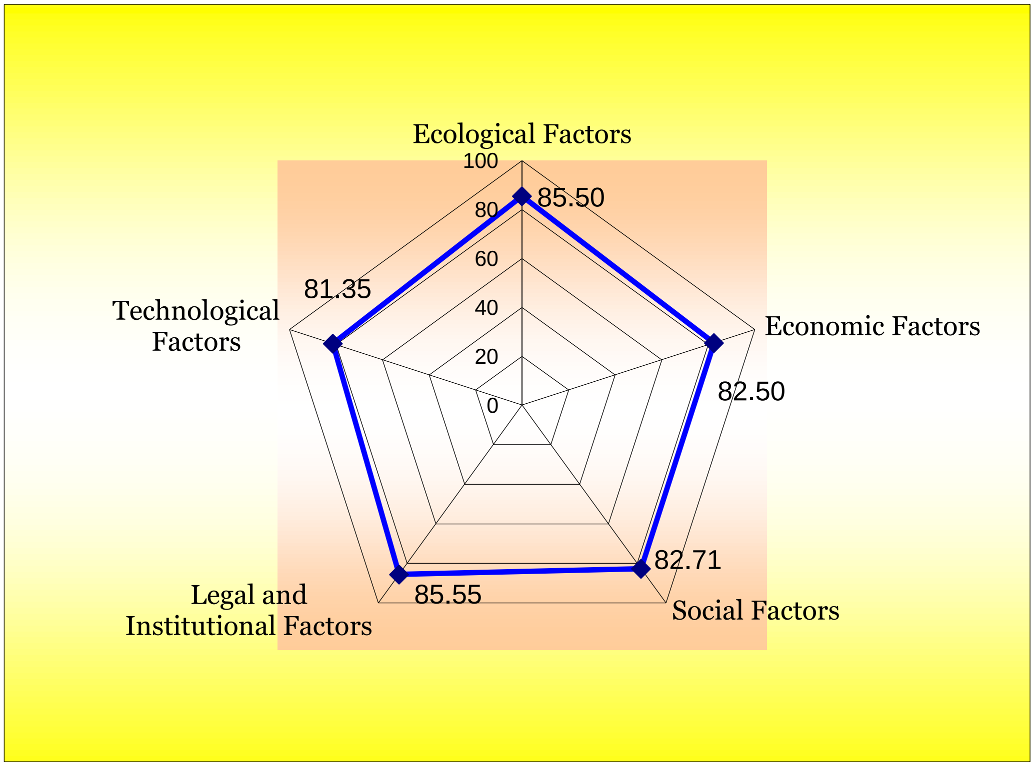

Figure 21.
Kite diagram of the sustainability status of mine avalanche front mass expectation in the future mass in the Kutai Kartanegara district.

The current status of multidimensional sustainability of underground mine collapse in Kutai Kartanegara Regency is 48.74%, indicating a sufficient status. The current condition can be improved to achieve stability in underground mine collapse. The ecological dimension includes 9 sensitive attributes; the economic dimension comprises 6 attributes; the social dimension has 6 attributes; the legal and institutional dimension contains 9 attributes; and the technological dimension consists of 5 attributes. As a result of the multidimensional analysis, the overall sustainability of underground mine collapses in Kutai Kartanegara Regency is 81.74%, which indicates good sustainability.

4. Discussion

This study indicates that the lithological sequence in the research area, from oldest to youngest, comprises a claystone unit, sandstone unit, siltstone unit, and alluvial deposits. The general fracture orientation is N216°E/85° or N126°E/85°, and N37°E/89° or N307°E/89°, with additional fractures dipping N183°E/84° or N93°E/84°. Fracture spacing ranges from 0.15 to 2 m, lengths from 0.9 to 1.2 m, and apertures from 2 to 5 mm. The fractures are rather coarse to very coarse, filled with clay minerals, and show moderate weathering.

Claystone, sandstone, and siltstone are sedimentary rocks of medium to high hardness, typically breakable with a geological hammer. Coal in the study area is of medium hardness but highly fractured, making it brittle. Coal seams occur with thicknesses between 1 and 2.5 m and are of good quality, with calorific values ranging from 3,700 to 5,100 kcal/kg GAR (Gross As Received), classifying them as sub-bituminous. These properties make the coal suitable for longwall mining, where excavation can be effectively performed using a drum shearer.

Based on the Rock Mass Rating (RMR) classification, the direct roof has a score of 53.0 and the main roof 58.5, both falling into Class III. Class III corresponds to medium rock mass quality, with values between 41 and 60. This classification allows for engineering estimates of rock cohesion, internal friction angle, and deformation modulus, which are essential in evaluating underground mining stability.

The analysis shows that for an unsupported 4 m tunnel advance, the roof rock would collapse within 6 days and 16 hours. This highlights the suitability of employing self-advancing support systems, which maintain roof stability during active mining while allowing controlled collapse behind the supports to reduce overburden load.

Empirical and numerical methods are critical in assessing rock mass behavior for underground mine design and collapse prevention [22, 23]. The RMR system provides a reliable basis for managing rock mass stability and designing efficient, safe, and economical underground excavations [21].

For this study area, the recommended method is full-face excavation using a drum shearer, consistent with previous findings [13].

The full-face method is particularly effective in longwall coal mining, as it enables the complete extraction of the coal seam while utilizing a self-advancing support system. Once the support advances by 4 m, the roof is expected to collapse within 6 days and 16 hours, consistent with the natural stand-up time of the rock mass.

Despite its economic potential, mining activity presents significant risks to surrounding communities. Historically, mining has caused post-mining land degradation, posing hazards such as landslides, subsidence, water contamination, flooding, and gas releases [24]. These risks endanger the environment and threaten human health and safety [25].

Land instability can lower property values and reduce land-use potential for agriculture or construction, leading to economic hardship in mining-dependent communities. Environmental consequences include disrupted drainage patterns, increased sedimentation, erosion of water bodies, and reduced water quality, which affect both human populations and wildlife. Consequently, post-mining risks create a complex legacy of environmental degradation, public safety concerns, and social insecurity [25].

Multidimensional Scaling (MDS) analysis of the five sustainability dimensions, ecological, economic, social, legal–institutional, and technological, demonstrated an overall score of 48.74, indicating a *moderate* level of sustainability. By improving sensitive attributes, the score could increase to 81.74, reflecting *good* sustainability.

Mining sustainability is especially critical for surrounding communities. Previous studies have highlighted issues such as unstable slopes, the role of local Micro, Small, and Medium Enterprises (MSMEs), community involvement through NGOs, pit supervisor concerns, and the application of landslide prevention technology [26].

Multidimensional environmental management requires integrated approaches that address occupational risk, pressure management in production zones, and the interaction between geological, geotechnical, and design criteria. Successful examples include improved ground response monitoring, accelerated cave growth, and increased production rates through effective DMLZ pressure management[13].

This study recommends targeted improvements across sustainability dimensions. For the ecological dimension, vegetation cover, soil surface conditions, groundwater levels, spring protection, and ground stability need enhancement. For the economic dimension, employment opportunities and support for local SMEs should be strengthened. Socially, efforts should focus on improving community income and welfare. In the legal–institutional dimension, compliance with safety standards and stakeholder involvement in monitoring must be ensured.

Technological efforts should emphasize landslide control and water pumping systems. These findings align with previous research stressing continuous monitoring, hazard assessment, and sustainable land-use planning in ex-mining areas [27].

Sustainable management of ex-mining land is an urgent global concern. Long-term impacts of mining require integrated strategies, including: (1) geo-ecological and hydrogeological techniques to minimize underground risks; (2) geological monitoring systems to evaluate and protect surface stability; (3) preservation and adaptive reuse of industrial mining heritage; and (4) economic transformation planning to ensure resilient and prosperous post-mining communities. These strategies, supported by international best practices, highlight the importance of linking local resilience with global sustainable development goals [28].

5. Conclusion

This study indicated that the lithology in the study area, from old to young is a mudstone unit, sandstone unit, siltstone unit, and alluvial deposits. The general position pattern of the dip direction fracture is N216°E with a dip of 85°, or N126°E / 85°, and a dip direction of N37°E with a dip of 89°, or N307°E / 89° and a dip of 84° with a direction of N183°E or N93° E / 84°. The fracture spacing ranges from 0.15 meters to 2 meters, with lengths between 0.9 meters and 1.2 meters. The opening width of fractures varies from 2 mm to 5 mm, and the roughness is described as rather coarse to very coarse. The filler material is clay minerals, with fairly good weathering. In the study area, there is a coal seam. Based on the rock mass classification of the rock mass rating, the weighting value of the direct roof is 53.00, and the main roof is 58.50. The average stand-up time of the L layer, with the tunnel advancing 4 meters and without support, is estimated to collapse after 6 days and 16 hours. The results of the Multi-Dimensional Scaling indicated the current sustainability status across five dimensions: ecology, economy, social, law, institutions, and technology, with a score of 48.74% (sufficient). This sustainability status can be improved by increasing the sensitive attributes, which could raise the score to 81.74%, indicating good sustainability.

Transparency:

The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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References

[1] Sujiman, "The effect of mining activities on the quality conditions of Fe in Wastewater at Tenggarong East Kalimantan," in *E3S Web of Conferences (Vol. 125, p. 07016). EDP Sciences*, 2019.

[2] U. Z. Rehman, M. Noor, H. Sajjad, T. Muhammad, and S. S., "Numerical modelling for the engineering analysis of rock mass behaviour due to sequential enlargement of Lowari tunnel Chitral Khyber Pakhtunkhwa, Pakistan," *International Journal of Geotechnical Engineering*, vol. 13, no. 1, pp. 54–60, 2019.

[3] L. L. Li LiPing *et al.*, "Cause analysis of soft and hard rock tunnel collapse and information management," *Polish Journal of Environmental Studies*, vol. 23, no. 4, pp. 1227–1233, 2014.

[4] R. L. Sousa and H. H. Einstein, "Lessons from accidents during tunnel construction," *Tunnelling and Underground Space Technology*, vol. 113, p. 103916, 2021. https://doi.org/10.1016/j.tust.2021.103916
[5] W. Zhang, X. Tang, W. Yang, J. Jiang, H. Zhang, and P. Li, "Review of tunnels and tunnelling under unfavourable geological conditions," *Geological Journal*, vol. 59, no. 9, pp. 2668-2689, 2024. https://doi.org/10.1002/gj.4937
[6] H. Sajjad, N. Mohammad, M. Khan, Z. U. Rehman, and M. Tahir, "Comparative analysis of rock mass rating prediction using different inductive modeling techniques," *International Journal of Mining Engineering and Mineral Processing*, vol. 5, no. 1, pp. 9-15, 2016. https://doi.org/10.5923/j.mining.20160501.02
[7] S. W. Tun and S. K. Singal, "Management of hydropower tunnels to prevent collapse and remedial measures," *Hydro Nepal: Journal of Water, Energy and Environment*, vol. 19, pp. 31-37, 2016. https://doi.org/10.3126/hn.v19i0.15349
[8] Q. Zhang, X. Huang, H. Zhu, and J. Li, "Quantitative assessments of the correlations between rock mass rating (RMR) and geological strength index (GSI)," *Tunnelling and Underground Space Technology*, vol. 83, pp. 73-81, 2019. https://doi.org/10.1016/j.tust.2018.09.015
[9] J. Kundu, K. Sarkar, A. K. Singh, and T. Singh, "Continuous functions and a computer application for Rock Mass Rating," *International Journal of Rock Mechanics and Mining Sciences*, vol. 129, p. 104280, 2020. https://doi.org/10.1016/j.ijrmms.2020.104280
[10] M. Brook, B. Hebblewhite, and R. Mitra, "Coal mine roof rating (CMRR), rock mass rating (RMR) and strata control: Carborough Downs Mine, Bowen Basin, Australia," *International Journal of Mining Science and Technology*, vol. 30, no. 2, pp. 225-234, 2020. https://doi.org/10.1016/j.ijmst.2020.01.003
[11] G. Somodi, N. Bar, L. Kovács, M. Arrieta, Á. Török, and B. Vásárhelyi, "Study of rock mass rating (RMR) and Geological Strength index (GSI) correlations in granite, siltstone, sandstone and quartzite rock masses," *Applied Sciences*, vol. 11, no. 8, p. 3351, 2021. https://doi.org/10.3390/app11083351
[12] J. Satria, I. G. B. Indrawan, and N. I. Setiawan, "Engineering geological characteristics based on rock mass rating (RMR) and geological strength index (GSI) in Tunnel Number 1 of the Sigli-Aceh toll road," in *E3S Web of Conferences (Vol. 325, p. 01014). EDP Sciences*, 2021.
[13] P. M. Hatini, "Analysis of support requirement in the underground mine of PT ANTAM TBK UBPE Pongkor," *Jurnal Eksakta Kebumian*, vol. 2, no. 2, pp. 155–163, 2021.
[14] K. Simanjuntak, A. Primadiansyah, N. Soumilena, and W. Teweng, "Driving and managing stress in the Deep Mill Level Zone caving mine. In R. Castro, F. Báez, & K. Suzuki (Eds.)," in *MassMin 2020: Proceedings of the Eighth International Conference & Exhibition on Mass Mining (pp. 394–405). University of Chile*, 2020.
[15] Z.-X. Zhang, *Rock fracture and blasting: theory and applications*. Oxford, UK: Butterworth-Heinemann, 2016.
[16] V. Mutambo, S. Kangwa, and M. Fisonga, "Mining method selection for extracting moderately deep ore body using analytical hierarchy process at mindola sub-vertical shaft, Zambia," *Cogent Engineering*, vol. 9, no. 1, p. 2062877, 2022. https://doi.org/10.1080/23311916.2022.2062877
[17] P. Gabriele *et al.*, "Sustainable development for underground mining of strategic industrial minerals: The geological and geotechnical modelling as a key factor," presented at the Mechanics and Rock Engineering, from Theory to Practice (IOP Conf. Ser.: Earth and Environmental Science, Vol. 833, 012138). IOP Publishing, 2021.
[18] Y. Zhang, H. Qi, C. Li, and J. Zhou, "Enhancing safety, sustainability, and economics in mining through innovative pillar design: A state-of-the-art review," *Journal of Safety and Sustainability*, vol. 1, no. 1, pp. 53-73, 2024. https://doi.org/10.1016/j.jsasus.2023.11.001
[19] J. Huang, C. Tian, L. Xing, Z. Bian, and X. Miao, "Green and sustainable mining: Underground coal mine fully mechanized solid dense stowing-mining method," *Sustainability*, vol. 9, no. 8, p. 1418, 2017. https://doi.org/10.3390/su9081418
[20] Ministry of Energy and Mineral Resources Directorate General of Mineral and Coal, *Road map for development and utilization of coal 2021–2045*. Jakarta, Indonesia: Ministry of Energy and Mineral Resources, 2021.
[21] Z. U. Rehman, S. Hussain, M. Tahir, N. Mohammad, S. Sherin, and N. Dasti, "Prevention and mitigation management of tunnel collapse and failure during construction-a review," *International Journal of Economic and Environmental Geology*, vol. 12, no. 2, pp. 72-79, 2021.
[22] Z. T. Bieniawski, *Engineering rock mass classifications: A complete manual for engineers and geologists in mining, civil, and petroleum engineering*. New York: John Wiley & Sons, 1989.
[23] B. Celada, I. Tardáguila, P. Varona, A. Rodríguez, and Z. Bieniawski, "Innovating tunnel design by an improved experience-based RMR system," in *Proceedings of the World Tunnel Congress*, 2014.
[24] C. Tisdell and S. Svizzero, "Unsustainable mining development and the collapse of some ancient societies: Economic reasons," *International Journal of Research in Sociology and Anthropology*, vol. 5, no. 3, pp. 20-28, 2019. https://doi.org/10.20431/2454-8677.0503003
[25] V. Bondarenko *et al.*, "A new concept for complex mining of mineral raw material resources from DTEK coal mines based on sustainable development and ESG strategy," *Mining of Mineral Deposits*, vol. 17, no. 1, pp. 1-16, 2023.
[26] S. Sujiman and H. Sundek, "Mine landslide management sustainability model in Kutai Kartanegara Regency, East Kalimantan, Indonesia," *Environmental Research, Engineering and Management*, vol. 80, no. 1, pp. 50-63, 2024. https://doi.org/10.5755/j01.erem.80.1.33272

[27] D. M. Nalmpant-Sarikaki, A. I. Theocharis, N. C. Koukouzas, and I. E. Zevgolis, "A framework for effective multi-hazard risk assessment in post-mining areas," *Safety*, vol. 11, no. 1, p. 18, 2025. https://doi.org/10.3390/safety11010018

[28] R. Misa, A. Sroka, and D. Mrocheń, "Evaluating surface stability for sustainable development following cessation of mining exploitation," *Sustainability*, vol. 17, no. 3, p. 878, 2025. https://doi.org/10.3390/su17030878

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