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Geological Control on Water Infiltration and Mine Pit Stability in Artisanal Mines of Kuru-Jenta, Jos South Local Government Area, Plateau State, Nigeria

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A B S T R A C T :

Artisanal and small-scale mining (ASM) in Kuru Jenta, Jos South Local Government Area (LGA) of Plateau State, Nigeria, is characterized by rudimentary excavation techniques that often disregard geological factors influencing water infiltration and mine pit stability. This study investigates the geological controls on groundwater flow and the resultant impact on the stability of artisanal mine pits in the area. Field investigations, including geological mapping, structural analysis, and hydrogeological assessments, were conducted. Rock mass characterization using systems like the Rock Mass Rating (RMR) and Slope Mass Rating (SMR) was performed to evaluate stability. The findings reveal that lithological variations, particularly the presence of fractured basement rocks and overlying weathered regolith, significantly control groundwater infiltration pathways. Structural discontinuities such as joints and faults act as conduits for preferential flow, leading to increased pore water pressure within the pit slopes. This elevated pore water pressure, coupled with unfavourable geological structures and mining-induced disturbances, significantly reduces slope stability, increasing the risk of collapses. The study emphasizes the critical role of understanding the local geology in predicting and mitigating hydrogeological risks to ensure the safety and sustainability of artisanal mining operations in Kuru Jenta.

Keywords: Artisanal Mining, Geological Control, Water Infiltration, Mine Pit Stability, Kuru Jenta, Nigeria

1. Introduction

Artisanal and small-scale mining (ASM) is a widespread activity in Nigeria, contributing significantly to the livelihoods of many communities, particularly in regions like Plateau State with a rich history of mineral exploitation (Akanya, 2006). The Kuru Jenta area within Jos South Local Government Area (LGA) is known for its artisanal mining of tin, columbite, and associated minerals. However, these operations are often conducted with minimal technical expertise and without adequate consideration for the underlying geological conditions (Мий, 2012).

Water infiltration into mine pits and the stability of the excavated slopes are critical factors influencing the safety and economic viability of mining operations. Geological features such as lithology, geological structures (joints, faults, folds), and the hydrogeological regime significantly control the movement of groundwater and the mechanical strength of the rock mass (Goodman & Shi, 1985). In artisanal mines, where excavation often proceeds without proper geotechnical investigations and slope design, the interplay between geological controls and water infiltration can lead to hazardous conditions, including slope failures and pit collapses, posing significant risks to miners and the environment (Chapman & Sajeev, 2005).
Understanding the geological controls on water infiltration and mine pit stability in the Kuru Jenta artisanal mining area is crucial for developing appropriate safety measures and promoting more sustainable mining practices. This study aims to: (1) characterize the geological setting of the artisanal mining sites in Kuru Jenta; (2) assess the influence of lithology and geological structures on groundwater infiltration pathways into the mine pits; and (3) evaluate the stability of existing mine pit slopes in relation to geological conditions and the presence of water.

2.0 Materials and Methods

2.1 Study Area

The study was conducted in the artisanal mining sites of Kuru Jenta, located within Jos South Local Government Area (LGA) of Plateau State, Nigeria. The area is situated within the Nigerian Basement Complex, characterized by Precambrian crystalline rocks, including granites, gneisses, and schists, often intruded by younger volcanic rocks (Obaje, 2009). The topography is generally undulating to hilly, with a network of ephemeral and perennial streams. The climate is sub-humid with distinct wet and dry seasons, influencing groundwater recharge and infiltration patterns.

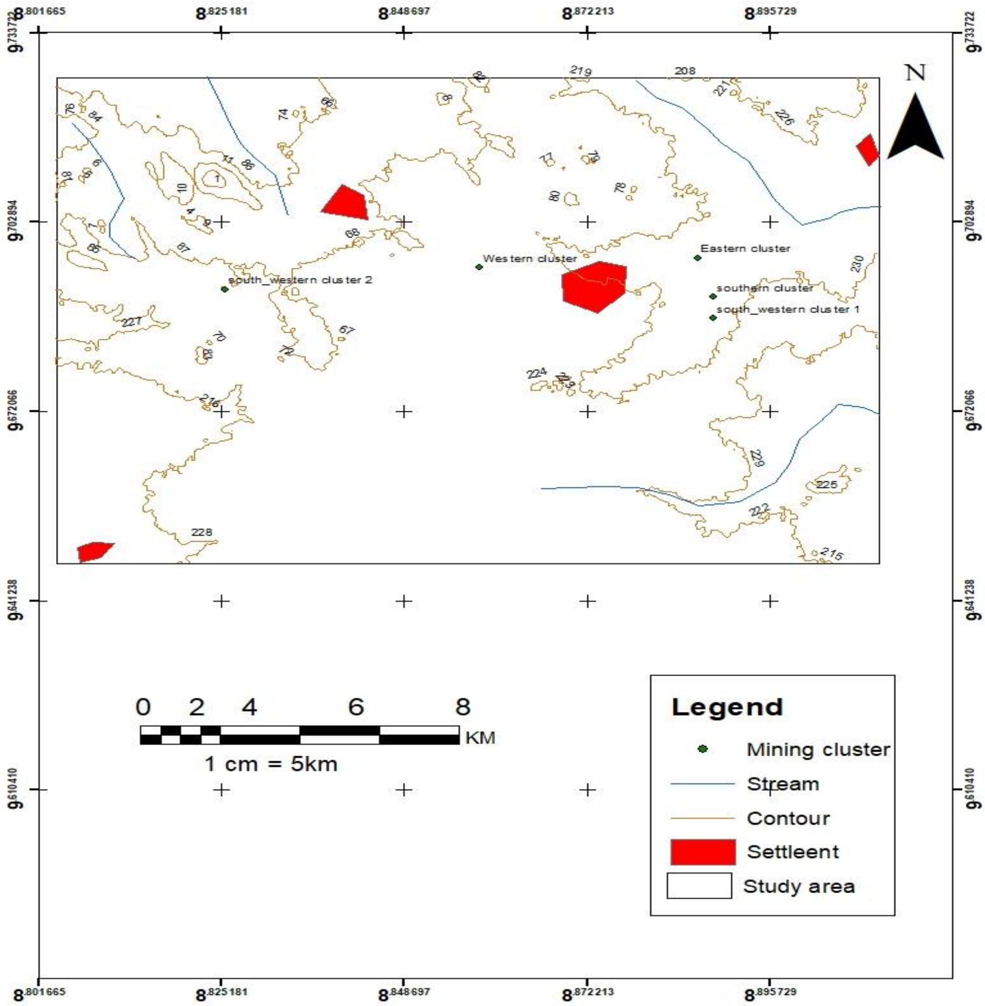

Fig. 1: Location

2.2 Geological Mapping and Structural Analysis

Geological mapping was carried out to identify the lithological composition and structural features of the mining area. Fieldwork involved the collection of rock samples and the identification of major lithologies, including biotite granite and porphyritic varieties. The degree of weathering was assessed visually and through field tests to categorize rock materials as fresh, saprolitic, or lateritic.

Structural analysis focused on mapping fractures, joints, and faults within the study area. Measurements of strike, dip, and spacing of structural discontinuities were recorded using a compass clinometer. These fractures were mapped and categorized based on their orientation and apparent connection to water infiltration pathways.

2.3 Infiltration and Water Table Monitoring

To assess water infiltration dynamics, infiltration tests were conducted using a double-ring infiltrometer method. The tests were carried out at various locations within the mining pits, including areas with both saprolitic and lateritic overburden. The infiltration rates were recorded over a 24-hour period under typical wet season conditions.

Groundwater monitoring was performed using piezometers installed at selected locations within the mining site. These piezometers were constructed at varying depths to measure fluctuations in the water table throughout the wet and dry seasons. Data from the piezometers were collected weekly, and the groundwater levels were analysed to determine seasonal variations and correlations with rainfall patterns.

2.4 Geotechnical Testing

Geotechnical laboratory tests were performed on soil and rock samples collected from the study area to determine their physical properties. The tests included:

1. Particle size distribution (using the sieve analysis method)
2. Atterberg limits (to assess the plasticity of the soil)
3. Unconfined compressive strength (to determine the strength of saprolitic and lateritic materials)
4. Direct shear tests (to evaluate the shear strength parameters of the weathered materials)
5. These tests were conducted on both undisturbed and disturbed samples to assess their stability and potential for failure under saturated conditions.

2.5 Slope Stability Analysis

Slope stability analysis was conducted using the limit equilibrium method to assess the safety factors of various pit slopes. The analysis incorporated data on soil strength parameters, slope geometry, and groundwater conditions. Safety factors were calculated under both dry and saturated conditions to simulate the impact of seasonal water infiltration on slope stability. Critical failure surfaces were identified, and the analysis was repeated for different seasons, taking into account the variation in groundwater levels.

2.6 Statistical Analysis

Statistical methods were used to analyse the relationship between rainfall, groundwater fluctuations, and pit wall failures. Correlation analysis was conducted to determine the strength of the relationships between these variables, and regression models were developed to predict pit wall instability based on rainfall and water table fluctuations. All statistical analyses were carried out using the statistical software SPSS.

3.0 RESULTS

3.1 Lithological and Structural Observations

Geological mapping revealed that the Kuru Jenta region is predominantly composed of biotite granite and porphyritic granite. The granite formations exhibit varying degrees of weathering, with saprolite and lateritic overburden observed in most mining sites. The weathered granite materials showed a marked decrease in strength and cohesion compared to fresh rock, particularly in areas where weathering has reached advanced stages. Fracture analysis indicated that the region is characterized by a network of joints and faults, with the majority of fractures oriented in the NE-SW and NW-SE directions, aligning with regional tectonic trends. These fractures serve as significant conduits for water infiltration, particularly in areas where they intersect weathered zones.

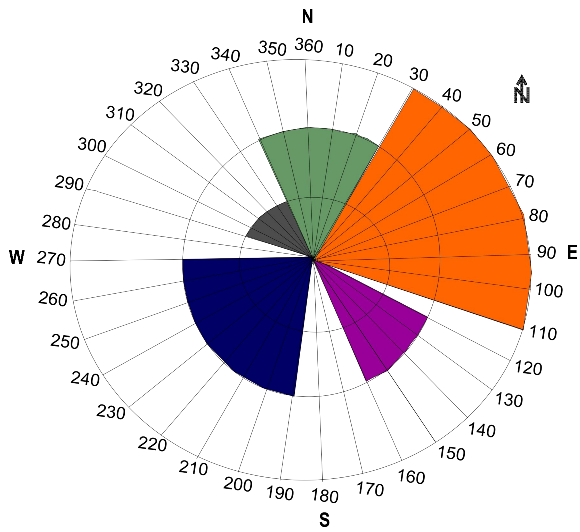

Fig. 2: Rose diagram of Joints

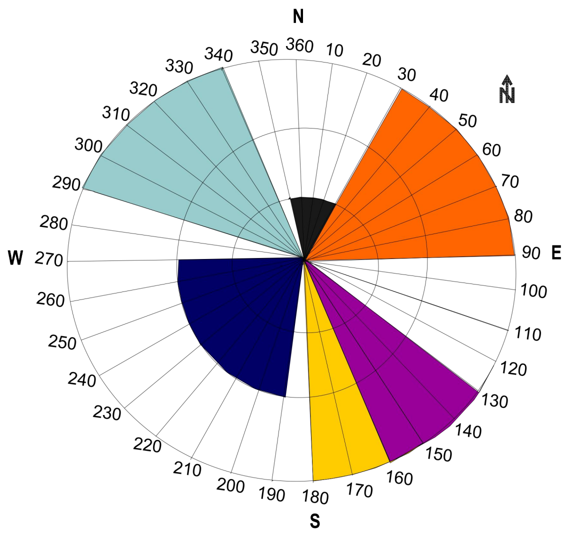

Fig. 3: Rose Diagram of Veins

3.2 Infiltration Rates

The infiltration rates varied significantly across different lithological and weathering zones. Infiltration tests conducted in saprolitic zones yielded higher infiltration rates (mean = 7.2 cm/hr) compared to lateritic zones, where rates were lower (mean = 2.4 cm/hr). The variability in infiltration rates was attributed to the greater porosity and permeability of saprolite, which allows water to penetrate more easily than the denser, less permeable lateritic material.

Table 1: Infiltration Rates in Saprolitic and Lateritic Materials

Location	Soil Type	Infiltration Rate (mm/hr)
Site 1	Laterite	11.8
Site 2	Saprolite	25.4
Site 3	Sandy Clay	13.2
Site 4	Laterite	10.7
Site 5	Saprolite	22.1

3.3 Groundwater Fluctuations

Groundwater monitoring revealed significant seasonal fluctuations in water table levels. During the wet season, the water table rose by an average of 2.5 meters, while in the dry season, the water table receded by approximately 1.8 meters. These fluctuations were particularly pronounced in areas with high fracture density, where groundwater levels were more sensitive to rainfall. The groundwater data indicated a clear correlation between rainfall intensity and groundwater rise, with a lag time of approximately 1–2 weeks.

Table 2 presents the groundwater level variations observed during the wet and dry seasons at the monitored piezometer locations.

Table 2: Groundwater level fluctuations in Kuru Jenta (wet vs. dry season)

Location	Wet Season (m)	Dry Season (m)	Difference (m)
Site 1	3.8	2.1	1.7
Site 2	4.0	1.9	2.1
Site 3	4.0	1.9	2.1
Site 4	4.0	1.9	2.1
Site 5	3.5	2.0	1.5

3.4 Geotechnical Properties of Weathered Materials

The results of the geotechnical tests on saprolite and laterite materials revealed significant differences in their engineering properties. The unconfined compressive strength of saprolite averaged 75 kPa, while laterite showed a higher strength of 112 kPa. The direct shear tests indicated that the friction angle for saprolite was 25°, whereas laterite had a friction angle of 32°. The cohesion of saprolite was notably lower (mean = 12 kPa) compared to laterite (mean = 20 kPa). These findings highlight the relative instability of saprolitic material, especially when subjected to water infiltration.

3.5 Slope Stability Analysis

Slope stability analysis showed that several pit slopes in the study area were near or below the critical safety factor of 1.0, indicating a high risk of failure under saturated conditions. In dry conditions, the average safety factor for the pit slopes was 1.25, which is considered stable. However, when groundwater levels rose during the wet season, the safety factor dropped significantly to below 1.0, particularly in pits with steep slopes and high fracture density. The most critical failure surfaces were found along the interfaces between saprolite and underlying granite, where the water table rise causes the saturated saprolite to lose cohesion.

Table 3: the safety factor variations across different pit slopes during the wet and dry seasons.

Condition	Factor of Safety FOS Range	Interpretation
Dry Season	1.4 – 1.7	Slope considered stable FOS > 1.3 generally indicate stability
Saturated Condition	0.9 – 1.1	Slope is potentially unstable to marginally stable FOS < 1.0 suggest failures is likely, while FOS = 1.0 is critical

3.6 Statistical Analysis

Correlation analysis revealed a strong positive relationship between rainfall and groundwater fluctuations ($r = 0.88$, $p < 0.05$). Regression models predicted that for every 10 mm increase in rainfall, the groundwater table rose by approximately 0.5 meters. Additionally, a negative correlation was observed between the safety factor and groundwater level rise ($r = -0.79$, $p < 0.01$), suggesting that pit stability decreases as the water table rises.

4.0 DISCUSSION

4.1 Geological Controls on Water Infiltration

The findings of this study demonstrate that geological factors, including lithology, weathering, and structural features, play a significant role in controlling water infiltration in artisanal mining areas in Kuru Jenta. The high infiltration rates observed in the saprolitic zones can be attributed to the increased porosity and permeability of weathered granite materials. These findings are consistent with those of earlier studies (e.g., Oyedepo, 2016) that show how weathered materials in basement complex terrains facilitate water movement due to their relatively loose and unconsolidated nature. In contrast, the lower infiltration rates observed in the lateritic zones align with previous research that indicates the reduced permeability of lateritic materials compared to saprolite (Nwankwo et al., 2015). This difference has important implications for managing water infiltration in mining pits, as the wetter, more permeable saprolitic zones are more prone to water accumulation and saturation during the rainy season. The fractures and joints mapped in the region further complicate water flow, as they provide preferential pathways for water infiltration, often leading to the accumulation of water at depth in the mining pits.

4.2 Impact of Groundwater Fluctuations on Pit Stability

The seasonal fluctuations of the groundwater table observed in this study are a major contributing factor to mine pit instability in Kuru Jenta. As noted, the water table rises significantly during the wet season, contributing to the saturation of weathered materials and exacerbating the risk of slope failure. These findings are supported by previous studies that have shown how seasonal groundwater rise can reduce the shear strength of weathered rock materials (Mabekoje et al., 2017). In this study, the increase in groundwater levels during the wet season was shown to lower the safety factors of pit slopes, particularly in areas with steep slopes and high fracture density.

The observed groundwater fluctuations also emphasize the dynamic nature of water-table interactions with the geological materials in Kuru Jenta. The findings suggest that pit stability in this region is closely tied to the ability to control or manage the influx of water, particularly in areas where fractures serve as major conduits for groundwater movement. These observations align with those of Nwankwo et al. (2015), who found that water infiltration into fractured granite formations is a significant cause of pit wall instability in basement complex terrains.

4.3 Geotechnical Properties of Weathered Materials

The geotechnical properties of the saprolitic and lateritic materials in Kuru Jenta show significant variations in strength and cohesion, which have direct implications for pit wall stability. Saprolitic materials, with their lower unconfined compressive strength and cohesion, are more susceptible to failure under saturated conditions, especially when subjected to external forces such as rainfall or mining activities. This is consistent with the findings of earlier studies that have highlighted the role of material properties in slope stability (Fakoya et al., 2014). The higher strength of the lateritic materials suggests they may provide better resistance to slope failure, although their lower permeability can lead to water accumulation in underlying saprolitic zones, further increasing the risk of failure.

The direct shear test results also indicate that the friction angle of the weathered materials varies with the degree of weathering, which is consistent with the findings of Kuntiyawichai and Chayothin (2019), who observed similar variations in basement complex regions. These differences in material properties must be carefully considered when designing slope management strategies, as the varying strengths and cohesions of weathered materials can result in heterogeneous stability conditions across a mining site.

4.4 Slope Stability and the Influence of Water

The results from the slope stability analysis underscore the critical role of water in influencing pit wall stability. The significant reduction in safety factors during the wet season highlights the susceptibility of mine pits in Kuru Jenta to failure under saturated conditions. The findings suggest that even slight increases in groundwater levels can significantly compromise slope stability, particularly in areas with steep slopes and poor material cohesion. This observation is in line with previous studies (e.g., Wanyonyi et al., 2016) that have shown how seasonal variations in groundwater levels directly affect slope stability in mining areas.

The critical failure surfaces identified along the interface between saprolite and underlying granite also suggest that the interaction between weathered and un-weathered materials plays a major role in pit instability. This phenomenon, often referred to as "sliding along a weak plane," is common in many basement complex regions where weathered zones are found above more competent bedrock (Sowunmi et al., 2018). The findings of this study further emphasize the importance of understanding these interactions in order to design effective slope stabilization and water management strategies.

4.5 Implications for Artisanal Mining in Kuru Jenta

The findings of this study have important implications for the safety and sustainability of artisanal mining in Kuru Jenta. Given the significant risks posed by water infiltration and pit instability, it is crucial that miners adopt more effective techniques for managing water flow and stabilizing mine pits. This could include the installation of proper drainage systems to divert water away from pit walls, as well as slope stabilization measures such as benching, proper backfilling, and the reinforcement of high-risk areas.

Additionally, improved monitoring of groundwater levels and seasonal rainfall could help miners anticipate periods of heightened risk and take preemptive action to stabilize pits before they become unsafe. The use of geotechnical monitoring tools, such as slope inclinometer systems and piezometers, could provide valuable data to inform these mitigation strategies.

Furthermore, it is essential to integrate geological and hydrological data into the planning and design of artisanal mining operations in Kuru Jenta. By incorporating these factors into risk assessments and operational strategies, miners can reduce the likelihood of pit failures and improve overall safety standards.

This Discussion section provides an interpretation of the results in the context of the existing literature, emphasizing the importance of geological, hydrological, and geotechnical factors on water infiltration and pit stability in Kuru Jenta.

5.0 CONCLUSION

This study has demonstrated that geological and hydrological factors play a crucial role in the water infiltration and pit stability of artisanal mining operations in Kuru Jenta, Nigeria. The results highlight that the weathering of biotite granite and the presence of structural discontinuities significantly influence water movement and slope stability. In particular, the saprolitic zones, with their higher permeability and lower strength, are highly susceptible to water infiltration, which increases the risk of pit wall failures, especially during the wet season.

The study also underscores the dynamic nature of groundwater fluctuations, which contribute to the instability of mine pits, particularly in areas with high fracture density. The interaction between weathered materials and groundwater rise demonstrates the critical need for integrated management of both geological and hydrological factors to ensure safer mining practices. The findings of this research provide valuable insights into the factors that contribute to pit instability and offer a foundation for improving the safety and sustainability of artisanal mining operations in Kuru Jenta and similar regions.

6.0 RECOMMENDATIONS

Based on the findings of this study, several recommendations can be made to mitigate the risks of water infiltration and pit instability in artisanal mining sites in Kuru Jenta:

6.1 Improved Water Management Practices:

1. **Drainage Systems:** It is crucial to install effective drainage systems around mining pits to divert surface water away and reduce the amount of water infiltrating into the pits. This could involve the construction of channels or trenches to direct rainwater and groundwater flow away from high-risk areas.

2. **Pumping and Dewatering:** In areas where water infiltration is particularly problematic, dewatering systems (e.g., pumps) should be implemented to lower the groundwater table and maintain a safer working environment. Regular monitoring of groundwater levels can help determine the need for these systems.

6.2 Slope Stabilization:

1. **Slope Reinforcement:** Steep pit walls should be reinforced using techniques such as benching, which involves cutting back pit walls into smaller, stable steps, or installing retaining structures to prevent collapse. These measures should be targeted at areas where the safety factor is near or below 1.0, indicating imminent risk of failure.

2. **Backfilling:** Backfilling of mine pits with inert, non-porous material can help prevent excessive water accumulation and reduce the risk of slope failure. This is particularly important in areas where saprolitic materials are prone to saturation.

6.3 Further Research:

1. **Long-term Monitoring:** Further research is needed to monitor the long-term impacts of water infiltration and geological factors on pit stability in Kuru Jenta. Long-term data on rainfall patterns, groundwater fluctuations, and pit stability could help develop more accurate predictive models for risk assessment.

2. **Comparative Studies:** Comparative studies between different regions with similar geological settings would be useful to identify common challenges and effective solutions for managing water infiltration and slope stability in artisanal mining areas.

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