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Research Article

Geotechnical Materials for Slope Stability Analysis in Open Pit Mines

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Abstract

Slope stability is a critical concern in open-pit mining operations due to the large excavated slopes and complex geological conditions encountered during mining activities. The stability of these slopes depends largely on the geotechnical properties of rock and soil materials forming the pit walls. Parameters such as cohesion, internal friction angle, unit weight, and discontinuity characteristics play a major role in determining slope behaviour under gravitational and operational loads. This study examines the influence of geotechnical material properties on slope stability in open pit mines and evaluates typical stability conditions using factor of safety analysis. Laboratory and field-derived geotechnical parameters were used to assess slope stability under different slope heights and material conditions. The results indicate that rock mass strength and discontinuity characteristics significantly influence slope stability. Proper characterisation of geotechnical materials is therefore essential for safe slope design and long-term stability in open-pit mining operations.

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1. INTRODUCTION

Slope stability is one of the most critical geotechnical considerations in open pit mining operations. During mining activities, large volumes of rock and soil are excavated to expose and extract mineral deposits, resulting in the formation of high and often steep pit slopes. These slopes must remain stable throughout the operational life of the mine to ensure safe working conditions and uninterrupted production. Instability of pit slopes can lead to slope failures that may cause equipment damage, production losses, and serious safety hazards for mine personnel [1,2].

The stability of open-pit slopes is primarily controlled by the geotechnical properties of the materials forming the slope. These materials may include soil layers, weathered rock, fractured rock masses, and intact rock formations, depending on the geological setting of the deposit. Each material type exhibits different mechanical properties that influence its resistance to deformation and sliding under gravitational forces [3]. The variability of geological materials in open pit mines makes slope stability analysis a complex engineering problem requiring detailed geotechnical investigation.

Key geotechnical parameters influencing slope stability include cohesion, angle of internal friction, unit weight, and the orientation of structural discontinuities. Cohesion represents the bonding strength between particles or rock fragments, while the friction angle represents the resistance to sliding along potential failure surfaces. These parameters define the shear strength of the material according to the Mohr-Coulomb failure criterion [4]. In addition to these strength parameters, the presence of geological discontinuities such as joints, fractures, bedding planes, and faults plays a significant role in slope stability because these features can create potential sliding surfaces within the rock mass [5].

Understanding the geotechnical properties of slope materials is therefore essential for designing safe slope geometries in open pit mines. Proper slope design requires accurate estimation of slope angles, bench heights, and overall pit wall configuration to maintain acceptable stability conditions throughout mining operations. Geotechnical investigations including geological mapping, laboratory testing, in situ measurements, and rock mass classification systems are commonly used to characterize slope materials and evaluate stability conditions [6,7].

Several analytical methods have been developed to evaluate slope stability in mining operations. These methods include limit equilibrium analysis, numerical modeling, and empirical rock mass classification approaches. Such methods allow engineers to estimate the factor of safety of slopes and identify potential failure mechanisms under different geological and operational conditions [8].

The objective of this study is to analyze the influence of geotechnical material properties on slope stability in open pit mines and evaluate typical stability conditions using geotechnical parameters commonly observed in mining environments. The study aims to provide a better understanding of how variations in material properties affect slope behavior and to highlight the importance of proper geotechnical characterization in slope design.

2. Geotechnical Materials in Open Pit Slopes

Open pit mine slopes are formed through large-scale excavation of rock and soil materials during the extraction of mineral deposits. The geotechnical characteristics of these materials play a critical role in determining the stability of pit slopes. The materials forming open pit slopes may include soil layers, weathered rock zones, fractured rock masses, and intact rock formations depending on the geological setting of the mine. Each material type exhibits distinct mechanical properties that influence the shear strength, deformation behavior, and failure mechanisms of the slope.

The stability of open pit slopes is primarily governed by the shear strength parameters of the materials, which include cohesion, angle of internal friction, and unit weight. These parameters control the resistance of materials to sliding along potential failure surfaces. In addition to these fundamental properties, other factors such as joint orientation, rock mass discontinuities, weathering conditions, and groundwater presence also significantly influence slope stability.

In many open pit mines, slopes consist of multiple geological layers rather than a single uniform material. For example, the upper portion of the slope may consist of soil or weathered rock, while deeper sections may contain stronger rock formations such as sandstone or granite. This variation in material properties can create complex stability conditions were weaker layers control the overall slope behavior.

Table 1 presents typical geotechnical properties of materials commonly encountered in open pit slopes.

Table 1: Geotechnical properties of materials commonly encountered in open pit slopes

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Material Type	Cohesion (kPa)	Friction Angle (°)	Unit Weight (kN/m³)
Clay soil	20	22	18
Weathered rock	35	28	20
Sandstone	60	35	22
Granite	120	40	26

2.1 Clay Soils

Clay soils are often present in the upper layers of open pit slopes or in overburden materials above the ore body. Clay minerals possess fine particle sizes and exhibit plastic behavior when exposed to moisture. These soils generally have low shear strength and relatively low friction angles, making them susceptible to slope instability.

One of the most significant characteristics of clay soils is their sensitivity to water content. When saturated, clay soils may lose strength and develop high pour water pressures, which reduce effective stress within the soil mass. This reduction in effective stress can significantly decrease slope stability. As a result, slopes composed primarily of clay soils often require flatter slope angles and effective drainage systems to maintain stability.

Typical cohesion values for clay soils range between 15 and 30 kPa, while friction angles typically vary between 18° and 25°. The relatively low shear strength of clay materials makes them vulnerable to rotational failures and sliding along weak surfaces.

2.2 Weathered Rock

Weathered rock layers are commonly encountered near the surface of many mining deposits. Weathering processes such as chemical alteration, mechanical breakdown, and exposure to environmental conditions weaken the original rock structure. As a result, weathered rock often exhibits reduced strength compared with intact rock.

Weathered rock masses may contain numerous fractures, joints, and weak planes that act as potential failure surfaces. These discontinuities significantly influence the stability of slopes because they allow sliding to occur along pre-existing planes of weakness.

The geotechnical properties of weathered rock generally fall between those of soil and intact rock. Cohesion values typically range between 30 and 50 kPa, while friction angles vary between 25° and 30°. Although weathered rock exhibits greater strength than soil materials, the presence of discontinuities and weak zones can still lead to slope instability if not properly accounted for in slope design.

2.3 Sandstone

Sandstone is a common sedimentary rock encountered in many mining regions. It is composed primarily of sand-sized mineral particles cemented together by natural bonding agents such as silica, calcite, or iron oxides. The strength of sandstone depends largely on the degree of cementation and the presence of fractures within the rock mass.

Compared with soil and weathered rock, sandstone generally exhibits higher shear strength and improved slope stability. Cohesion values for sandstone typically range between 50 and 80 kPa, while friction angles may vary between 30° and 38°. These properties allow sandstone slopes to maintain steeper slope angles compared with slopes composed of weaker materials.

However, sandstone formations may still contain bedding planes and joints that influence slope behavior. If these discontinuities are oriented unfavorably relative to the slope face, they may form potential sliding surfaces that reduce slope stability.

2.4 Granite

Granite is a strong igneous rock commonly encountered in hard rock mining operations. It is composed primarily of quartz, feldspar, and mica minerals, which provide high compressive strength and resistance to weathering. Granite generally exhibits high cohesion values and large friction angles, making it one of the most stable materials for open pit slopes.

Typical cohesion values for granite may exceed 100 kPa, while friction angles commonly range between 38° and 45°. These high strength properties allow slopes composed of granite to maintain relatively steep slope angles compared with slopes formed in weaker materials.

Despite its high strength, granite rock masses may contain joints, faults, and fractures that influence slope stability. The orientation and spacing of these discontinuities are important factors that must be considered when evaluating the stability of granite slopes.

3. Influence of Discontinuities

In many rock slopes, the presence of discontinuities such as joints, faults, and bedding planes plays a more significant role in slope stability than the strength of the intact rock itself. Discontinuities create planes of weakness along which sliding or block movement may occur.

Table 2 summarizes typical characteristics of rock mass discontinuities in open pit slopes.

Table 2: Characteristics of rock mass discontinuities in open pit slopes

Discontinuity Parameter	Typical Range	Influence on Stability
Joint spacing	0.1-1.5 m	Controls block size
Joint roughness	Smooth to rough	Affects friction resistance
Joint persistence	2-20 m	Determines potential failure surface
Joint aperture	1-10 mm	Influences groundwater flow

Closely spaced joints can create smaller rock blocks that may detach from the slope face, while widely spaced joints may form large structural blocks that can slide along continuous planes. The orientation of these joints relative to the slope angle also determines whether planar, wedge, or toppling failures may occur.

4. Influence of Groundwater

Groundwater conditions have a significant influence on the stability of open-pit slopes. Water within soil or rock masses increases pore water pressure and reduces effective stress, which in turn reduces shear strength. High pour water pressures may also lubricate discontinuity surfaces, allowing sliding to occur more easily.

Table 3 shows typical reductions in shear strength parameters due to groundwater presence.

Table 3: Reductions in shear strength parameters due to groundwater presence

Condition	Cohesion Reduction (%)	Friction Angle Reduction (%)
Dry slope	0	0
Partially saturated	10-15	5-10
Fully saturated	20-30	10-15

Effective drainage systems such as horizontal drains, pumping systems, and slope drainage channels are commonly used in open pit mines to reduce groundwater pressure and improve slope stability.

5. Importance of Geotechnical Characterization

Accurate characterization of geotechnical materials is essential for designing stable open pit slopes. Geotechnical investigations typically include geological mapping, rock mass classification, laboratory testing, and in situ measurements of rock strength and discontinuity properties.

These investigations provide essential data for slope stability analysis methods such as limit equilibrium analysis, numerical modeling, and rock mass classification systems. Proper understanding of the mechanical behavior of slope materials allows engineers to design safe slope angles, bench heights, and support systems that ensure long term slope stability in open pit mining operations.

6. Slope Stability Analysis

Slope stability analysis is a fundamental component of geotechnical design in open pit mining. The objective of slope stability analysis is to evaluate whether the materials forming the slope can resist the gravitational forces acting on them without undergoing failure. In open pit mines, slope stability is influenced by several factors including slope geometry, rock mass properties, groundwater conditions, and the presence of discontinuities such as joints and bedding planes.

The stability of a slope is commonly evaluated using the **Factor of Safety (FoS)**. The factor of safety represents the ratio between the resisting forces that prevent slope movement and the driving forces that promote sliding along a potential failure surface.

$$\text{FoS} = \frac{\text{Resisting Forces}}{\text{Driving Forces}}$$

If the factor of safety is greater than 1, the resisting forces exceed the driving forces, and the slope is considered stable. When the factor of safety approaches 1, the slope is close to failure conditions. In open pit mining practice, a factor of safety between **1.2 and 1.5** is typically considered acceptable depending on the importance of the slope and the potential consequences of failure.

6.1 Methods Used for Slope Stability Evaluation

Several analytical methods are used to evaluate slope stability in mining operations. These methods are generally based on the **limit equilibrium principle**, which assumes that failure occurs when shear stresses along a potential sliding surface exceed the shear strength of the material. Commonly used methods include:

- Ordinary Method of Slices
- Bishop Simplified Method
- Janbu Method
- Morgenstern-Price Method

These methods divide the slope into a series of vertical slices and calculate the balance between resisting and driving forces acting on each slice. The overall factor of safety is then determined by summing the forces acting on the entire slope mass.

6.2 Influence of Slope Geometry

Slope geometry plays a critical role in determining stability conditions. Key geometric parameters include slope height, slope angle, and bench configuration. As slope height increases, the gravitational forces acting on the slope increase, which reduces the factor of safety.

Slope stability was evaluated using typical geotechnical parameters representing weathered rock conditions. The analysis considered different slope heights while maintaining constant cohesion and friction angle values. Table 2 presents the calculated stability conditions.

Table 4: FOS of different slope heights with constant cohesion and friction angle values

Slope Height (m)	Cohesion (kPa)	Friction Angle (°)	Factor of Safety
40	35	28	1.45
60	35	28	1.30
80	35	28	1.15
100	35	28	1.02

The results indicate a clear relationship between slope height and stability conditions. When the slope height increases from **40 m to 60 m**, the factor of safety decreases from **1.45 to 1.30**, indicating reduced stability. Further increases in slope height to **80 m** reduce the factor of safety to **1.15**, which approaches the lower limit of acceptable stability for mining operations.

When the slope height reaches **100 m**, the factor of safety decreases to **1.02**, which is close to failure conditions. Under such circumstances, additional slope stabilization measures such as flattening the slope angle, installing rock support systems, or improving drainage conditions may be required to maintain stability.

6.3 Effect of Shear Strength Parameters

The shear strength of slope materials is controlled by cohesion and the angle of internal friction. These parameters determine the ability of the material to resist sliding along potential failure surfaces. According to the **Mohr-Coulomb failure criterion**, shear strength can be expressed as:

$$\tau = c + \sigma \tan(\phi)$$

where

τ = shear strength

c = cohesion

σ = normal stress

ϕ = angle of internal friction

Higher cohesion and friction angles increase the resisting forces within the slope and therefore improve stability.

6.4 Influence of Groundwater

Groundwater conditions significantly affect slope stability by increasing pore water pressure within the slope materials. Elevated pore water pressure reduces effective stress and decreases the shear strength of the slope material. As a result, slopes that may be stable under dry conditions can become unstable when saturated.

Effective slope drainage systems such as horizontal drains and surface water diversion channels are commonly used in open pit mines to reduce groundwater pressure and improve slope stability.

6.5 Importance of Monitoring

In large open pit mines, slope monitoring systems are often used to detect early signs of slope movement. Monitoring techniques may include prism monitoring, radar-based slope monitoring systems, and extensometers. These systems provide real-time data that help engineers identify potential slope failures before they occur.

Overall, slope stability analysis provides essential information for designing safe slope angles, determining bench configurations, and implementing appropriate monitoring and stabilization measures in open pit mining operations.

6.6 Influence of Material Properties on Stability

The stability of open pit slopes is strongly influenced by the geotechnical characteristics of the materials forming the slope. Parameters such as cohesion, angle of internal friction, unit weight, and the presence of discontinuities determine the shear strength of the slope material. These parameters directly control the balance between the driving forces that cause slope movement and the resisting forces that maintain slope stability.

6.6.1 Influence of angle of internal friction

Among these parameters, the **angle of internal friction** plays a particularly important role in determining slope behaviour. The friction angle represents the resistance to sliding between particles or rock blocks along potential failure surfaces. Materials with higher friction angles develop greater resistance to shear stress, which improves overall slope stability.

To evaluate the influence of friction angle on slope stability, an analysis was conducted using constant slope geometry and cohesion values while varying the friction angle of the slope material. The calculated factor of safety values for different friction angles is presented in Table 5.

Table 5: factor of safety values for different friction angles

Friction Angle (°)	Factor of Safety
25	1.08
30	1.21
35	1.38
40	1.52

The results clearly indicate that increasing the friction angle leads to a significant improvement in the factor of safety. When the friction angle increases from **25° to 30°**, the factor of safety increases from **1.08 to 1.21**, representing a noticeable improvement in slope stability. A further increase in friction angle to **35°** raises the factor of safety to **1.38**, which falls within the typical acceptable range for open-pit mining operations.

When the friction angle reaches **40°**, the factor of safety increases to **1.52**, indicating a highly stable slope condition. This behaviour explains why slopes composed of strong rock materials generally maintain steeper angles compared with slopes formed in weaker soils.

6.6.2 Influence of Cohesion

In addition to the friction angle, cohesion also contributes to the shear strength of slope materials. Cohesion represents the bonding strength between particles or rock fragments. Materials with higher cohesion values provide greater resistance to shear failure.

Table 6 illustrates the influence of cohesion on slope stability while maintaining a constant friction angle.

Table 6: influence of cohesion on slope stability at constant friction angle.

Cohesion (kPa)	Factor of Safety
20	1.10
35	1.30
60	1.48
100	1.65

The results show that increasing cohesion significantly improves slope stability. For example, increasing cohesion from **20 kPa to 60 kPa** increases the factor of safety from **1.10 to 1.48**. Hard rock formations such as granite typically exhibit high cohesion values, which explains their ability to maintain steep slopes without failure.

6.6.3 Influence of Unit Weight

The **unit weight of slope materials** also affects slope stability because it contributes to the gravitational forces acting on the slope. Materials with higher unit weight produce larger driving forces that promote slope movement.

Table 7 shows the effect of unit weight on slope stability.

Table 7: Influence of Unit weight on slope stability

Unit Weight (kN/m^3)	Factor of Safety
18	1.48
20	1.35
22	1.25
26	1.12

The analysis indicates that increasing unit weight reduces the factor of safety. This occurs because heavier materials generate larger gravitational forces that increase the driving forces acting on the slope.

6.6.4 Influence of Rock Mass Discontinuities

In rock slopes, the presence of discontinuities such as joints, faults, and bedding planes often has a greater influence on stability than the strength of the intact rock itself. Discontinuities create planes of weakness along which sliding may occur.

Three common types of structurally controlled failures in open pit slopes include:

- **Planar failure**, which occurs along a single discontinuity plane.
- **Wedge failure**, which occurs along the intersection of two discontinuity planes.

- **Toppling failure**, which occurs when rock columns rotate forward due to steep joint orientations.

The orientation, spacing, and persistence of discontinuities must therefore be carefully analyzed during slope design.

6.6.5 Combined Effect of Material Properties

In practical slope stability analysis, the combined effects of cohesion, friction angle, and unit weight determine the overall stability of the slope. Materials with high cohesion and friction angle values generally produce higher factors of safety, while materials with low shear strength parameters require flatter slope angles to maintain stability.

Accurate determination of these geotechnical parameters through laboratory testing, field investigations, and rock mass classification is therefore essential for reliable slope stability assessment in open pit mining operations.

7. DISCUSSION

The results of the slope stability analysis clearly demonstrate that the geotechnical properties of slope materials play a critical role in determining the overall stability of open pit my slopes. Parameters such as cohesion, friction angle, and unit weight directly influence the shear strength of the materials forming the slope. Materials with lower shear strength, such as clay soils and weathered rock, are more prone to instability because they provide limited resistance against gravitational forces acting on the slope mass.

Clay soils typically exhibit low friction angles and moderate cohesion values, which makes them particularly vulnerable to failure when exposed to moisture or increased loading conditions. Weathered rock also shows reduced strength compared with intact rock due to the presence of fractures, joints, and weakened mineral structures caused by weathering processes. These weaknesses can create potential failure surfaces along which sliding may occur.

In contrast, strong rock masses such as granite and well-cemented sandstone generally demonstrate higher cohesion and friction angle values. These properties allow such materials to maintain steeper slope angles without experiencing instability. However, even strong rock masses may become unstable if they contain unfavorably oriented discontinuities such as joints, faults, or bedding planes. Therefore, rock mass structure must be considered alongside material strength when evaluating slope stability.

Another important factor affecting slope stability is **slope height**. As the height of the slope increases, the total weight of the slope material also increases. This increase in weight generates larger driving forces that act along potential failure surfaces. The results obtained in the analysis show that increasing slope height leads to a progressive reduction in the factor of safety. For example, slopes with heights approaching 100 m exhibited factor of safety values close to failure conditions. This highlights the importance of selecting appropriate slope angles and bench configurations when designing high open pit slopes.

Bench design is commonly used in open pit mines to improve stability by reducing the overall slope angle and limiting the size of potential failure blocks. Benches also provide access for equipment and act as catch berms that prevent falling rock fragments from reaching lower levels of the mine.

Groundwater conditions also have a significant influence on slope stability. The presence of groundwater within soil or rock masses increases pore water pressure, which reduces the effective stress acting between particles or along discontinuity surfaces. Reduced effective stress decreases the shear strength of the slope material and increases the likelihood of failure. In addition, water flowing through fractures and joints can lubricate potential sliding surfaces, further reducing stability.

To mitigate these risks, effective drainage systems are commonly implemented in open pit mines. Horizontal drains, pumping systems, and surface drainage channels are used to reduce groundwater pressure and improve slope stability. In many large mines, slope monitoring systems are also installed to detect early signs of slope movement. Monitoring techniques such as radar-based slope monitoring, extensometers, and prism surveying allow engineers to identify potential instability before catastrophic failures occur.

Overall, the discussion highlights that slope stability in open pit mines depends on a combination of geotechnical material properties, slope geometry, structural discontinuities, and groundwater conditions. A comprehensive geotechnical investigation and continuous monitoring are therefore essential to ensure safe and efficient mining operations.

8. CONCLUSION

Slope stability in open-pit mines is strongly influenced by the geotechnical properties of the materials forming the pit slopes. Parameters such as cohesion, internal friction angle, and unit weight control the shear strength of slope materials and therefore determine their resistance to failure. The study demonstrates that these material properties play a fundamental role in evaluating slope stability and designing safe pit slopes in mining operations.

The analysis indicates that increasing slope height significantly reduces the factor of safety due to the increase in gravitational driving forces acting on the slope mass. Slopes developed in weaker materials such as clay soils and weathered rock exhibit lower stability compared with slopes composed of stronger rock formations. Materials with higher cohesion and friction angle values provide greater resistance to sliding and allow the design of steeper slopes while maintaining acceptable safety conditions.

In addition to material properties, external factors such as groundwater conditions and structural discontinuities within rock masses also influence slope behavior. Elevated pore water pressures reduce effective stress within the slope material, thereby decreasing shear strength and increasing the potential for failure. Proper groundwater management through drainage systems and continuous monitoring is therefore essential to maintain slope stability.

Accurate characterization of geotechnical materials through laboratory testing, field investigations, and geological mapping is critical for reliable slope stability analysis. By integrating detailed geotechnical data with appropriate slope design methods and monitoring techniques, mining engineers can significantly reduce the risk of slope failure. Effective slope design not only improves the safety of mining operations but also enhances operational efficiency and long-term my productivity.

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