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# Mine Landslide Management Sustainability Model in Kutai Kartanegara Regency, East Kalimantan, Indonesia

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This research aims to identify the geological and lithological structures of mine land, determine the slope stability of the land, and determine the sustainability of landslide management in Kutai Kartanegara Regency, East Kalimantan, Indonesia. This present research was conducted in Samboja and Sebulu sub-districts, Kutai Kartanegara Regency, East Kalimantan, Indonesia. Data collection concerning the geological structure, lithology, and sustainability of coal mine landslides was carried out. Rock data, such as its physical and mechanical properties, were taken from complete coring drilled and then analyzed in a geomechanics laboratory. This procedure was carried out in three locations, with the first and second samples collected in the Kampungbaru Formation representing the youngest formation. In addition, the third taken in the Pulubalang Formation represents the oldest coal-bearing formation. The data relating to the avalanche condition were collected through surveys, interviews, and filling out questionnaires using a purposive sampling method. The respondents were 13 mining engineering heads from various mine sites in Kutai Kartanegara Regency, three mining environmental experts, and four academics. The results showed that of the 50-joint data, those with potential positions for landslides were located at N333°E/61° and N110°E/74°. The most dominant lithology in the study area was claystone, followed successively by sandstone, siltstone, and shale, with a specific gravity between 2.55 and 2.66. The dominant claystone indicated a relatively prone area. Meanwhile, the strength of the mechanical properties of the rock (direct shear) cohesion ranged from 17.80 and 174.53 kPa, with shear angles ranging from 10.88° to 42.01°. Based on the design of the slope stability in the three locations, this study demonstrated the maximum slope angle ranging from 29° to 37°, a height of 50.17 to 70.16 meters, a single slope height of 10 meters with an angle ranged from 32° to 44°, and a factor of safety (FOS) ranging from 1.326 to 1.452 with stable conditions. Multi-dimensional scaling (MDS) simulation results of the sustainability status comprised of a total of 49 attributes derived from five dimensions, namely ecological, economic, social, law, institutional and technological, demonstrated a score fell of 50.01. Furthermore, to increase the sustainability score, this study identified some sensitive factors as follows: condition of the slope of the mine slope, MSME business of residents, role of NGOs in mine landslides, concern of pit supervisory personnel for mine landslides, and mastery of mine landslide technology. Hence, the projection sustainability score increased to 82.00, which was achieved in the good category.

**Keywords:** landslide, mining, sustainability, multi-dimensional scaling, lithology.

## Introduction

Open pit mining projects are long-term operations with the risk of significant human-caused physical and environmental impacts. Physically, it can be seen from large-scale horizontal expansion activities and the use of heavy-duty mechanical equipment (Pavloudakis et al., 2018). These impacts significantly change the shape of the mine's initial physical geographic environment and represent an important risk to mining operations, including landslides (Spanadis et al., 2021). Mine landslides are among the risks that must be considered when carrying out coal mining. These risks have a potential impact on the lives, livelihoods and safety of the human community living in the wider mining area. Mine landslides are a common geological hazard that has caused significant loss of life and property around the world. Natural hazards, particularly those related to landslides and other disasters are a matter of increasing concern as climate extremes present an increasing trend worldwide (Van Westen et al., 2013). Increasing the depth of an open pit mine further increases the possibility of landslides occurring both in the low-wall and high-wall areas and can disrupt mining activities (Musa and Saptono, 2015). Within the framework of sustainable planning and development of such projects, risk impact investigations are essential to take appropriate countermeasures before a disastrous event occurs at the mine (Spanidis et al., 2021).

Mining is one of the main elements of the economy in several developing countries, including Indonesia. In 2020, 16.07 billion tons of coal reserves were realized in East Kalimantan, making this province the largest producer of coal reserves in Indonesia (Ministry of Energy and Mineral Resources Report, 2021). The mining area based on the Mining Designated Area Development Plan 2016–2036 in East Kalimantan is 5 231 444 hectares. Among the areas, 1 114 406 hectares are situated in Kutai Kartanegara Regency. Currently, the mining industry in the Kalimantan region is concerned about the occurrence of landslides in several areas (Rangga et al., 2022).

Several studies have been conducted on mine landslides with a focus on predicting mine landslide susceptibility (Hong et al., 2016; Su et al., 2021; Salmi et al., 2018; Luo et al., 2019), identification of causal factors (Ma et al., 2021; Salmi et al., 2017) and erosion mechanisms (Nie et al., 2015). Bednarczyk (2017) has stated that open pit mines in Poland have a slope safety factor between 0.75 to 1.65 and 1.12 to 1.60 for dump areas. Another study in America shows that the slope of an open pit mine tends to be stable when the safety factor is greater than 1.2 (Kolapo et al., 2022).

Research on management aspects of disaster risk is rare. Research on management aspects that has been carried out focused on safety, risk assessment and monitoring (Fell et al., 2005; McGowran and Donovan, 2021; Baczynski et al., 2017; 2022). Landslide occurrence has significantly affected socio-economic activities in the areas and is the primary cause of biophysical degradation (Ajake, 2022). Satellite monitoring is one method of landslide control. Research on sustainability disaster risk management seeks to integrate technical aspects with social aspects. Research on aspects of disaster risk management is still rarely carried out. Mine management needs to pay attention to its sustainability aspects. The sustainability of mining management experienced by the surrounding ecological-socioeconomic system requires a holistic approach. In a previous study conducted on mining in the Arctic region, Tolvanen offered 4 dimensions of management sustainability including 1) environmental, 2) economic, 3) social and 4) legal dimensions (Tolvanen et al., 2019). In this research, one dimension is added, namely technology. This is based on the use of technology for exploration, extraction and waste processing (Rhyner et al., 2017; Dychkovskyi et al., 2018; Aznar-Sánchez et al., 2018). This research aims to identify the geological and lithological structures of mine land, determine the slope stability of the land, and determine the sustainability of landslide management in Kutai Kartanegara

Regency, East Kalimantan, Indonesia. The results of this research are expected to be able to encourage the sustainability of disaster risk management based on social capacity.

## Methods

This present research was conducted in Samboja and Sebulu sub-districts, Kutai Kartanegara Regency, East Kalimantan, Indonesia. The field studies were carried out in three locations, with the first and second samples collected in Samboja. The first and second locations in Samboja were situated in Kampungbaru Formation. It represents the youngest formation with declivous slopes. The third location was situated in the Pulubalang Formation. It represents the oldest coal-bearing formation with a steeper slope. Data collection concerning the geological structure, lithology, and sustainability of coal mine landslides was carried out for 14 months (May 2021 to July 2022). Meanwhile, information on the physical and mechanical properties of the rocks was obtained from 2018 to 2020. Rock data, such as its physical and mechanical properties, were taken from complete coring drilled and then analyzed in the geomechanics laboratory. The geological structure of the rock was mapped directly on the field by taking as many as 50 joint data. The physical and mechanical properties of the first and second locations were analyzed at the Rock Mechanics Laboratory, Research, and Development Center for Mineral and Coal Technology, Bandung, Indonesia. Meanwhile, the samples from the third location were analyzed in the rock mechanics laboratory, Civil Engineering Department, Samarinda State Polytechnic.

The data relating to landslides management sustainability were collected through surveys, interviews, and filling out questionnaires using a purposive sampling method. The respondents were 13 mining engineering heads from various mine sites in Kutai Kartanegara Regency, three mining environmental experts, and four academics. The respondents were selected based on predetermined criteria. General criteria include an understanding of mining or environmental problems and a minimum of 10 years of service. Respondents from mining companies were selected from companies close to the study location, representing medium and large companies. Environmental experts consist of supervisors from local governments, environmental impact analysis consultants and NGO members. The academics consists of environmental and mining experts. The questionnaire questions consist of 5 dimensions as follows: ecology, economy, social, technology, legal and institutional factors. The selection of this dimension is based on the global sustainability perspective terminology which focuses on three main pillars including ecology, economy and social (Brown et al., 1987; Blackburn, 2012). Furthermore, to answer the local context, this research determines two additional dimensions including technology, legal and institutional factors. This was chosen because mining area management is closely related to the use of technology and must pay attention to legal regulations supported by strong institutions (Bridge, 2004; Tolvanen et al., 2019).

The geological structure data were analyzed with the dips 6.01 program. Classification parameters of joint and their rating are presented in *Table 1*.

**Table 1.** *Classification parameters of joint and their rating*

| Parameter | Range of Values | | | | |
|---|---|---|---|---|---|
| Discontinue/joint Spacing (meter) | > 2 | 0.6–2 | 0.2–0.6 | 0.06–0.2 | < 0.006 |
| | Very wide | Wide | Moderate | Close | Very close |
| Joint condition | (0) Weak gouge > 5 mm thick, continuous | Slickenside/gauge < 5 mm, tension 1 – 5mm, continuous | The fracture surface is rather rough, stretches < 1 mm, is slightly weathered | The surface of the fracture is rather rough, stretches < 1 mm, is slightly weathered | |
| | Very weak | Weak | Moderate | Strong | Very strong |

Data on the physical and mechanical properties of the rock were analyzed using the slide 6.0 program, and then were compared with the mine slope stability criteria according to Indonesia Ministerial Decree Number 1827 K/30/2018, as in *Table 2* below.

Determining the sustainability of mine landslide management influenced by technical information, which is part of the ecological, economic, social, legal, and institutional data as well as technological type was done by Multi-Dimensional Scaling (MDS), and the result was presented as MDS Rap-Bengkawan.

**Table 2.** *Mine slope stability criteria (Indonesia Standard)*

| Slope Type | Avalanche Severity (Consequences of Failure/ COF) | Acceptance Criteria | | |
|---|---|---|---|---|
| | | Static factor of safety (Min) | Dynamic factor of safety (Min) | Landslide probability (Probability of failure) |
| Single slope | Low to tall | 1.1 | 0 | 25–50% |
| Overall slope | Low | 1.2–1.3 | 1 | 15–20% |
| | Intermediate | 1.3 | 1.05 | 10% |
| | Tall | 1.3–1.5 | 1.1 | 5% |

## Results and Discussion

### Joint condition

From the field data results, as many as 50 joints at the research location were examined using stereographic slide analysis. The possible occurrence of an inverted avalanche has a slope in the nearly vertical joint plane, with a shear fracture direction of 1 relative to the Northwest (N 333° E). This is in addition to the southeastern joint slope (61° S), which is relative to the landmarks (N 110° E), and the southwest joint (74° S). The results of the joint stereographic analysis at the research location are shown in *Figs. 1* to *3*.

**Fig. 1.** *The percentage value of the polar projection from joint measurements at the research location*

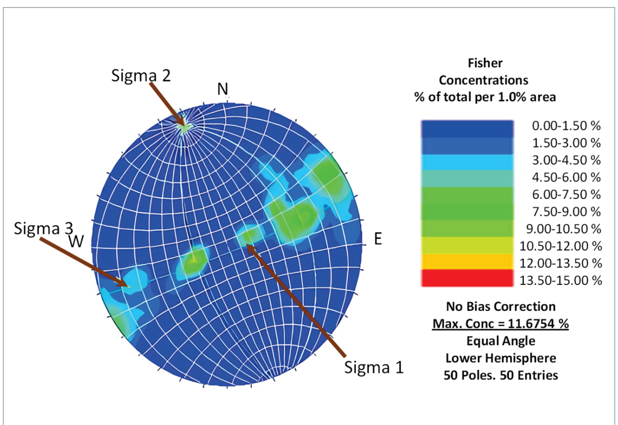



**Fig. 2.** *Stereographic projection of the force values from joint measurements at the research location*

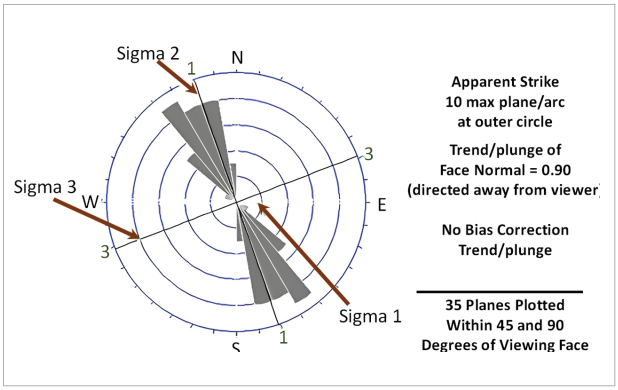
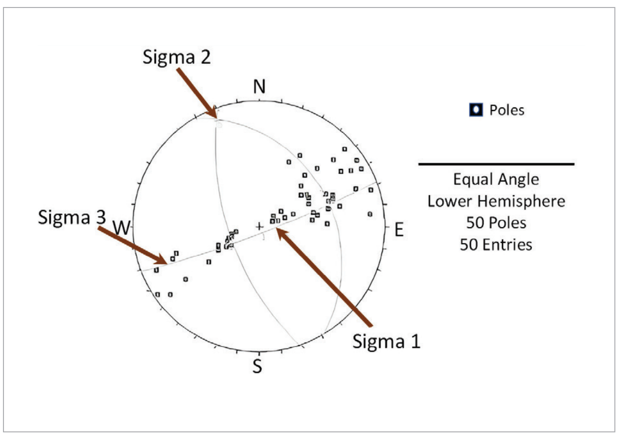



**Fig. 3.** *Polar projections from joint measurements at the research location*



## Lithological conditions

The most dominant lithology of the slope-forming materials at the research location was claystone, followed successively by sandstone, siltstone, and shale. Based on the laboratory analysis results, the rock's physical properties are identified as follows: the first location in Samboja sub-district was part of the Kampungbaru Formation, which was the upper coal-bearing formation. It has diverse lithologies, and five samples were obtained based on their specific gravities, within the range of 2.55 to 2.61. Meanwhile, with respect to the strength of the mechanical properties, the peak cohesion is within 74.25 kPa and 120.70 kPa, with a shear angle at peaks between 10.88° and 42.01°.

The second location in Samboja sub-district is also part of the Kampungbaru Formation, where four samples with less diverse lithologies, and a specific gravity of 2.60 to 2.66, were obtained. Regarding the strength of the mechanical properties, the peak cohesion is within the range of 17.80 kPa and 174.53 kPa, with shear angles at peaks between 28.35° and 39.82°.

The third location is situated in Sebulu sub-district, part of the Pulubalang Formation, with four less diverse lithological samples and a specific gravity within the range of 2.64 to 2.67. In relation to the strength of the mechanical properties, the peak cohesion obtained is within the range of 0.108 kg/cm$^2$ and 0.323 kg/cm$^2$, with shear angles at peaks between 43.83° and 84.645°.

The data analysis results obtained from the first location proved that slope stability has a FOS (factor of safety) value, overall angle, and height of 1.326, 29°, and 50.628 meters, respectively. *Fig. 4* shows that under stable conditions, the single slope is 9.99 meters high, with a 3-meter embankment at an angle of 32°. Meanwhile, at the second location, the FOS value, overall angle, and slope height are 1.452, 32°, and 50.170 meters, respectively. *Fig. 5* shows that under stable conditions, the single slope is 10.034 meters high, with a 3-meter embankment, at an angle of 36°. The third location has a FOS value, overall angle, and height of 1.433, 37°, and 70.156 meters, respectively. *Fig. 6* shows that under stable conditions, the single slope is 10.020 meters high, with a 3-meter embankment at an angle of 44°.

**Fig. 4.** *Design of the Slope Stability Model. The first research location was in Samboja sub-district with a FOS (factor of safety) value, overall angle, and slope height of 1.326, 29°, and 50.628 meters, respectively. The single slope is 9.99 meters high, has a 3-meter berm, and an angle of 32° under stable conditions*

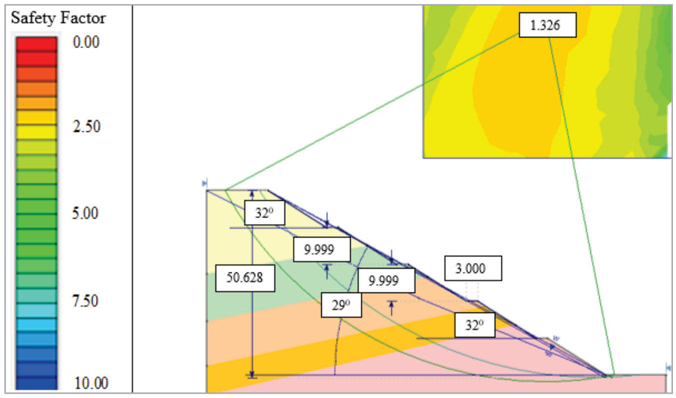



**Fig. 5.** *Design of the Slope Stability Model. The second research location is in Samboja sub-district with a FOS (factor of safety) value, overall angle, and slope height of 1.452, 32°, and 50.170 meters, respectively. The single slope is 10.034 meters high, has a 3-meter berm, and an angle of 36°, under stable conditions*

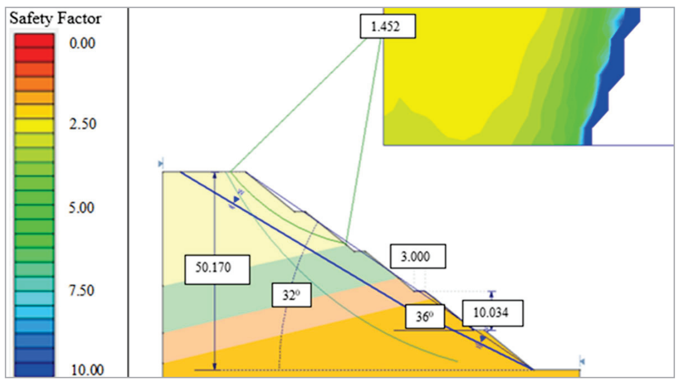
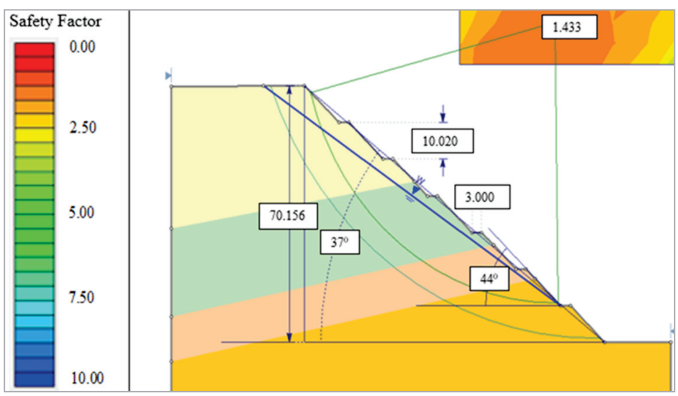



**Fig. 6.** *Design of the Slope Stability Model. The third research location is in Sebulu sub-district with a FOS (factor of safety) value, overall angle, and slope height of 1.433, 37°, and 70.156 meters, respectively. The single slope is 10.020 meters high, has a 3-meter berm, and an angle of 44°, under stable conditions*



## Sustainability of mine slides management

Determining the sustainability of mine landslide management is influenced by technical information, which was part of the ecological, economic, social, legal, and institutional data as well as technological type. Attributes that can affect the sustainability level of the ecological dimension were 13 elements, namely 1) mine slope conditions, 2) lithological specific gravity conditions, 3) rock strength conditions (uniaxial test), 4) rock strength conditions (shearing test), 5) rock strength conditions (uniaxial test), movement or slide, 6) rock surface conditions, 7) rock cohesion, 8) vegetation growth on mine slopes, 9) spring conditions on mine slopes, 10) geohydrological conditions, 11) rainy level, 12) joint space, and 13) joint conditions, as shown in *Fig. 7*. The results of the analysis show that the joint space has the highest score, while the spring condition on the slope has the lowest score.

Based on the MDS analysis, the ecological sustainability index is 48.98%, which is perceived as a lower limit (*Fig. 8*).

**Fig. 7.** *Leverage attributes of ecological dimensions of mine slides at the research location*

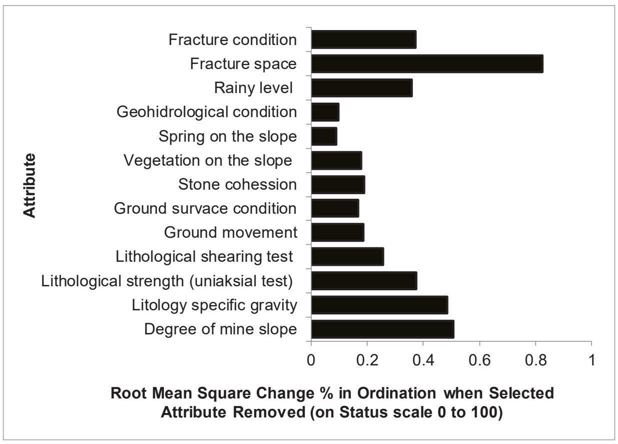
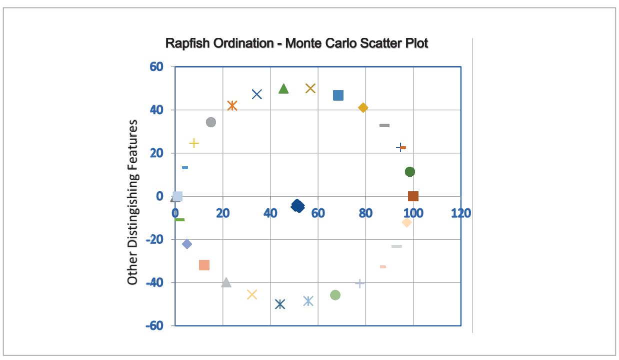



**Fig. 8.** *Current mine avalanche sustainability index at research locations ecological dimensions of 48.98%*




The economic dimension at the research location has the following attributes: 1) absorption of labor, 2) company income generated from mines due to landslides, 3) MSME businesses of local residents, 4) GRDP (gross regional domestic income), 5) income of residents from mine due to landslide, and 6) village institutional income. Its attribute leverage and the sustainability index at the research location are shown in *Fig. 9*. The results of the analysis show that village institutional income has the highest score, while enterprise income has the lowest score.

Based on the MDS analysis, the economic sustainability index was 51.36%, which is perceived as a moderate limit (*Fig. 10*).

**Fig. 9.** *Leverage attributes of the economic dimensions of mine slides at the research location*

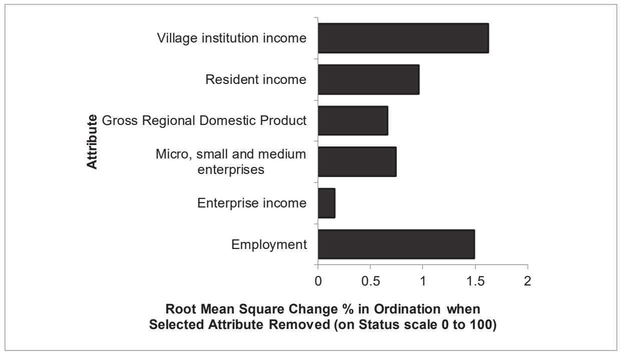
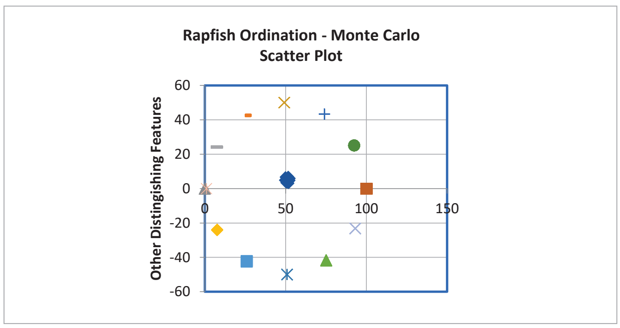



**Fig. 10.** *The current mine avalanche sustainability index at the economic dimension*




The social dimension that affects the level of sustainability consists of eight attributes, namely 1) the company's relationship with residents around the landslide site, 2) the role of community leaders in mine landslide disasters, 3) community knowledge of mine landslides, 4) the influence of this incident on the social sector, 5) the role of NGOs, 6) community perceptions of these occurrences, 7) mine landslide monitoring NGOs, 8) the role of company stakeholders, and 9) leaders in mine landslide disasters, as shown in *Fig. 11*. The results of the analysis show that other stakeholder roles have the highest score, while NGOs monitoring on landslides have the lowest score.

**Fig. 11.** *Leverage attributes of the social dimension of mine slides at the research location*

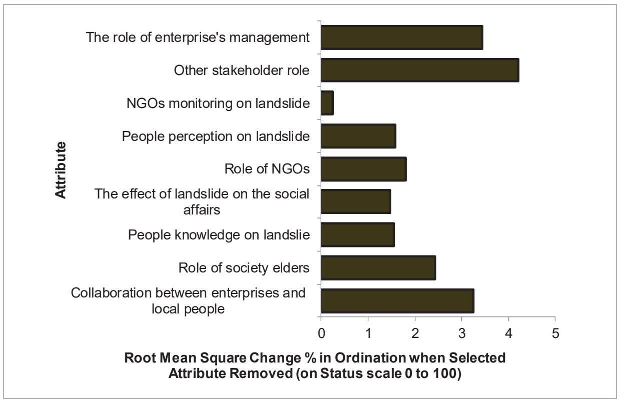
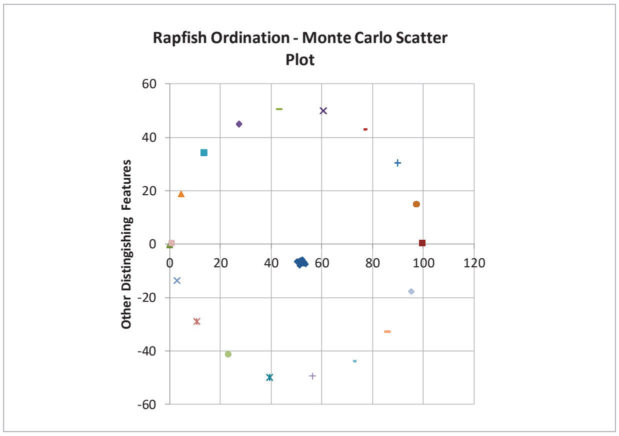



**Fig. 12.** *The current mine avalanche sustainability index at the social dimension research location is 47.02*




Based on the MDS analysis, the social sustainability index was 47.02%, which is perceived as a lower limit (*Fig. 12*).

The legal and institutional dimensions, which have an impact on the level of sustainability, consist of 12 attributes, namely 1) availability of regulations regarding mine landslides, 2) concern of pit supervisor personnel in respect to mine landslides, 3) concern of legal personnel, 4) socialization of legal personnel about landslides, 5) a department that oversees this phenomenon, 6) law enforcement in the event of landslides, 7) compliance with the condition of safety factors, 8) awareness of officials in monitoring mine slides, 9) tools CCTV to monitor it, 10) supervision of mine inspectors in monitoring landslides, 11) availability of local institutions dealing with landslides, and 12) legal institutional responsibilities in mine landslides, as shown in *Fig. 13.* The results of the analysis show that the availability of local institutions dealing with landslides has the highest score, while the availability of regulations regarding mine landslides has the lowest score.

**Fig. 13.** *Leverage attribute legal and institutional dimensions of mine slides at the research location*

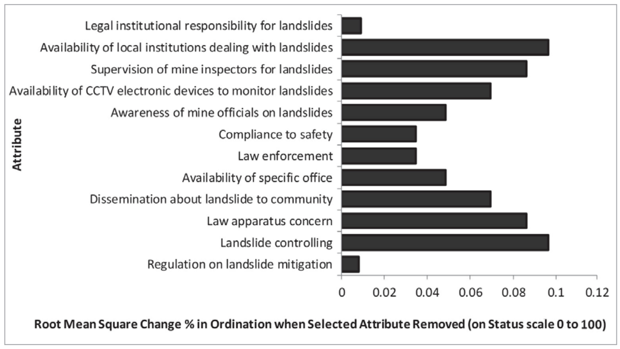
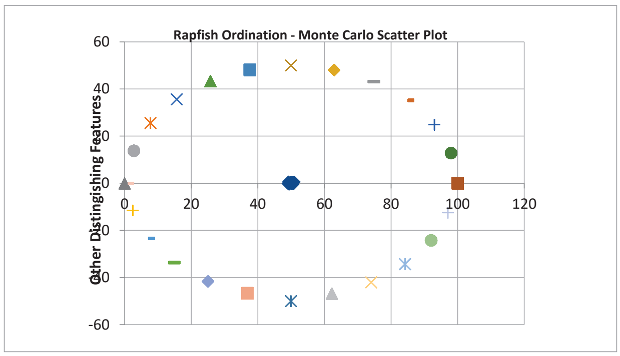



**Fig. 14.** *Current mine avalanche sustainability index at research locations legal and institutional dimensions of 49.97*




Based on the MDS analysis, the social sustainability index was 49.97%, which is perceived as a lower limit (*Fig. 14*).

The technological dimension that influences the level of sustainability consists of eight attributes, namely 1) technology in determining landslides, 2) repairing mine slopes, 3) monitoring mine slopes, 4) monitoring mine slides, 5) pumping water in mine location, 6) handling water flowing down the slope of the mine, 7) mastery of technology for mine avalanches, and 8) mastery of technology for avalance monitoring, as shown in *Figs.*

*15* and *16*. The results of the analysis show that water pumping technology at the avalanche site has the highest score, while mastery of technology for avalanche monitoring has the lowest score.

**Fig. 15.** *Leverage attributes of the technological and institutional dimensions of mine slides at the research location*

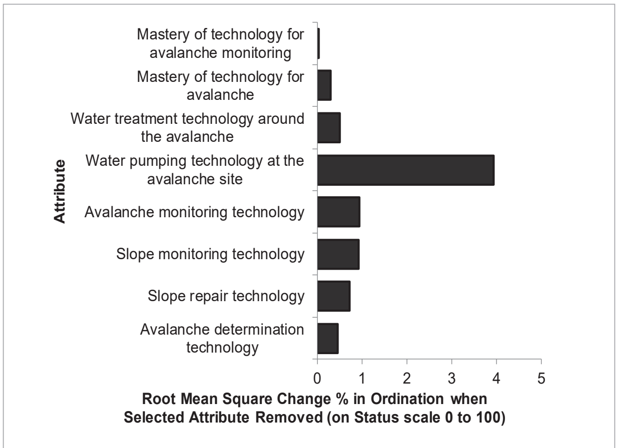
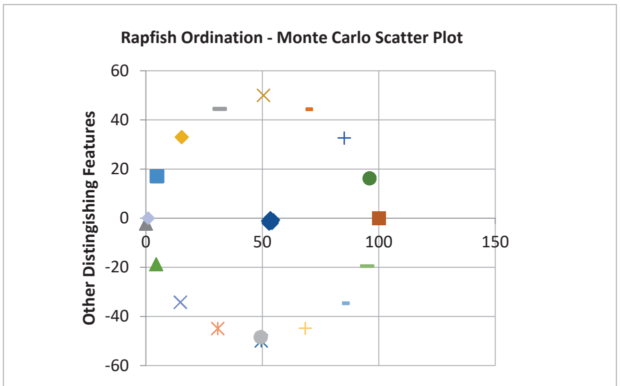



**Fig. 16.** *Current mine avalanche sustainability index at research locations technology and institutional dimensions*

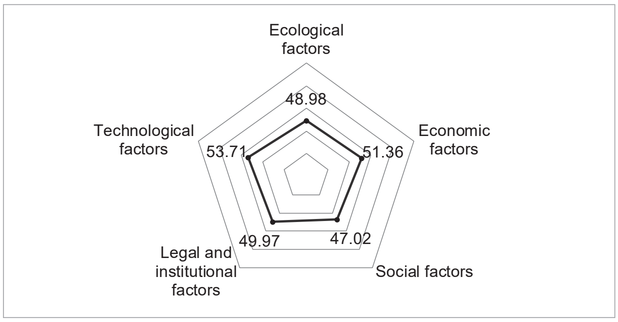



Based on the MDS analysis, the technolocial and institutional sustainability index was 53.71%, which is perceived as a moderate limit (*Fig. 16*).

## Current status of multidimensional sustainability

The analysis results from the multidimensional Rap-bengkawan sustainability of coal mines landslide management in Kutai Kartanegara Regency currently obtained a sustainability index value of 50.01%, including a moderate sustainable status (*Table 3*). This was based on an assessment of the attributes of the five sustainability dimensions, including ecological, economic, socio-cultural, legal and institutional, and technological dimensions (*Fig. 17*).

**Fig. 17.** *Flyover diagram of the current mine slide sustainability status in Kutai Kartanegara Regency*




## Status of multidimensional sustainability future expectations

The expected sustainability status entails making simple improvements to sensitive attributes. This study identified several attributes sensitive for elevating the score of sustainability. In ecological dimensions, the factors included were mine slope, lithological specific

**Table 3.** *Determination of the current multidimensional weight and sustainability status of coal mine avalanches in Kutai Kartanegara Regency*

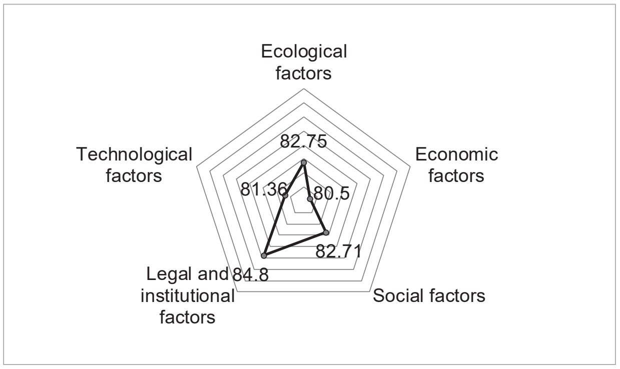
| No. | Dimensions | Combined Weight | Weighted Weight | Sustainability Value | Total Value |
|---|---|---|---|---|---|
| 1 | Ecology | 0.35 | 0.38 | 48.98 | 18.63 |
| 2 | Economy | 0.32 | 0.35 | 51.36 | 18.09 |
| 3 | Social and Culture | 0.11 | 0.12 | 47.02 | 5.66 |
| 4 | Law and Institutions | 0.07 | 0.07 | 49.97 | 3.64 |
| 5 | Technology | 0.07 | 0.07 | 53.71 | 4.00 |
| | Total | 0.91 | 1.00 | 251.04 | 50.01 |

**Table 4.** *Determination of the weight and multidimensional sustainability status of the future expectations of coal mine avalanches in Kutai Kartanegara Regency*

| No. | Dimensions | Combined Weight | Weighted Weight | Sustainability Value | Total Value |
|---|---|---|---|---|---|
| 1 | Ecology | 0.35 | 0.38 | 82.75 | 31.47 |
| 2 | Economy | 0.32 | 0.35 | 80.50 | 28.35 |
| 3 | Social and Culture | 0.11 | 0.12 | 82.71 | 9.95 |
| 4 | Law and Institutions | 0.07 | 0.07 | 84.80 | 6.17 |
| 5 | Technology | 0.07 | 0.07 | 81.36 | 6.06 |
| Total | | 0.91 | 1.00 | 412.12 | 82.00 |

gravity, rock movement or slide, soil surface, vegetation growth, geohydrological, joint spacing, and stiff conditions. In economic dimensions, the factors comprised MSME of local residents, state income, income of residents from mines due to landslides. In social dimensions, the factors were constituted of the role of NGOs in mine landslide monitoring, and the role of corporate stakeholders. The legal and institutional dimensions consisted of concern of pit supervisor personnel for mine landslide, legal personnel's concern, counseling from legal personnel and pit supervisors, deliberating with the parties involved against mine avalanches, law enforcement in the event of an avalanche, compliance with the conditions of safety factors in mine avalanches, awareness of officials in monitoring this phenomenon, corruption level of pit supervisors and law enforcement in mine avalanches. Technological dimensions comprised mastery of mine landslide technology, water handling technology at the slope location, mine slope monitoring technology, and mine slope avalanche monitoring technology. Further calculation with the improvement of all sensitive factors increased the MDS score to 82.00% (*Table 4*) which meant highly sustainable, as shown in *Fig. 18*.

**Fig. 18.** *Kite diagram of the sustainability status of the mine avalanche in the future in Kutai Kartanegara Regency*




## Discussion

Lands prone to landslides occur in mining areas frequently. The impact of landslides can be experienced by both the industry and the surrounding community. Landslides can be triggered by 3 main factors: the slope, slope materials (rock/soil), and rainfall (Trisnawati and Hidayatillah, 2014). High rainfall was reported to trigger catastrophic rockslides in Sicuan Province, China (Ma et al., 2018). Apart from that, open pit mining activities are also prone to landslides, especially at landfill locations. A pile is a rock-soil mass consisting of a mixture of soil and rock that is removed from a mine and stacked at a certain location. The main disaster that affects waste heaps is landslides, and the key to preventing landslides is to control the stability of the slopes of waste dumps. The spatial distribution of embankments, slope sediment height, surface slope, slope water depth, strength of mixed materials, and other factors can all influence the stability of embankment slopes (Verma and Armstrong-Altrin, 2013; Huang et al., 2018). Disasters that impact waste disposal can be prevented effectively if the influence of the four aspects of external forces, the physical and mechanical properties of the base, the physical and mechanical properties of the disposal material, and the impacts caused by water can be controlled properly.

Based on the results of research at the study site, the joint spacing (discontinue) and the fracture condition were included in the second criterion meaning that it is classified as moderately discontinued with a spacing of 0.20 meters to 0.60 meters. The joint conditions are characterized by moderately rough fracture surfaces, less than one mm stretch, and slightly weathered with moderate strength. Therefore, this area is classified as a moderate landslide hazard. In addition, the lithology of the area is composed of fine to medium dendritic rocks such as sandstone, siltstone, mudstone, coal, and shale.

Previous studies have shown a high potential for landslides on land with claystone lithology. The alternating layers of sand and claystone (that breaks into flakes and parts of various dimensions when dry) are the principal cause of instability in this area (Igwe, 2013). This effect increases in areas with alternating layers of sandstone, greywacke, claystone, and siltstone (Tonggiroh, 2021). From the three locations studied, the level of lithological strength ranges from low to moderate. The results of the slope stability analysis show that several locations have stable FOS values with a fairly high slope of up to 29–45°. This shows that in carrying out the process of stockpiling used mining materials, the mining industry has paid attention to the level of slope. If the slope is more than that, then the land becomes vulnerable to landslides. On land with steep slopes and low stability, revegetation efforts with a variety of plant types can increase land stability. Uniform plants may increase FOS from 23% to 30%, while combined plants increase from 28% to 31%. *Pinus merkusii* demonstrated some advantages in maintaining stability (Zayadi et al., 2022).

Based on the geological and lithological structures of mine land, and the slope stability of the land, sustainable management must be applied to anticipate the landslide potential and manage its risk. To increase the sustainability score, this study identified some sensitive factors as follows: the condition of the slope of the mine slope, MSME businesses of local residents, the role of NGOs in mine landslides, the concern of pit supervisory personnel for mine landslides, and mastery of mine landslide technology. From a geographical aspect, the slope of the land is an important factor; therefore, sloping land management is important. Landslides are mainly located on steep slopes (Chen and Huang, 2013). Hence, mapping and structuring landslide-prone areas based on slope are important to prevent casualties (Anderson and Holcombe, 2013). Therefore, all related stakeholders are expected to contribute to safe and sustainable slope management.

From the economic aspect, MSME businesses of local residents need to get priority treatment. Communities around mining areas are generally poor; therefore, community empowerment efforts are needed to improve their standard of living. Mining companies can utilize corporate social responsibility financing schemes to empower communities around mining areas by involving the government and other parties (Primawati, 2013; Ferlianta and Praditya, 2018). This effort has an important impact because it can increase community independence and participation in disaster mitigation. Increasing the capacity of MSMEs (micro, small and medium enterprises), this effort can be carried out through developing a productive economy and increasing the human resource capacity of MSMEs, for example, through training, comparative studies, and apprenticeships in the field of marketing (Cahyono, 2021). This result is also supported by the results of the study by Ajake et al. (2022) who stated that the efforts of various stakeholders in terms of financial support (65%) were not supporting sustainable results.

From the social as well as legal and institutional aspects, the role of NGOs in mine landslides and the concern of the personnel in charge of the pit for mine landslides are important in increasing sustainability. Both are an important part of monitoring and control activities. NGOs have an important role starting from educating the public about awareness to handling disaster victims. Personnel in charge of the pit for mine landslides have an important role in monitoring potential landslide events. This requires monitoring not only actual movement, but also environmental factors including rainfall, soil water content, temperature, and relative (air) humidity, as well as geotechnical parameters, such as pore water pressure. Monitoring of these parameters plays an important role in supporting the development of slope stability models (Springman et al., 2013). This allows for the correlation of movement events with their triggering mechanisms and helps inform the causality underlying process-response models so that possible risks can be controlled. For this reason, the task of field actors also needs to be supported by integrated research so that the results can be utilized directly in the field.

Given the escalating costs of landslides, the problem for local governments is to establish institutional structures for effective and efficient landslide risk management. Moreover, a long-term and sustainable approach to reducing losses associated with additional landslides and land failures requires national and international commitment from both the private and public sectors (Anderson and Holcombe, 2013).

From an institutional perspective, local governments (for example, districts, sub-districts and villages or municipalities), non-governmental organizations (NGOs), the private sector and community-based organizations are always the first to respond to any type of disaster or emergency event prior to the arrival of a disaster (Mondal et al. 2018; Nature and Ray-Benner, 2021). Previous studies have reported that NGOs have done a good job of raising awareness about landslides among the public (Alam and Ray-Benner, 2021). Apart from that, together with the government and other stakeholders, NGOs can also play a role in landslide monitoring and community-based early warning systems (EWS) (Fathani et al., 2014). This has been the case in Indonesia since the proliferation of NGOs during the Indian Ocean tsunami (Lassa and Nugraha, 2015). Such proliferation occurs outside of disaster emergencies, as it also occurs in part in response to increasing exposure and vulnerability around the world.

One of the comparative advantages of NGOs is their ability to operate at the grassroots level, where they work with the most at-risk and vulnerable communities. NGOs often take an inclusive and consensual approach to local disaster planning and resilience building (Lassa, 2018). Such operations often allow NGOs to understand and respond to the priorities and agendas of vulnerable people. For example, establishing structural interventions or land-use policies requires indigenous collaboration. Integrating alternative indigenous solutions is essential for monitoring and managing landslide hazard, especially in prone areas environment. In addition, it will promote sustainability and increase possibilities replication by other communities since beneficiaries of landslide risk reduction measures will be able to claim ownership of their disaster risk reduction efforts.

Incorporating a measure of disaster risk reduction into development plans will contribute to disaster risk mitigation. Therefore, it is necessary to propose an integrated framework that can minimize social vulnerability, reduce disaster risk, and increase community resilience and adaptive capacity as part of strengthening governance mechanisms. In addition, the government must continue to promote increased preparedness, response, recovery and reconstruction of affected land (Ndah and Odihi, 2017).

Finally, the aspect of mastering mine avalanche technology is an important factor that must be considered starting from identification technology (Zhu et al., 2014; Shahabi and Hashim, 2015; Vakhshoori et al., 2019), early warning systems (Interiry et al., 2012; Hidayat et al., 2019; Guzzetti et al., 2020), and post-slide handling technology (Lu, 2014; Murlidar et al., 2021; Ramesh, 2021). Of these three things, identification technology is the most developed, while post-slide land handling technology is generally still oriented towards mechanical handling, while efforts to develop land revegetation technology are still promising. Given the important role of soil in the landslide process, cliff stabilization efforts are important. Slope stabilization is very important for civil building and structural engineering and mining projects (Ramesh, 2021). The natural slope stability system is important for landslide prevention and rehabilitation efforts. These efforts help stabilize the ecosystem, manage the risk including landslide occurrence. It also helps to reduce costs and protect human life. A previous study recommended efforts to build native forest vegetation to reduce the risk of landslides. Layers of vegetation cause landslides disaster reduction is in its initial stages (Lu et al., 2014).

## Conclusions

The results showed that of the 50-joint data, those with potential positions for landslides were located at N333°E/61° and N110°E/74°. The most dominant lithology in the study area was claystone, followed successively by sandstone, siltstone, and shale, with a specific gravity between 2.55 and 2.66. The dominant claystone indicated a relatively prone area. Meanwhile, the strength of the mechanical properties of the rock (direct shear) cohesion ranged from 17.80 to 174.53 kPa, with shear angles ranging from 10.88° to 42.01°. Slope stability in the three research locations demonstrated a maximum slope angle ranging from 29° to 37°, a height of 50.17 to 70.16 meters, a single slope height of 10 meters with an angle within 32–44°, and a factor of safety (FOS) between 1.326–1.452 with stable conditions. The MDS simulation results of the sustainability status comprised a total of 49 attributes derived from five dimensions, namely ecological, economic, social, law, institutional, and technological, demonstrated a score of 50.01. Furthermore, to increase the sustainability score, this study identified some sensitive factors as follows: condition of the slope of the mine slope, MSME business of residents, role of NGOs in mine landslides, concern of pit supervisory personnel for mine landslides, and mastery of mine landslide technology. Hence, the projection sustainability score increased to 82.00, which was achieved in the good category.

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## References

Ajake, A. O., Eneyo, V., Akpan, N., Obi, F., Eja, E., Kharbish, S., and Eldosouky, A. M. (2022) Analysis of participatory dimensions of landslide disaster and risk management in some rural communities of south eastern, Nigeria. Carpathian Journal of Earth and Environmental Sciences, 17(2), 323-338. https://doi.org/10.26471/cjees/2022/017/225

Anderson, M. G., and Holcombe, E. (2013) Community-based landslide risk reduction: managing disasters in small steps. World Bank Publications. https://doi.org/10.1596/978-0-8213-9456-4

Aznar-Sánchez, J. A., García-Gómez, J. J., Velasco-Muñoz, J. F., and Carretero-Gómez, A. (2018) Mining waste and its sustainable management: advances in worldwide research. Minerals, 8(7), 284. https://doi.org/10.3390/min8070284

Bednarczyk (2017) Slope Stability Analysis for the Design of a New Lignite Open-Pit Mine. Procedia Engineering, 191, 51-58. https://doi.org/10.1016/j.proeng.2017.05.153

Blackburn, W. R. (2012) The sustainability handbook: the complete management guide to achieving social, economic and environmental responsibility. Routledge.

Bridge, G. (2004) Contested terrain: mining and the environment. Annu. Rev. Environ. Resour., 29, 205-259. https://doi.org/10.1146/annurev.energy.28.011503.163434

Brown, B. J., Hanson, M. E., Liverman, D. M., and Merideth, R. W. (1987) Global sustainability: Toward definition. Environmental management, 11, 713-719. https://doi.org/10.1007/BF01867238

Cahyono, S. A., Wuryanta, A., and Lastiantoro, C. Y. (2021) The local knowledge to mitigate the landslide disaster in Beruk village, Jatiyoso sub-district, Karanganyar regency. In IOP Conference Series: Earth and Environmental Science (Vol. 874, No. 1, p. 012015). IOP Publishing. https://doi.org/10.1088/1755-1315/874/1/012015

Chen, C. Y., and Huang, W. L. (2013) Land use change and landslide characteristics analysis for community-based disaster mitigation. Environmental monitoring and assessment, 185(5), 4125-4139. https://doi.org/10.1007/s10661-012-2855-y

Dychkovskyi, R. E., Vladyko, O. B., Maltsev, D., and Cabana, E. C. (2018) Some aspects of the compatibility of mineral mining technologies. Rudarsko-geološko-naftni zbornik, 33(4). https://doi.org/10.17794/rgn.2018.4.7

Fathani, T. F., Karnawati, D., and Wilopo, W. (2014) An adaptive and sustained landslide monitoring and early warning system. In Landslide science for a safer geoenvironment (pp. 563-567). Springer, Cham. https://doi.org/10.1007/978-3-319-05050-8_87

Ferlianta, W., and Praditya, A. (2018) Kolaborasi Pemerintah Dengan Perusahaan Pertambangan Melalui Program Pengembangan Dan Pemberdayaan Masyarakat. Jurnal Analis Kebijakan, 2(2). https://doi.org/10.37145/jak.v2i2.36

Guzzetti, F., Gariano, S. L., Peruccacci, S., Brunetti, M. T., Marchesini, I., Rossi, M., and Melillo, M. (2020) Geographical landslide early warning systems. Earth-Science Reviews, 200, 102973. https://doi.org/10.1016/j.earscirev.2019.102973

Hong, H., Pourghasemi, H. R., and Pourtaghi, Z. S. (2016) Landslide susceptibility assessment in Lianhua County (China): a comparison between a random forest data mining technique and bivariate and multivariate statistical models. Geomorphology, 259, 105-118. https://doi.org/10.1016/j.geomorph.2016.02.012

Huang, W. P., Li, C., Zhang, L. W., Yuan, Q., Zheng, Y. S., and Liu, Y. (2018) In situ identification of water-permeable fractured zone in overlying composite strata. international Journal of rock Mechanics and Mining Sciences, 105, 85-97. https://doi.org/10.1016/j.ijrmms.2018.03.013

Igwe, O. (2013) ICL/IPL activities in West Africa: landslide risk assessment and hazard mapping approach. Landslides, 10(4), 515-521. https://doi.org/10.1007/s10346-013-0401-9

Kolapo, P., Oniyide, G. O., Said, K. O., Lawal, A. I., Onifade, M., and Munemo, P. (2022) An Overview of Slope Failure in Mining Operations. Mining, 2, 350-384. https://doi.org/10.3390/mining2020019

Lassa, J. A. (2018) Roles of non-government organizations in disaster risk reduction. In Oxford Research Encyclopedia of Natural Hazard Science. https://doi.org/10.1093/acrefore/9780199389407.013.45

Lassa, J. A., and Nugraha, E. (2015) From shared learning to shared action in building resilience in the city of Bandar Lampung, Indonesia. Environment and Urbanization, 27(1), 161-180. https://doi.org/10.1177/0956247814552233

Lu, P. L. (2014) Using multiple vegetation layers to reduce the risk of rainfall-induced landslides and facilitate post-landslide slope rehabilitation. Access International Journal of Agricultural Science, 2(2), 13-17.

Luo, X., Lin, F., Zhu, S., Yu, M., Zhang, Z., Meng, L., and Peng, J. (2019) Mine landslide susceptibility assessment using IVM, ANN and SVM models considering the contribution of affecting factors. PLoS One, 14(4), e0215134. https://doi.org/10.1371/journal.pone.0215134

Ma, G., Hu, X., Yin, Y., Luo, G., and Pan, Y. (2018) Failure mechanisms and development of catastrophic rockslides triggered by precipitation and open-pit mining in Emei, Sichuan, China. Landslides, 15, 1401-1414. https://doi.org/10.1007/s10346-018-0981-5

Ma, S., Qiu, H., Hu, S., Yang, D., and Liu, Z. (2021) Characteristics and geomorphology change detection analysis of the Jiangdingya landslide on July 12, 2018, China. Landslides, 18(1), 383-396. https://doi.org/10.1007/s10346-020-01530-3

McGowran, P., and Donovan, A. (2021) Assemblage theory and disaster risk management. Progress in Human Geography, 45(6), 1601-1624. https://doi.org/10.1177/03091325211003328

Mondal, D., Chowdhury, S., and Basu, D. (2018) Role of panchayat (Local self-government) in managing disaster in terms of reconstruction, crop protection, livestock management and health and sanitation measures. Natural Hazards, 94(1), 371-383. https://doi.org/10.1007/s11069-018-3393-x

Murlidhar, B. R., Yazdani Bejarbaneh, B., Jahed Armaghani, D., Mohammed, A. S., and Tonnizam Mohamad, E. (2021) Application of tree-based predictive models to forecast air overpressure induced by mine blasting. Natural Resources Research, 30(2), 1865-1887. https://doi.org/10.1007/s11053-020-09770-9

Musa, R. H., and Saptono, S. (2015) Analisis Karakteristik Longsor Lereng Lowwall Tambang Terbuka Batubara Ditinjau Dari Monitoring Radar. PROSIDING TPT XXIV DAN KONGRES IX PERHAPI 2015.

Ndah, A. B., and Odihi, J. O. (2017) A systematic study of disaster risk in Brunei Darussalam and options for vulnerability-based disaster risk reduction. International Journal of Disaster Risk Science, 8(2), 208-223. https://doi.org/10.1007/s13753-017-0125-x

Nie W, Huang RQ, Zhang QG, Xian W, Xu FL, Chen L (2015) Prediction of experimental rainfall-eroded soil area based on s-shaped growth curve model framework. Applied Sciences-Based 5(3):157-173. https://doi.org/10.3390/app5030157

Pavloudakis, F., Spanidis, P.-M., Roumpos, C. (2019) Investigation of Natural and Technological Hazards and associated Risks in Surface Lignite Mines. In Proceedings of the 2nd International Conference on Natural Hazards and Infrastructure (ICONHIC), Chania, Crete, Greece, 23-26 June 2019. [Google Scholar]

Primawati, A. (2013) Peranan Corporate Social Responsibility dalam Pemberdayaan Masyarakat di Tabalong, Kalimantan Selatan. Sosio Konsepsia: Jurnal Penelitian dan Pengembangan Kesejahteraan Sosial, 3(1), 1-26.

Ramesh, G. (2021) Slope and landslide stabilization: a review. Indian J Struct Eng (IJSE), 1(2), 13-16. https://doi.org/10.54105/ijse.A1304.111221

Rangga, B., Akbar, A. A., and Herawati, H. (2022) The impact of soil and rock mining on freshwater provisioning services in Peniraman Village, Mempawah Regency, West Kalimantan. Journal of Degraded and Mining Lands Management, 10(1). https://doi.org/10.15243/jdmlm.2022.101.3905

Rhyner, C. R., Kohrell, M. G., Schwartz, L. J., and Wenger, R. B. (2017) Waste management and resource recovery. CRC Press. https://doi.org/10.1201/9780203734278

Salmi, E. F., Nazem, M., and Karakus, M. (2017) Numerical analysis of a large landslide induced by coal mining subsidence. Engineering Geology, 217, 141-152. https://doi.org/10.1016/j.enggeo.2016.12.021

Shahabi, H., and Hashim, M. (2015) Landslide susceptibility mapping using GIS-based statistical models and Remote sensing data in tropical environment. Scientific reports, 5(1), 1-15. https://doi.org/10.1038/srep09899

Singh, T. N. (2013) A finite element approach of stability analysis of internal dump slope in Wardha valley coal field, India, Maharashtra. American Journal of Mining and Metallurgy, 1(1), 1-6.

Spanidis, P. M., Roumpos, C., and Pavloudakis, F. (2021) A fuzzy-AHP methodology for Planning the risk management of Natural hazards in surface mining projects. Sustainability, 13(4), 2369. https://doi.org/10.3390/su13042369

Springman, S. M., Thielen, A., Kienzler, P., and Friedel, S. (2013) A long-term field study for the investigation of rainfall-induced landslides. Geotechnique, 63(14), 1177-1193. https://doi.org/10.1680/geot.11.P.142

Su, Q., Tao, W., Mei, S., Zhang, X., Li, K., Su, X., Guo, J., and Yang, Y. (2021) Landslide Susceptibility Zoning Using C5. 0 Decision Tree, Random Forest, Support Vector Machine and Comparison of Their Performance in a Coal Mine Area. Frontiers in Earth Science, 9, 781472. https://doi.org/10.3389/feart.2021.781472

Tolvanen, A., Eilu, P., Juutinen, A., Kangas, K., Kivinen, M., Markovaara-Koivisto, M., Naskali, A., Salokannel, V., Tuulentie, S., and Similä, J. (2019) Mining in the Arctic environment-A review from ecological, socioeconomic and legal perspectives. Journal of environmental management, 233, 832-844. https://doi.org/10.1016/j.jenvman.2018.11.124

Tonggiroh, A. (2021) Influence of Geomorphology and Siltstone Structure on the Land Vulnerability in Mamberamo Raya, Papua, Indonesia. Journal of Hunan University Natural Sciences, 48(6).

Trisnawati, D., and Hidayatillah, A. S. (2022) The Relationship of Lithology with Landslide Occurrences in Banyumanik and Tembalang Districts, Semarang City. In IOP Conference Series: Earth and Environmental Science (Vol. 1047, No. 1, p. 012026). IOP Publishing. https://doi.org/10.1088/1755-1315/1047/1/012026

Vakhshoori, V., Pourghasemi, H. R., Zare, M., and Blaschke, T. (2019) Landslide susceptibility mapping using GIS-based data mining algorithms. Water, 11(11), 2292. https://doi.org/10.3390/w11112292

Van Westen, C. J. (2013) Remote sensing and GIS for natural hazards assessment and disaster risk management. Treatise on geomorphology, 3, 259-298. https://doi.org/10.1016/B978-0-12-374739-6.00051-8

Verma, S. P., and Armstrong-Altrin, J. S. (2013) New multi-dimensional diagrams for tectonic discrimination of siliciclastic sediments and their application to Precambrian basins. Chemical Geology, 355, 117-133. https://doi.org/10.1016/j.chemgeo.2013.07.014

Zayadi, R., Putri, C. A., Irfan, M. N., Kusuma, Z., Leksono, A. S., and Yanuwiadi, B. (2022) Soil Reinforcement Modelling on a Hilly Slope with Vegetation of Five Species in the Area Prone to Landslide in Malang, Indonesia. Environmental Research, Engineering and Management, 78(3), 56-72. https://doi.org/10.5755/j01.erem.78.3.30670

Zhu, A. X., Wang, R., Qiao, J., Qin, C. Z., Chen, Y., Liu, J., and Zhu, T. (2014) An expert knowledge-based approach to landslide susceptibility mapping using GIS and fuzzy logic. Geomorphology, 214, 128-138. https://doi.org/10.1016/j.geomorph.2014.02.003