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Original Research

## Integrating Geotechnical and Environmental Strategies for Sustainable Mining Operations: A Case study of Makerwal Coal Mine, Pakistan

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### Abstract

Coal mining poses significant risks and environmental concerns. Our main focus is particularly on the Makerwal coal mine located in the Surghar Ranges, Pakistan. This study focuses on geotechnical and environmental evaluations to improve the safety and sustainability of the Makerwal coal mine. Geotechnical assessments of sandstone, shale, and coal seams determined critical parameters to check the geotechnical metrics and environmental compliance for safe mining exploration and exploitation, including rock strength, cohesion, friction angle, and hydraulic conductivity. Uniaxial Compressive Strength (UCS) values varied from 110 MPa for sandstone to 11 MPa for coal, indicating structural deformation and reduced stability. Proximate and ultimate coal analysis revealed variations in physical and chemical properties, affecting combustion efficiency and emissions. Slope stability analysis using Geo5 software and Bishop's method identified critical zones with a factor of safety (FoS) ranging from 1.1 to 2.8 under dry and saturated conditions and hydraulic conductivity ( $10^{-4}$  to  $10^{-6}$  m/s). Environmental evaluations highlighted elevated particulate matter (PM10 and PM2.5) levels exceeding WHO standards by 35% and 45%, while groundwater pH and noise levels were mostly within limits. Mitigation strategies include reinforced rock bolting, retaining structures, slope monitoring systems, eco-friendly backfilling, and groundwater recharge systems. These measures address subsidence, enhance slope stability, and reduce environmental impacts. This framework integrates advanced geotechnical methods and environmental management strategies to support safer, more sustainable coal mining in Makerwal.

**Keywords:** World Health Organization, Makerwal Coal Mine, Pakistan Mineral Development Corporation, Safety in Mines Research Advisory Committee, Environmental Management System.



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## 1. Introduction

Coal mining and deep excavation projects pose significant environmental and safety challenges due to the extensive disturbance of land and the generation of large volumes of waste. As the demand for coal continues to drive deep mining operations, geotechnical engineering offers sustainable solutions that not only mitigate environmental impacts but also enhance operational safety (Brodny and Tutak, 2022). The integration of innovative geotechnical strategies in deep coal mining, emphasizing practices such as waste recycling, foundation reuse, and sustainable treatment of excavated materials is explored. By addressing critical issues such as soil degradation, water pollution, and the responsible management of dredged sediments, these solutions aim to reduce the carbon footprint and resource consumption typically associated with mining activities (Roque et al., 2022). Sustainable mining practices are defined as a concept that incorporates sustainable development principles across the mine life cycle be it, exploration, mine production or closure. Highly challenging is the optimization of the theoretical and methodological issues of planning and developing of coal mine, and the formation of a standard for its sustainable development as this research effort strives to look at conditions or sustainability and the imperative actions for sustainability (Singh and Kumar, 2024). However, the technological developments of the modern world are still unable to offer sustainable mining in many regions. Nevertheless, available methods and tools can minimize that effect. Mineral extraction and post-mining site development can be made environmentally friendly by adopting better land rehabilitation techniques, adopting efficient low-impact mining practices, and utilizing method of recycling the waste material produced in the mining process. Moreover, there is an opportunity and a great prospect in switching to electric-powered equipment, which would also help make the sector more environmentally friendly (Masood et al., 2020).

Though coal is a major source of energy that supports economic growth it has severable social and environmental impacts. Mining methods endanger life through respiratory illnesses and accidents, Pneumoconiosis is the worst occupational disease for underground coal miners, principally arising from the inhalation of airborne coal dust containing high levels of free silica (Ijaz et al., 2020). Other related diseases include; silicosis and tuberculosis and are also categorized under pneumoconiosis. These conditions show that coal mining poses a great risk to human health, water, and ecosystems and has detrimental impacts on communities. Managing energy demand together with controlling the negative influence on health and the environment is the key to the sustainable development of the coal industry (Laney and Weissman, 2014).

The work done by Islam et al., (2024) highlights several key approaches that can be applied to deep coal mining, including the reuse of construction and demolition waste (C&DW) and the recycling of excavated soil and rock, both of which help minimize waste disposal and reduce CO<sub>2</sub> emissions. In addition, higher learning scientific projects based on South Africa, Canada, and Australian mining giants have attempted to develop safe and effectual deep mining technologies so that mining businesses are still lucrative and mum their injurious effects on the environment. These efforts together with the water and soil conservation best management practices are the foundations of sustainable deep excavation in the coal mining stewing a way for boosted safety and minimized environmental impacts (Onifade et al., 2024). Construction industry is recognized



as one of the most significant sources of negative impacts on the environment because it demands great amounts of resources and energy, and produces large amounts of waste. New generation global threats to humanity health have emerged after the beginning of the 2020 such the Covid-19 health crisis linked to environmental geotechnics addressing Construction and Demolition Waste (C&DW) management, there has been a major focus on reusing and recycling non-hazardous industrial waste and by-products Petkar, (2014). The study conducted by Raqeb et al., (2023) also states that (C&DW) approach helps reduce the depletion of global raw materials, such as stone and gravel, which are consumed at an alarming rate due to construction activities. The reuse of C&DW is particularly valuable in reducing the environmental impact of construction projects. By recycling these materials, the construction industry can reduce CO<sub>2</sub> emissions, lower costs associated with transporting materials and waste, and decrease the need for landfill space (Alsheyab, 2022). The European Union has introduced various regulations that encourage this practice, particularly in the context of geotechnical works, where significant volumes of earth and rock are excavated for infrastructure projects (Haas et al., 2021). Bottom ash and coal fly ash can be very useful and important in the area of deep excavation for coal mining hence deserves to be recycled. The study conducted by Northey et al., (2016) emphasizes the effects of mining sites on water quality and establishes that factors like the geographical location, the climate, the type of mining being done, and the level of technological development affect the quality of water in the mining areas. The study conducted by Hamraoui et al., (2024) suggests that an increasing trend in mineral extraction has been observed in the recent years, primarily driven by escalating global demand for mineral resources, which have caused several ecological issues. According to expectations, the global annual generation of solid tailings is predicted to grow to 19 billion tons by 2025, which will further complicate their handling. TSFs are the largest bodies of water within mining areas of any operation given their current size. Further, the original work shows that mismanagement of water content in tailings poses a big risk to their overall stability which can lead to failure of dams and disastrous consequences on the environment. To such important challenges, mining is beginning to seek fresh ideas on sustainable development, including tailings dewatering and water recycling.

Mining operations, especially in coal mining, often result in extensive soil degradation, including the loss of arable land due to the accumulation of waste materials such as tailings, low-grade ore, and mined waste rock (Song et al., 2024). High costs involved in straight straightforward discharge of waste that contains heavy metals and other pollutants into the farmland may lead to poor yields in crops, poor quality of the resultant crops, and poor health among the people and livestock that are fed on such crops. The presence of this contaminant with weighty metals for example arsenic, cadmium, and lead threatens the future of the local agricultural food-producing capacities to the extent of the biosphere. Re-use of foundations in urban mining undertakings Re-use of foundation has turned out to be an important key activity in sustainable development especially in cities where space and resources are scarce. Environmental and geotechnical conditions increase with the extent of ground congestion, particularly in older cities and thus require innovative underground construction like the reuse of foundations (Arora et al., 2021). This practice can lead to substantial reductions in project delays, foundation costs, and carbon emissions, while also preserving archaeological sites and existing infrastructure. The study conducted by Wang et al., (2021) show



that value-added agriculture, economic expansion, and a rise in remittances received all contribute to the reduction of carbon emissions from the chosen panel countries. However, increasing the number of coal industries and enhancing the financial system lead to higher CO<sub>2</sub> emissions. In contrast, the short-run ARDL estimation indicates that CO<sub>2</sub> emissions rise significantly as remittance inflow and agricultural value added rise, but this effect is negligible when it comes to financial development, economic growth, and industry value added (Magnusson et al., 2015). Soil and rock disposal are some of the main environmental issues that shall be expected during implementation of big projects include disposal of the excavated soil and rock. Even though excavated material contains attributes that can be used again, the material is often dumped in a landfill, which is not desirable. The new European regulations have led to the planned use of both clean and very slightly contaminated soil through BMPs that do not result in the designation of the excavated material as waste. In the context of the application of the presented approach in coal mining, integrating soil reuse can decrease CO<sub>2</sub> emission by 14 kg per ton of material and decrease material handling expenses by 85% (Cristóbal et al., 2024). Stabilization/solidification (S/S) treatments of sediments using sustainable binders, such as biochar and mussel shell flour (MSF), have shown promise in reducing the environmental impact of sediment disposal. The goal of these treatments is to neutralize hazardous elements preventing their discharge into the environment, at the same time sediments can be recycled for use in construction purposes or port reinforcement. However, having initially been developed to address marine pollution, the general concepts of S/S treatment can be implemented to deal with contaminated soils and waste in coal mining processes. If used as a binder, this method will help mining industries cut on emissions of carbon and also eliminate unwanted compounds from polluting the environment (De Gisi et al., 2020).

The complicated challenges related to safety and environment deep mining, the research activities have been synchronized worldwide shown in Table. 1, where South Africa, Canada, Australia, and China are most active. Apart from the programs; the South African Safety in Mines Research Advisory Committee (SIMRAC); the Canadian Rock burst Research Program (CRRP) and the Ultra-Deep Mining Network (UDMN) aim at achieving safety with profitability (Hermanus et al., 2015; Muthelo et al., 2022). The created initiatives are intended to counterbalance the threats connected with ultra-deep excavation and to reach the development of geotechnical solutions taking into consideration the economic and environmental factors. Applying geotechnical systems including waste recycling reuse of foundation, and sound sediment management can thus greatly improve the environmental sustainability of deep excavation in coal mining (Muthelo et al., 2022). The adoption of these practices not only minimizes the environmental impact and contributes to safer mining operations by reducing waste generation and ground disturbance. Future research should explore how these practices can be further optimized for mining-specific applications, particularly in areas with stringent environmental regulations (Utembe et al., 2015). Deep coal mining exposes numerous geotechnical hazards such as ground instability, surface subsidence, and environmental issues due to erosion and groundwater contamination. Traditional excavation techniques often neglect the end-of-cycle sustainability of mining sites and their related landscapes. The geotechnical challenges, which institute a requirement for operational safety together with reduction of mining activities footprint on the environment, were suggested to initiate innovation in this field (Bell et al., 2000). The main focus of this study is on Makerwal





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Canada	Canadian Rockburst Research Program (CRRP) Ultra-Deep Mining Network (UDMN)	Rockburst prevention and mitigation Deep mining technology and safety	Improve safety and reduce hazards in mining Enhance safety with profitability	(Muthelo et al., 2022).
Australia	Safety in Mines Research	Safety and environmental challenges in mining	Implicit focus on sustainable mining	(Tynan et al., 2018; Jang and Topal, 2020).
China	Safety in Mines Research	Safety and environmental challenges in mining	Implicit focus on sustainable mining and geohazards assessments	(Yang et al., 2022).

## 2. Study Area

The study area of this research is on the Makerwal Coal Mine (Fig.2), located in Makerwal village in the Mianwali District, Pakistan. The region has been a significant coal mining region since the early 20th century. The area's coal reserves are mined through underground techniques, in different sections within the Surghar Ranges. The keen objectives of this study are to explore the present challenges typical of deep mining operations, such as ground instability and subsidence. These issues are exacerbated by the region's fractured rock formations and high groundwater tables, making it prone to water infiltration and rock falls. Despite the demand for coal from Makerwal, the long-term sustainability of the mining industry is put in jeopardy by this environmental concern. Fig. 2 represents the map of the study area.



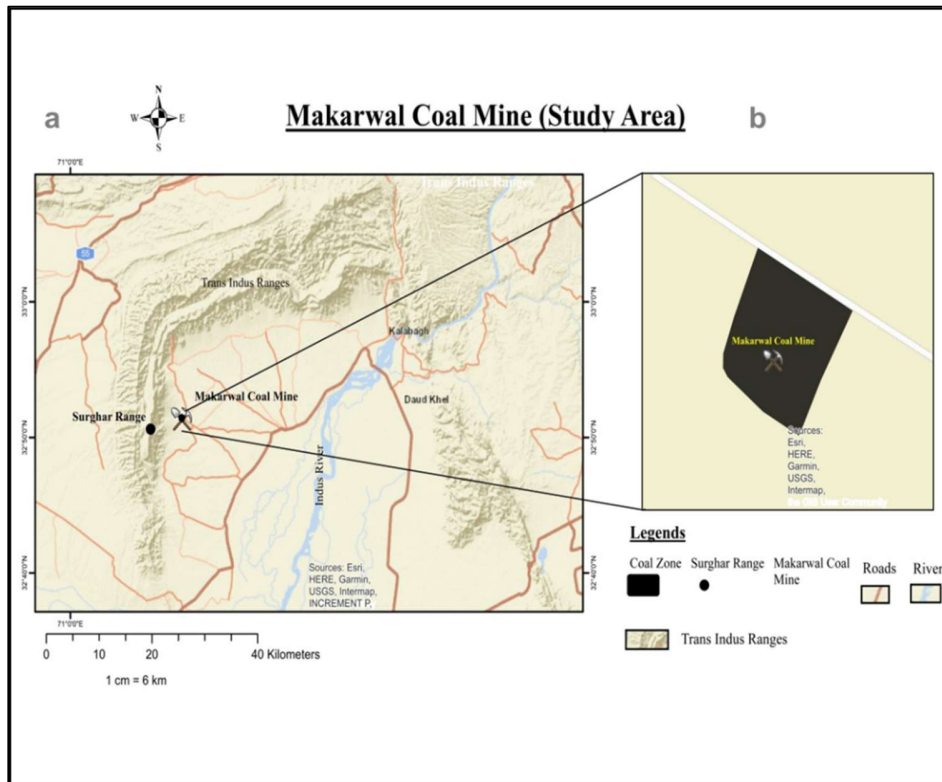


Figure 2. Map of the Makerwal coal mine. (a) mine located near the Surghar ranges part of Trans-Indus Ranges, (b). Coal mine transit

### 3. Research Methodology

The research will take a structured approach to develop the geotechnical techniques for the mine site through the following steps of the concerned study, data and samples were collected directly from the mine site in sampling bags with sample numbers for proximate and ultimate analyses to assess coal composition and geological conditions. These provided foundational data for further evaluations. Geotechnical parameters, including rock strength, cohesion, hydraulics, and depth, were analyzed using UCS tests (ASTM D-7012). These properties were crucial for characterizing mine stability factors. Using Geo5 software, slope stability was analyzed based on geotechnical data, limb angles, excavation material, and safety factors. Geo5 provides robust modelling capabilities using established methods (e.g., Bishop's Simplified Method) to calculate the Factor of Safety and design effective mitigation measures. However, its accuracy depends on reliable input data and assumptions of geological homogeneity, which may oversimplify complex conditions. Integrating Geo5 with field investigations and real-time monitoring enhances its reliability and ensures comprehensive slope stability analysis. Field investigations complemented computational models to improve accuracy. The environmental impacts of mining on air, water, and land systems were evaluated. Sustainable measures were proposed to mitigate harm and ensure compliance with environmental standards. The environmental compliance was performed at the mine site using the Environmental Management System (EMS) standard procedure for mine environmental compliance ISO 14001.



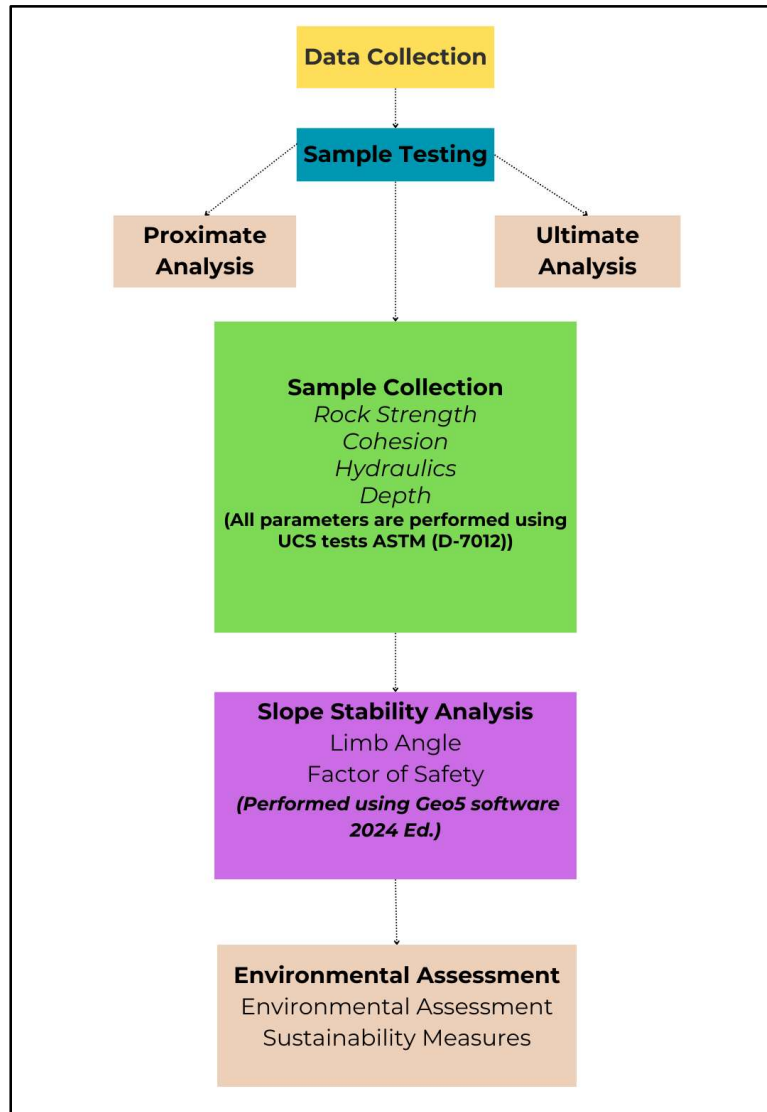


Figure 3. Research Methodology.

## 4. Result Analysis

### 4.1 Site Investigation

For this study, geotechnical analysis was carried out using data collected from Makerwal, Strata build-up forming the Surghar Range. This coalfield is also a sub-block of the massive Surghar and Salt Range Coal fields, which have potential Paleocene-age (Eocene) lignite or low-grade sub-bituminous and bituminous coals deposits those, are known as an economical source to generate electric power in Pakistan. Complex geological formations in the area include a varying thickness of coal seams within sedimentary sequences (Fig. 1).



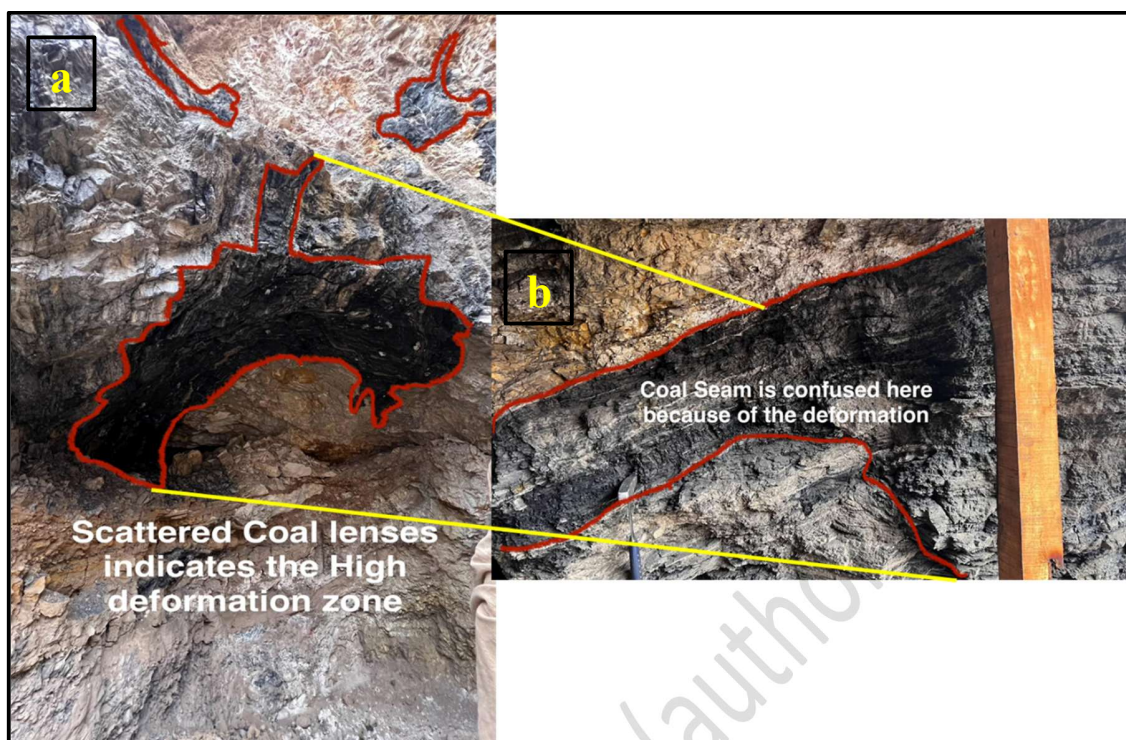


Figure 4. Contact between Hangu sandstone and exposed coal seam bed at Makerwal coal mine (a) Scattered coal lenses (b) Deformation in the rock layers disrupts the coal seam, creating a complex geological structure.

The samples used for this analysis were collected from multiple areas of the mine, i.e., the top bench (55"), and the bottom bench (14") and comprise each site in its entirety. The intention was to provide a full range of geotechnical and coal quality properties across various strata within the mine. This form of sampling provides a comprehensive idea of coal property variation in vertical and lateral directions, which is vital for the estimation of economic viability but also significant for protecting the safety and continuity while mining in this region.

The obtained samples were subjected to proximate Analysis and ultimate Analysis, which yielded important information about the coal's chemical and physical characteristics tested by hydrocarbon development Institute of Pakistan. These studies aid in evaluating the coal's viability for a range of industrial uses, including metallurgical operations and power production. They are also essential in figuring out the coal's environmental impact, particularly concerning waste management and emissions.

Proximate analysis mainly involves the identification of the physical properties of the coal which will play a major role in evaluating the performance of the coal when in combustion as well as the quality aspect of the coal (Schernikau, 2024). The type of proximate analysis commonly used tends to include moisture content, which is the measure of the amount of water in the coal, this affects the heat value and coals handling ability, and volatile matter which is the substances produced during the heating of coal such as hydrocarbons and other gases. Higher volatile matter refers to a more reactive coal while ash content refers to the non-combustible materials left behind if after burning coal which is essential in the knowledge of efficiency in combustion and amount of waste

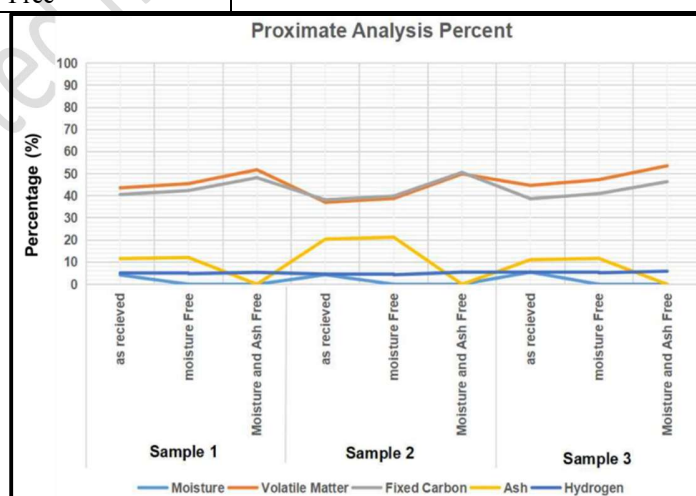


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produced and fixed carbon, it is the solid combustible residue remaining once the volatile matter has been subtracted. Its heating value and handling characteristics, and volatile matter, which refers to the components that vaporize when coal is heated, such as hydrocarbons and other gases. Higher volatile matter suggests a more reactive coal, whereas ash content denotes the non-combustible residue left after coal burning, which is critical for understanding combustion efficiency and waste volume and fixed carbon, this is the solid combustible residue remaining after volatile matter is removed. It counts for much in making the coal and its energy content an important parameter. The results of the samples obtained from the studied coal mine are summarized in Table 1.

Table 2. Proximate Analysis Percent of the Makerwal Coal Mine.

Proximate Analysis Percent						
Source Sample	Condition	Moisture	Volatile Matter	Fixed Carbon	Ash	Hydrogen
Makerwal Coal Mine (Top bench 55")	As Received	4.2	43.6	40.6	11.6	5.1
	Moisture Free	-	45.5	42.4	12.1	4.8
	Moisture and Ash Free	-	51.8	48.2	-	5.4
Makerwal Coal Mine (Bottom bench 14")	As Received	4.3	37.1	38.2	20.4	4.6
	Moisture Free	-	38.8	39.9	21.3	4.3
	Moisture and Ash Free	-	49.9	50.6	-	5.5
Makerwal Coal Mine	As Received	5.5	44.7	38.7	11.1	5.5
	Moisture Free	-	47.3	41	11.7	5.2
	Moisture and Ash Free	-	53.6	46.4	-	5.9



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Figure 5. Proximate Analysis of Coal Samples: Percentage variations in moisture, volatile matter, fixed carbon, ash, and hydrogen content for three coal samples under different conditions (as received, moisture-free, and moisture- and ash-free).

The ultimate analysis provides a chemical breakdown of the coal, which is required to understand its elemental composition (Schernikau, 2024). The typical components examined include carbon (C), the principal ingredient that contributes to coal's calorific value. Hydrogen (H) is a component of the combustion process that adds to coal's heat output. Sulphur (S) is important to measure, as high sulphur means that toxic gases like sulphur dioxide will be emitted, thus affecting the quality of air. Nitrogen (N) is an input that contributes to the emission of nitrogen oxides (NO<sub>x</sub>) during the combustion process and is regulated by many sectors throughout the country. In combustion, oxygen (O) combines with carbon and hydrogen, which affects the total combustion efficiency. From the researched samples of the coal mine, Table 2 sums the data that has been analyzed.

Table 3. Ultimate Analysis Percent of the Makerwal Coal Mine.

Ultimate Analysis Percent						
Source Sample	Condition	Carbon	Nitrogen	Oxygen	Sulfur	Ash
S1 - Makerwal Coal Mine (Top bench 55")	As Received	60.2	0.7	17.5	4.9	11.6
	Moisture Free	62.9	0.8	14.3	5.1	12.1
	Moisture and Ash Free	71.5	0.9	16.4	5.8	-
S2 - Makerwal Coal Mine (Bottom bench 14")	As Received	52.6	0.6	16.9	4.9	20.4
	Moisture Free	55.0	0.7	13.6	5.1	21.3
	Moisture and Ash Free	70.0	0.8	17.2	6.5	-
S3 - Makerwal Coal Mine (Middle bench)	As Received	62.3	0.8	16.2	4.1	11.1
	Moisture Free	65.9	0.8	12.0	4.4	11.7
	Moisture and Ash Free	74.7	0.9	13.6	4.9	-



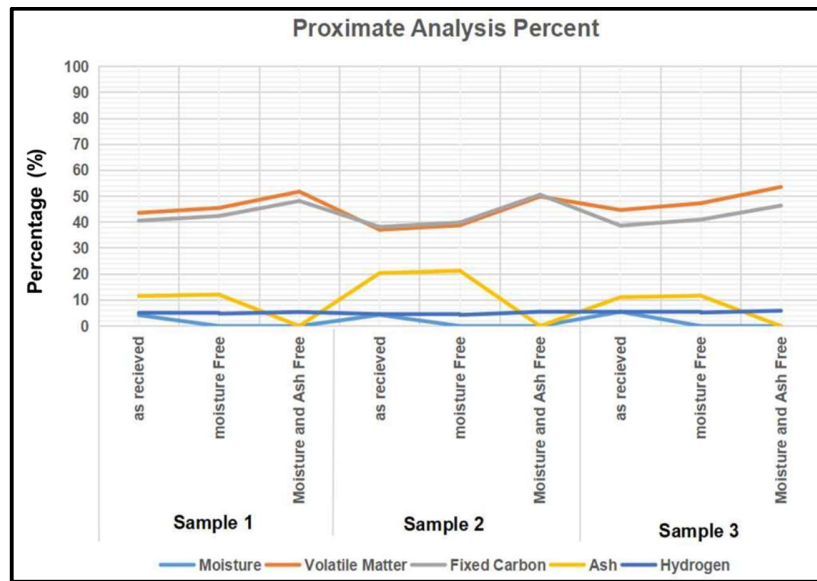


Figure 6. Ultimate Analysis of Coal Samples: Percentage composition of carbon, nitrogen, sulfur, oxygen, and ash for three coal samples under varying conditions (as received, moisture-free, and moisture- and ash-free).

## 4.2 Geotechnical Assessment

For the geotechnical assessment, such as rock strength, cohesion, friction angle, hydraulic conductivity, depth of the water table, and groundwater flow patterns at Makerwal Coal Mine in the Surghar Ranges, investigations were done on the field testing, laboratory analysis, and hydrogeological studies. The studied parameters include rock strength. The RS is the ability of the rock mass or the banded matrix to withstand forces without any breaking and deformation. The area is subjected to highly deformed strata, for that Uniaxial compressive strength (UCS) of the coal bearing formation was conducted at the mine site. The studied samples were sandstone of the Hangu Formation, shales of Patala Formation and coal seams; the result shows that the strength of sandstone is 110 MPa, for shale 44MPa and coal seams shows lower strength of 11 MPa this is due to the structural complexities and intense deformation. The UCS test was conducted under American Standards for Testing Materials (ASTM-D7012). The equation used for the analysis of sample is given below, after (ISRM, 2007) :

$$\sigma = \frac{\rho}{A} \dots \dots (1)$$

Where;

$\sigma$  is the uniaxial compressive strength in MPa,  $\rho$  is the force of failure (deformation in rock) in kN, and A is the sample area or zone in mm.

For the rock samples, the following parameters were considered for the cohesion test done in the lab, a value of comprehensive stress ( $\sigma^1$ ) obtained from the field measurement, and the value of angle of friction ( $\phi^0$ ) obtained from the field measurement. The values obtained for the sandstone sample were 3.17 MPa, shale 0.7 MPa and for the coals seam 0.16 MPa, regarding the angle



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measured in the field using measuring tape. The parameter was calculated using the following equation, after (ISRM, 2007; Jaeger et al., 2009) :

$$C = \tau - \sigma_n \cdot \tan(\phi) \dots \dots (2)$$

Where;

$\tau$  = shear strength of the rock (the maximum shear stress the rock can withstand before failure),  $C$  = cohesion of the rock (the inherent shear strength without the influence of normal stress,  $\sigma_n$  = normal stress acting on the failure plane,  $\phi$  = internal friction angle of the rock (measured in degrees or radians) and  $\tan(\phi)$  = tangent of the internal friction angle, which represents the frictional resistance to shear.

The friction angle is the angle between the maximum resistance of the rock and the shear strength, the friction angle values obtained was for the sandstone the value is  $40^\circ$ , for shale the friction angle is  $32.5^\circ$  and for the coal seam the friction angle is  $21.2^\circ$ .

Table 4. Geotechnical Assessment for the studied parameters.

Geotechnical Assessment Results			
Source Sample	Rock Strength( $\sigma$ ) (UCS)	Cohesion (C)	Friction Angle ( $^\circ$ )
Sandstone	110	3.17	40
Shale	44	0.7	32.5
Coal Seam	11	0.16	21.2

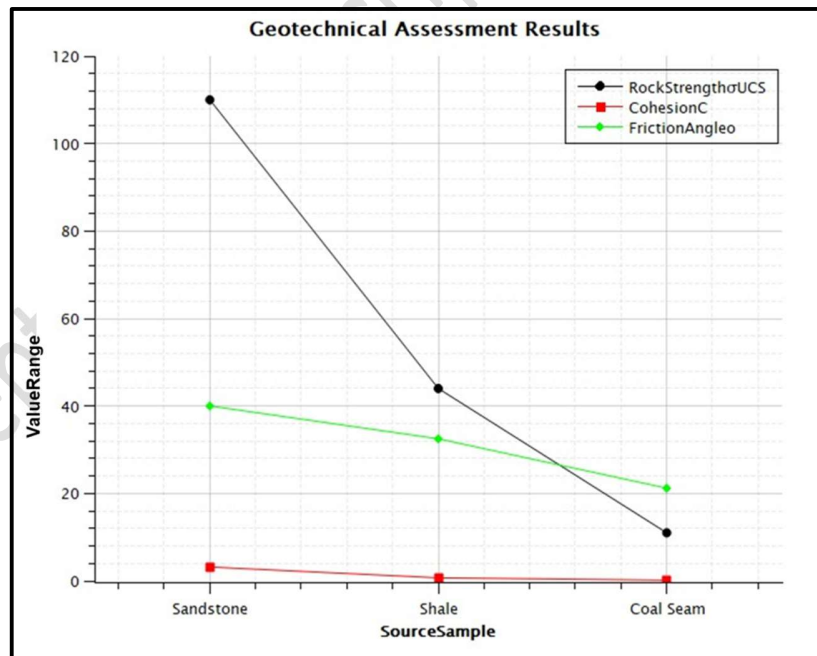


Figure 7. Geotechnical Assessment Results: Variation in rock strength (UCS), cohesion, and friction angle across sandstone, shale, and coal seam samples, highlighting the declining stability parameters in coal seams.



Hydraulic conductivity is the measure of the material's capacity to transmit water through the porous media, but in the coal-bearing formations the hydraulic conductivity depends on permeability of rocks as well. In the Makerwal coal mine, the ranges for the hydraulic conductivity for sandstone varies between  $10^{-4}$  to  $10^{-6}$  m/s, for shale the value ranges from  $10^{-8}$  to  $10^{-10}$  m/s and for coal seams the value ranges from  $10^{-5}$  to  $10^{-7}$  m/s, as per the source information tested by the hydro engineer of the Pakistan Mineral Development Corporation (PMDC). In the Makerwal coal mine, generally groundwater flow is controlled by regional faulting and folding of Surghar Ranges, the flow is influenced by the fractures and faults in the sandstone and coal seams, the flow direction is from higher elevation (hill slopes) towards the mine. The localized flow towards the dewatering points is due to the active groundwater extraction for the mine operations.

### 4.3 Slope Stability Analysis

The Makerwal coalfield is characterized by the north-trending Makerwal anticline, an asymmetric geological structure. The angles of dip vary with the strata being between  $30^\circ$  and  $45^\circ$  on the western limb, while the eastern limb is almost vertical. The slope stability analysis was conducted on both limbs, i.e., the west and east limbs. The geological features of the region, including the presence of steeply dipping coal seams, variable weathering profiles, and groundwater conditions, play a crucial role in determining the overall stability of mine slopes. These factors must be carefully considered when conducting slope stability assessments. The slope stability analysis was conducted through the slope stability analysis software (Geo5), and the factor of safety was calculated through the slope angle software (Civilis). This prediction is in accordance with the Bishop's simplified method. The geotechnical assessment conducted at the mine site for the studied parameters which includes the slope height, slope length and the depth of the water table in situ. The values obtained from the analysis shown in Table. 5a below;

Table 5a. Geometry inputs for the geotechnical assessment of the Makerwal coal mine.

Geometry Inputs		
Slope Height (m)	Slope Length (m)	Depth of Water Table (m)
31.8	110	22

The parameters studied for the rock profile inputs consist of the friction angle, cohesion factor and the layer thickness of the samples. The analysis revealed a reduction in friction angle within coal seam beds, as the thickness of the strata reduced due to the deformation and the geometry of slope indicates that the coal is subjected due to the high deformation style (folding and faulting), this can be the risk factor is extremely dipping areas.

Table 5b. Rock Profile inputs for the geotechnical assessment of Makerwal coal mine.

Rock Profile Inputs					
Strata Name	Layer (m)	Thickness	Weight (kN/m <sup>3</sup> )	Friction Angle $\Phi$ ( <sup>o</sup> )	Effective Cohesion C (kPa)
Sandstone	75.9		21.7	40	3.17
Shale	58.6		18	32.5	0.7
Coal	12		12	21.2	0.16



Analysis showed that the FoS for the mine slopes was between 1.1 and 2.8 under dry conditions, which implied a critical to unsafe stability. Nonetheless, under the wet scenario, when the slope is fully saturated, the FoS at some of the locations falls below 1. Using the above analysis, the result shows that the slope stability of the Makerwal coal mine is quite good, with a FoS of 2.49. However, the location is a highly deformed area and influenced by tectonic activities of the region and therefore may vary according to the potential risk factor. As it is depicted in the model displayed in Fig. 8, the slope stability model calculated for the mine was prepared. For distributed load, the value for sandstone is 50.0 kPa, for shale 28.0 kPa, and for the coal seam, 18.0 kPa respectively while the offset from the crest (baseline) set in blue is at 15m for sandstone, 10 m for shale, and 9.6m for the coal seam bed.

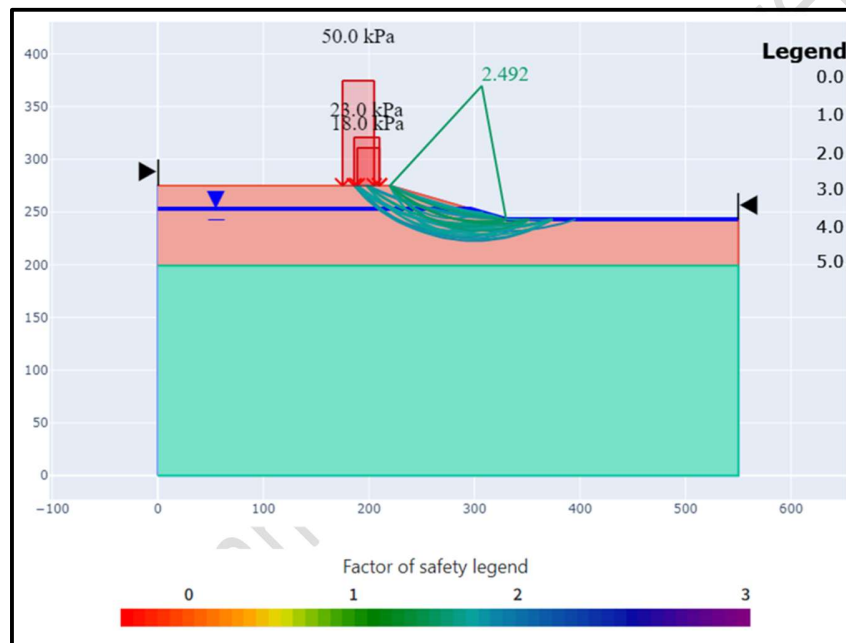


Figure 8. Slope stability model calculated for the Makerwal coal mine using Bishop simplified method on Geo5 analysis software.

#### 4.4 Environmental Assessment

In the Makerwal coal mine due to blasting, transportation, and coal processing, mining operations generate substantial quantities of dust and particulate matter. The assessment of air quality data from the Makerwal mine and nearby areas shows higher levels of particulate matter (PM10 and PM2.5) during peak mining activity. The measured PM10 levels were 35% higher than the World Health Organization's (WHO) allowed limits, while PM 2.5 exceeded the standards by 45%. The other assessment was conducted at the mine site was the noise pollution, as this is the major cause of the environmental issues near the mine site, upon assessment noise levels near the mine were recorded at 45-50 dB, which is considered to be in the limit range according to the WHO limits (70 dB). The standard of drinking water was also tested using pH meter, upon assessment we have



found the pH of the water sample from different source, near source (6.5) and far source (7), so the water near the source is not drinkable according to the WHO standard limit which is 7 in range of pH.

## *Discussion*

The Makerwal coal mine, located within the structurally complex Surghar Range, is of significant geological, economic, and environmental importance. The integration of geotechnical, coal quality, and environmental datasets reveals crucial insights regarding its viability for mining operations and its broader industrial and ecological implications.

The proximate and ultimate analysis of coal samples from different stratigraphic benches (top, bottom, and middle) within the mine provides a comprehensive understanding of coal physiochemical properties. Previously the research conducted by (Shahzad et al., 2014) explained the structural complexity of the Makerwal mine in terms of the coal-bearing formations; similarly in our research the variations also highlight the vertical and lateral heterogeneity typical of coal bearing formations in tectonically active zones. The proximate analysis indicates that the top bench (55") exhibits higher volatile matter (43.6-51.8%) and fixed carbon (40.6-48.2) compared to the bottom bench, similarly in the study conducted by (Khan et al., 2005) the higher volatile matter was nearly 62% and fixed carbon is (55-65%), the reason is due to the changes in the coal horizons and value of coal might be due to the compressional regime of Surghar Range but still the values of this result analysis suggest that top seam contains coal with better combustion characteristics as compared to the bottom and top seam can be a source and suitable for the power generation and thermal production in future. In contrast bottom bench show elevated ash content (20.4-21.3%) which can result in lower combustion as the efficiency of coal matter became low at the bottom bench. The middle bench with moderate ash content (11.1%) and higher carbon (62.3-74.7%) emerges as the potential source, more consistent and economically viable. The higher combustion leads to the cleaner production coal technology, but in the previous studies by (Shahzad et al., 2014) and (Malkani et al., 2016) this bench was not discussed due to its unexposed surface due to the deviation in the western limb angle as discussed earlier in this research. The ultimate analysis further supports this by demonstrating that the middle bench coal has highest carbon content, low sulphur and moderate nitrogen due to its new exposure to the surface. Low sulphur (4.1-4.9%) is particularly important for reducing SO<sub>2</sub> emissions due to the surrounding environmental conditions and exposure of different strata and complex carbonate zones surrounding the range the factor was also discussed in the study conducted by (Winarno et al., 2018), their results show the average concentration of sulphur as sulphur as (0.67 %), the presence of sub-bituminous coal, in a tectonically active but coal-rich setting emphasizes the stratigraphic importance of the Makerwal coal mine in meeting energy demands as discussed in the work done by the stratigraphic commission of Pakistan (Malkani et al., 2016; Ijaz et al., 2020).

The uniaxial compressive test (UCS) conducted using ASTM D-7012, results clearly show a descending trend in rock strength from sandstone (110 MPa) to shale (44MPa) and coal seam (11MPa), the results reflect the inherent mechanical weakness of coal seams, exacerbated by intense deformation and due to structural lineation and low angle dipping near the surface in



Surghar Range. The cohesion and friction angle values reinforce this observation, sandstone with high cohesion (3.17 MPa) and friction angle ( $40^{\circ}$ ), exhibits strong interparticle strata bonding and resistance to sliding (in case of deformation). Conversely, the coal seams, with cohesion of just (0.16 MPa) and friction angle ( $21.2^{\circ}$ ), are highly susceptible to slippage and deformation, particularly under dynamic loads and during wet conditions. These parameters are critical when modeling slope behavior as discussed in the research by (Ijaz et al., 2020) similarly, in this research also the slope behaviour is crucial factor while drilling at the mine face and depth. The slope geometry input and rock profile data, the steeply dipping beds especially on the eastern limb of Makerwal anticline spreading westward present slope stability risk if the extraction became in depth with concentrated zones. The presence of shallow mineralization and depth to rock is established to provide an understanding of the quality and mechanical properties of the coals seams and rock mass together with their bearing capacity on the structure of the mine, the fact was also discussed in detail study by Ali et al., (2022) that shows how remote sensing methods can be applied to the coal mining monitoring program to enable efficient and successful monitoring and to mitigate the negative effects of coal mining operations. The FoS values (1.1-2.8 under dry conditions) suggest marginal stability, with some slopes falling below critical safety thresholds during saturation. This highlights the importance of considering seasonal groundwater fluctuations and tectonic stress reactivations in ongoing slope monitoring.

The Makerwal coal mine hydraulic conductivity data indicates varied permeability characteristics across different lithologies. The sandstone units became more permeable due to the porous behavior and fluid capacity movement ( $10^{-4}$ - $10^{-6}$  m/s), while shale and coal with lower conductivity ( $10^{-7}$ - $10^{-10}$  m/s) restrict groundwater flow, potentially causing localized water pooling or pressure built-up within seams. The groundwater flow regime, dictated by the regional faulting and folding, directs water movement from elevated terrain toward mine workings. The dewatering operations around active mining areas further exacerbate drawdown effects, contributing to water table reduction and associated impacts on adjacent ecosystems and agriculture this factor was also discussed by research conducted by Alsheyab, (2022) but more related to construction waste and mine slurry. Monitoring of groundwater recharge and withdrawal is essential to minimize hydrogeological imbalance.

Developing appropriate geotechnical solutions for the Makerwal Coal Mine requires tackling stability, subsidence, and groundwater issues in order to improve operational safety and environmental sustainability. Given the mine's depth and the unique geology of the Surghar Range, these solutions must prioritize ground stability, erosion control, and groundwater management. Several measures toward stabilizing the slopes are under research to aid in preventing further danger of landslides and collapses. A novel approach to enhancing slope stability, especially on higher benches is through reinforced rock bolting and retaining structures. Strengthening technologies incorporated into comparable geological constitutions have revealed that the reinforcement cantilever framework enhances the strength of slopes by easing stress dispersion (Li et al., 2024). In addition to this, slope monitoring systems that contain sensors, that relay information in real-time can help in the determination of the earliest signs of slope instability to prevent failure (Mohanty et al., 2022).



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Since large-scale underground coal mining has led to surface subsidence issues thus the infrastructure and the people living around the mines are also at risk, subsidence control is also a major aim. It has been noted that the ministry had employed some methods including grouting and backfilling which has been effective in mitigating the effects of movements within the ground. In the backfilling process, fly ash is an example of eco-friendly material that has both geotechnical and environmental gains since fly ash is a mining byproduct hence is recycled in the process of backfilling, supporting structures (Vilakazi et al., 2022). A further aspect is the proper use of the water resource in the study area, particularly the groundwater as this has been significantly affected by the localized reduction in the water table brought about by the mining process on the nearby agricultural fields. Recharge systems may reduce the impact on the availability of water table while dewatering wells and barriers may help in controlling water table. Some permissible barriers should be placed at the edges of mines as a way of controlling the flow of water and maintaining balance, according to research (Thomas et al., 2020).

By using these geotechnical solutions at Makerwal, mining safety can be greatly increased and environmental effects can be lessened. The sustainable operation of Makerwal and other coal mining sites will depend on the ongoing development and improvement of these technologies, which are adapted to the unique geological features of the Surghar Range.

A substantial portion of the coal produced in the area comes from the Makerwal Coal Mine. Its operations do, however, have substantial and varied environmental effects, affecting biodiversity, land use, water resources, and air quality, as is the case with many coal mines. By evaluating these impacts, an Environmental Impact Assessment (EIA) aims to provide light on the extent of environmental deterioration and suggest mitigation strategies to lessen damage (Sadiq et al., 2017). As the air quality degradation is a major concern in Makerwal coal mine, with PM<sub>10</sub> and PM<sub>2.5</sub> levels exceeding WHO thresholds by (35-45%) is a major concern and alarming condition, similarly these levels are explained in detail study by Stewart, (2020) explaining the current global economy concentrates on profit at the expense of the health of miners. Similarly in our research concern these particulates, generated by blasting, crushing, and vehicular movement, pose health risks to nearby populations and mine workers. Noise pollution, although within acceptable WHO limits (45-50 dB), still contributes to chronic stress in nearby communities, this was better explained in the study conducted by Bialy et al., (2021) explaining the proposed specific solutions to reduce the impacts of noise on health and work comfort. This research underscores the need for buffer zones and sound barriers, particularly near residential areas of the Makerwal village. Water quality, assessed via pH analysis, reveals acidic conditions (pH 6.5) near the mine. This slightly acidic nature may stem from acid mine drainage (AMD), suggesting potential contamination risks to surface and groundwater systems. Such findings reinforce the necessity of water treatment facilities and regular monitoring protocols. The high deformed regime of the Surghar range makes a geotechnical challenges to keep this solutions and factor in consideration the implementation of reinforced rock bolting and retaining structures has been shown to effectively redistribute stresses and increase slope stability. These systems, particularly in higher benches, can mitigate the risk of large-scale landslides. Slope monitoring systems utilizing real-time sensors are recommended to detect precursors to slope failure. These include ground displacement, water pressure changes, and



vibrational anomalies. Furthermore, subsidence control is critical in underground workings. Grouting and backfilling with fly ash serve the dual purpose of structural reinforcement and environmental waste reuse. This aligns with circular economy principles, enhancing sustainability as this work has never been done in the recent past in the active Salt Range mines by Pakistan mineral development corporation. Groundwater management via recharge systems, dewatering wells, and hydraulic barriers will be essential to mitigate the environmental effects of water table drawdown and to support surrounding agricultural lands.

## 5. Conclusions

The Makerwal coal mine located in the structurally active Trans-Indus Ranges and belonging to the Paleocene age, holds strategic importance due to its economic significance and has potential in the low-grade coal production and energy generation for surrounding regions. Owing to increasing concerns regarding slope failures, groundwater depletion, and environmental degradation associated with deep coal mining, the study was designed to assess the geological and geotechnical significance of Makerwal coal mine. Emphasis was placed on addressing these issues within the context of local structural complexities evolving environmental conditions. A multidisciplinary approach was applied to investigate the geological conditions and mine safety challenges. Initially, the site visits were conducted to establish the stratigraphic context, followed by detailed sampling across top, middle and bottom coal benches, the lab test for the geotechnical parameters were performed after the initial chemical and physical (proximate and ultimate) analysis. Geotechnical investigation includes cohesion test, friction angle test and uniaxial compressive strength test (UCS), the test was performed in NESPAK lab using American Standard for Testing Materials (ASTM D-7012) standard procedure test and cohesion test was performed using same procedure and the data integration was performed using Geo5 software by Fine software Inc. The Environmental compliance was performed at the mine site using Environmental Management System (EMS) standard procedure for mine environmental compliance ISO 14001. The results highlights that the coal from the top bench exhibit high volatile matter and fixed carbon, making it suitable for thermal applications, while the bottom bench showed higher ash content and lower combustion efficiency. The geotechnical characterization reveals significant insights in rock strength and hydraulic conductivity among sandstone, shale, and coal seams, with sandstone exhibiting the highest strength (110 MPa) and hydraulic conductivity ( $10^{-4}$  to  $10^{-6}$  m/s) indicates its competence as a structurally stable and permeable unit. In contrast, coal seams present the lowest strength (11 MPa) and hydraulic conductivity ( $10^{-5}$  to  $10^{-7}$  m/s) highlighting their susceptibility to the mechanical failure and limited groundwater flow. Shale, typically intermediate in both properties shows moderate level of risk but still required the reinforcement and monitoring during mining operations due to the possibility of slow penetration and collapse of structure and hydraulic instability due to its high porous nature. These variations highlights the need for lithology-specific engineering designs and proper reinforcement methods in Makerwal coal mine block, quick and efficient mine design plans will be the best possible approach to target the bottom bench coal seams surrounded by the sedimentary rocks, with enhanced support system in coal bearing zones and coal bearing formation. Furthermore, the slope stability analysis demonstrated that the factor of safety (FoS) for dry conditions ranged between 1.1 and 2.8, while it dropped



below 1 in wet conditions, indicated marginal to critical stability, particularly under saturated conditions and during monsoonal groundwater fluctuations. These results stress the need for continuous slope monitoring and proactive stabilization measures, especially along steeply dipping eastern limbs of the Makerwal anticline. Environmental assessments underscored significant impacts, including particulate matter (PM10 and PM2.5) concentrations exceeding WHO limits by 35% and 45% respectively, and localized groundwater contamination with pH levels falling below the acceptable range near the mine. It is with such considerations in mind that these findings suggest the importance of taking proactive measures to reduce the impacts of mining onset. These findings highlight the dual utility and risk associated with mining in the Makerwal region. While coal reserves offer viable energy alternatives, with structural instability of the mine poses significant safety threats. Engineering interventions such as rock bolting, slope monitoring, and subsidence control via grouting and fly ash backfilling are critical for improving mine stability and aligning operations with circular economy practices. Groundwater protection through managed dewatering and recharge systems is also essential to safeguard downstream agricultural activities and drinking water sources.

Limitations of this study include the assumptions of homogeneity within rock masses and the exclusion of dynamic loading conditions (e.g., seismic effects) in the current stability models which is not discussed in the literature and the proper 2D and 3D seismic surveys have not been conducted in the past or near far to check mine integrity and life of the mine. Future research prospects should incorporate numerical modeling (e.g., finite element or discrete element methods) to capture more complex failure modes and time-development behaviors. Integration of real time monitoring data (e.g., through InSAR and ground-based LiDAR) would enhance the predictive capacity of slope stability assessments. Further investigation into the hydrogeological dynamics of the slope environment is recommended to better quantify the role of pore pressure fluctuations on slope stability.

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