Probability of Failure and Slope Safety Factors Based on Geological Structure of Plane failure on Open Pit Batu Hijau Nusa Tenggara Barat

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Abstract. Batu Hijau is a gold mine which is now run and managed by PT Amman Mineral Nusa Tenggara (PT AMNT) with open mining method. The located in Sekongkang District, West Sumbawa Regency - West Nusa Tenggara Province. The geological structure aspects are interesting as objects in this study, due to the condition is very tight and become to trigger for the slope failure. Slope stability is one of the important terms for supporting in open pit mining activities. One of the slope failure indication is the failure caused by the structure. Geological structure analysis performed with kinematic analysis which takes into account the probability of failure and type of failure. The probability of Failure can count by structure orientation, the orientation of the mine slope design, and friction angle with using dips 6 software. The percentage of slide obtained from the ratio between the critical point from the critical zone with the total critical point in stereographic projection. The count applied in all geotechnics domain with inputting of parameter structure orientation, the orientation of the mine slope design, and friction angle. The result shows between 0% to 2.63% of planar failure. The percentages show probability of failure but still in the safe category with 10% safety limit. Slope safety factor counts manually based on the mathematical formula applied to all domains in Batu Hijau Open Pit Mining. The result shows the value between 1.04 to 1.905 on planar failure. This value shows the condition of slope in the research site is stable.

1. Introduction
Batu Hijau is a gold mine which is now run and managed by PT Amman Mineral Nusa Tenggara (PT AMNT) with open mining method. The Optimalization of production and safety of mining work will be achieved well if the process of the mining runs well. A factor that can harm the mining operation is the slope stability of the mine. If the condition of the slope is unstable or disturbed then there may probably of the slope failure which can cause the safety of the workers in the mining process, less of company’s properties and the stability of the environment.

Slope failure is caused by internal and externals factors. Internal factor is such as the geological structure, geotechnical properties of rock and groundwater condition. While external factor is such as the weather, mining activities like blasting, dredging, loading and transportation of material. The slope failure that often takes in Batu Hijau Mine is wedge failure and plane failure.
The type of slope failure caused by geological structure can help us understand the conditional of mine slope with the limit equilibrium analysis. Limit equilibrium analysis is the method of analyzing the equilibrium from the rock mass which is potentially moving. The limit equilibrium method is comparing resisting force and driving force along the sliding surface of the failure. The comparing of the both force will raise the value of the safety factor (FS) of the slope when the condition of the equilibrium will be achieved when the value of safety factor is one [1]. Safety factor value of a slope is the smallest result of the calculation of all the overall sliding surface which is potential failure on the slope.

2. Geological Structure and Kinematic Analysis

2.1. Geological structure
The word structure is derived from the Latin word structure, to build, and we could say: A geologic structure is a geometric configuration of rocks, and structural geology deals with the geometry, distribution and formation of structures.

The geological structure due to tectonic forces will produce fractures, folds, and stocky Geological structures can produce discontinuities that could potentially of failure. The type of discontinuities such as joint, fault, shear zone, and foliation [2]. Here are the types of discontinuity as:

2.1.1. Joint. Joints are fractures in the rocks characterized by no movement along their surfaces. Although most joints are secondary structures, some are primary, forming at the time of formation of the rocks. Type of joint such as columnar joint, mud crack, secondary joint and sheet joint.

2.1.2. Fault. A fault is a fracture in the earth's rock units along which there has been an observable amount of movement and displacement. Unlike folds which form predominantly by compressional stress, faults result from either tension, compression or shear.

2.1.3. Shear zone. Shear zone, is a zone that has the destruction of shear strains. This zone is usually found in fault zones due to rock friction during movement (Fault).

2.2. Failure
Slope failure is the activity of slope material movements (soil, rock and debris of rocks) falling due to an unstable slope. Generally, slope stability is controlled by several factors, such as slope geometry, geological situations (the characteristic of physical materials, the hydrogeology, and the characteristic of engineering materials of the slope).

2.2.1. Type of failure
Types of slope failure collapse can be divided into 4 types are the plane failure, toppling failure and circular failure [3]. The types of failure are divided based on the influence of structures that affect and their movement. Here are the types of failure:

Figure 1. Types of failure a. plane failure, b. toppling failure c. circular failure, d. wedge failure [3].
a. Plane Failure
A plane failure is a comparatively rare sight in rock slopes because it is only occasionally that all the geometric conditions required to produce such a failure occur in an actual slope [4]. However, it would not be right to ignore the two-dimensional case because there are many valuable lessons to be learned from a consideration of the mechanics of this simple failure mode. Plane failure is particularly useful for demonstrating the sensitivity of the slope to changes in shear strength and ground water conditions—changes that are less obvious when dealing with the more complex mechanics of a three-dimensional slope failure. The condition can make a plane failure are:

- The plane on which sliding occurs must strike parallel or nearly parallel (within approximately ±20°) to the slope face.
- The sliding plane must daylight in the slope face, which means that the dip of the plane must be less than the dip of the slope face.
- The dip of the sliding plane must be greater \( \psi_p > \psi_f \) than the angle of friction of this plane, that is, \( \psi_p < \psi_f \).
- The upper end of the sliding surface either intersects the upper slope or terminates in a tension crack.
- Release surfaces that provide negligible resistance to sliding must be present in the rock mass to define the lateral boundaries of the slide. Alternatively, failure can occur on a sliding plane passing through the convex–nose of a slope.

b. Toppling Failure
Toppling failures occur when columns of rock, formed by steeply dipping discontinuities in the rock masses, rotates about an essentially fixed point at or near the base of the slope followed by slippage between the layers [3]. The centre of gravity of the column or slab must fall outside the dimension of its base in toppling failure. Jointed rock mass closely spaced and steeply dipping discontinuity sets that dip away from the slope surface are necessary prerequisites for toppling failure. The removal of overburden and the confining rock, as is the case in mining excavations, can result in a partial relief of the constraining stresses within the rock structure, resulting in a toppling failure. This type of slope failure may be further categorized depending on the mode such as flexural toppling, block toppling, and block flexural toppling [5].

c. Circular Failure
Circular failure is generally observed in the slope of soil, mine dump, weak rock and highly jointed rock mass. It is very important to identify the position of the most critical circle in the analysis of such failure. Although, field observations may provide valuable clues about the mode of failure (rotational, translational, compound, etc.) and possible position of the slip surface, the centre of the most critical circle can only be found by trial and error [6].

d. Wedge Failure
Wedge failure of rock slope results when rock mass slides along two intersecting discontinuities, both of which dip out of the cut slope at an oblique angle to the cut face, thus forming a wedge-shaped block [7]. The necessary structural conditions for this failure are summarized as follows:

- Two planes will always intersect in a line on the stereonet, the line of intersection is represented by the point where the two great circles of the planes intersect, and the orientation of the line is defined by its trend and its plunge
- The plunge of the line of intersection must be flatter than the dip of the face, and steeper than the average friction angle of the two slide planes, that is the inclination of the slope face \( \psi_f \) is measured in the view at right angles to the line of intersection. Note the \( \psi \) would only be the same as \( \psi_f \), the true dip of the slope face, if the dip direction of the line of the intersection were the same as the dip direction of the slope face.
- The line of intersection must dip in a direction out of the face for sliding to be feasible; the possible range in the trend of the line of intersection is between \( ai \) and \( ai \).
2.3. Kinematic Analysis
Potential failure type can occur on slopes fractured rock can be determined through the kinematic analysis. The kinematic analysis uses geological structure orientation parameters, slope orientation, and shear-angle rocks projected in the stereographic analysis so as to determine the type and direction of the landslide. The stereographic projection shows three-dimensional data orientation into two dimensions which are then analysed [3].

2.4. Limit Equilibrium Method
The limit equilibrium method is comparing resisting force and driving force along the sliding surface of the failure. The comparing of both force will raise the value of the safety factor (FS) of the slope when the condition of the equilibrium will be achieved when the value of safety factor is one [1]. Safety factor value of a slope is the smallest result of the calculation of all the overall sliding surface which is the potential failure on the slope.

2.4.1. Plane Failure Analysis
The limit equilibrium analysis of this method uses the boundary balance based on the total mass formed by the slope sliding and cracks that can cause the occurrence of landslides. This analysis will be explained by an illustration of figure 2 for the tension crack at the top of the slope and figure 3 in the tension crack pad of the slope section.

![Figure 2. Geometry of plane failure slopes and forces that work on the tension crack on slope surfaces [3]](image)

Based on the illustration of Figure 2 without involving the influence of external forces such as seismic, rock mass strength, and the load of other objects located on the slope wall, the Safety Factor value can be calculated using the following formula in figure 3:

\[
FS = \frac{\text{Resisting force}}{\text{Driving force}} - cA + \sum N \tan \phi
\]

\[
FS = \frac{cA + (W \cos \psi_p - U - V \sin \psi_p) \tan \phi}{W \sin \psi_p + V \cos \psi_p}
\]

\[
W = y_{f} \left(1 - \cot \psi_{f} \tan \psi_{p} \right) \left(bH + \frac{1}{2} H^{2} \cot \psi_{f} \right) + \frac{1}{2} b^{2} \left(\tan \psi_{s} - \tan \psi_{p} \right)
\]

\[
U = \frac{1}{2} y_{w} z_{w} \left(H + b \tan \psi_{s} - z \right) \csc \psi_{p}
\]

\[
\nu = \frac{1}{\rho c_{w} \varepsilon_{0}} \frac{1}{2}
\]

\[
A = (H + b \tan \psi_{s} - z) \csc \psi_{p}
\]

![Figure 3. Geometry of plane failure and forces that work on the tension crack on the slope [3]](image)
Based on the illustration of Figure 2 without involving the influence of external forces such as seismic, rock mass strength, and a load of other objects located on the sloped wall, the Safety Factor value can be calculated using the following formula in figure 4:

\[
FS = \frac{\text{Resisting force}}{\text{Driving force}} = \frac{cA + (W \cos \psi_p - U - V \sin \psi_p) \tan \phi}{\sum s}
\]

\[
U = \frac{1}{2} \gamma_w \hat{z}_w (H + b \tan \psi_s - z) \csc \psi_p
\]

\[
V = \frac{1}{2} \gamma_w \hat{z}_w^2
\]

\[
W = \frac{1}{2} \gamma_r H^2 \left[ \left( 1 - \frac{z}{H} \right)^2 \cot \psi_p \right] \times (\cot \psi_p \tan \psi_f - 1)
\]

**Figure 4.** Formula the safety factor value.

Geological Structures from window mapping, engineering properties, and back analysis of failure used as data for research. Kinematic analysis by Dips v.6 software (Rockscience, Inc.) uses to analyse failure to determine the probability of plane failure. Limit equilibrium analytic method count based on failure type caused by geological structure.

Projecting geometry of slope, joint orientation, and friction angle be used to determine PoF. A value of PoF is in form of percentage of amount all value entered with value included critical zone. Count of safety factor based on failure type, that is plane and wedge failure. This method uses mathematical count formulas to determine safety factor value [3, 8].

### 3. Results and Discussion

#### 3.1. Kinematic analysis result

The kinematic analysis applied to determine the percentage of failure probability in every failure based on structure orientation, the friction angle of structural geology, and slope orientation. All friction angle of discontinuity assumed 300. The kinematic analysis applied to 6 phase pit slopes split by geotechnical domain. All domains have the different orientation and slope each other (Table 1). Example for kinematic analysis that in Domain 1 has the orientation (Dip/Dip Direction) 410/N1900E shown at Figure 5.

| Domain | Slope Orientation (Dip/Dip Direction) | Value of Cohesion (c) |
|--------|--------------------------------------|-----------------------|
| 1      | 41/190                               | 112                   |
| 2      | 45/190                               | 154                   |
| 3a     | 41/270                               | 129                   |
| 3b     | 41/295                               | 129                   |
| 4      | 47/270                               | 118                   |
| 5      | 41/300                               | 159                   |
| 6      | 41/50                                | 187                   |
| 7a     | 43/75                                | 187                   |
| 7b     | 43/100                               | 187                   |
| 8      | 47/145                               | 154                   |
Figure 5. Kinematic analysis result of plane failure at Domain 1 by dips software

The result shows that Domain 1 is not potential to plane failure because there is no fault or joint data at the daylight zone (pink colored zone) for plane failure. So due to the result, failure probability at Domain 1 is 0%. The result of all Domains is shown in Table 2.

Table 2. The result of all Domains

| Domain   | Value Of POF (%) |
|----------|------------------|
| Domain 1 | 0                |
| Domain 2 | 1.96             |
| Domain 3a| 2.63             |
| Domain 3b| 0                |
| Domain 4 | 1.47             |
| Domain 5 | 2.17             |
| Domain 6 | 2.22             |
| Domain 7a| 0                |
| Domain 7b| 0                |
| Domain 8 | 0                |

3.2. Mathematical count of safety factor of slope in plane failure

Calculation of safety factor in plane failure applied to 10 section representatives to every kinematic analysis in all Domain. Calculation applied to major structure potential to plane failure if there is another structure causing plane failure (basal joint).

3.2.1. Section of domain 1 (Azimuth Section 24°). The calculation at section 1 (24°) applied to determination slope stability to plane failure. Based on the section, there is two structures that potential to plane failure, that is Ciremai Fault and Kerinci Splay Fault. (Figure 6).
Figure 6. Slope geometry and Structure at Section of Domain 1 (Azimuth Section 240°) to analyse safety factor value

Based on model in figure 6 the result shown below in table 3:

Table 3. Calculation data of FS at section of domain 1 (azimuth section 240°)

|         | Section 1a | Kerinci |
|---------|------------|---------|
| Ψs      | 5          | 5       |
| Ψp      | 25         | 25      |
| Ψf      | 41         | 41      |
| Φ       | 30         | 30      |
| Γa      | 9.82       | 9.82    |
| Γr      | 27         | 27      |
| Z       | 89.46      | 114.46  |
| Zw      | 0          | 0       |
| H       | 159.35     | 159.35  |
| B       | 0          | 0       |
| C       | 112        | 112     |
| FK      | 1.245      | 1.248   |

a. Ciremai Fault

Finding the value of A

\[ A = (159.35 + 0 \tan 50° - 89.46) \csc 250° \]

Finding the value of W

\[ W = -x 27 \times (159.35)^2 \left(1 - \frac{1}{\cot 250°} \right) \]

Finding the value of U and V

Because of cross section of domain 1 is not influenced by water below the surface in other words zw = 0 then the value of U and V = 0

So, the FK value of the landslide potential caused by the ciremai fault on the cross domain 1 is as follows:

\[ FK = \frac{112 \times 163.23 \times (6735267.999 \cos 25) \tan 30}{6735267.999 \sin 25} = 1.244639 \]
Based on the calculation, safety factor value at section domain 1 is 1.244 thus it can be concluded that the slope is in stable condition towards plane failure caused by Ciremai Fault with slicken slide 25°.

b. Kerinci Splay Fault Finding the value of A

\[ A = (159.35 + 0 \tan 50° - 114.46) \csc 25° \]
\[ A = 44.89 \times 2.36 = 106.22 \]

Finding the value of W

\[ W = \frac{159.35 \times 27 \times (159.35)^2}{\left(\cot 25° \tan 25° - 1\right)} \]
\[ W = 2778587.074 \text{ N} \]

Finding the value of U and V

Because of cross section of domain 1 is not influenced by water below the surface in other words \( zw = 0 \) then the value of U and V = 0

So, the FK value of the landslide potential caused by the ciremai fault on the cross domain 1 is as follows:

\[
FK = \frac{112 \times 106.22 \times (2778587.074 \times \cos 25°) \tan 30°}{2778587.074 \times \sin 25°}
\]

FK = 1.2483

Based on the calculation, safety factor value at section domain 1 is 1.2483 thus it can be concluded that the slope is in stable condition towards plane failure caused by Kerinci Splay Fault with slicken slide 25°.

Calculation of safety factor in other can be seen in the attachment. Calculation of safety factor in every structure that potential to plane failure for all section shows in Table 4. Based on safety factor calculation, the result is >1 that indicates all section has stable condition towards potential of plane failure [9].

Based on the calculation of safety factor in all Domain (Table 4), concluded that all slope has stable condition towards plane failure caused by geological structure. This result shows all slope have value >1 that shown stable condition. Besides, there is no failure indication in all point in the field.

4. Conclusions

Based on research on Batu Hijau Open Pit slope, the value of failure probability has the value relatively small with range 0% to 2.63% for plane failure, that indicates that the probability still in tolerance (under 10%). Based on the geotechnical analysis, the result shows that value of safety factor ranging between 1.04 to 1.905. this result shows the slope stability caused by plane failure still in stable condition because the safety factor is still above 1.00. The result explained above match with the actual condition on the field that shows the stable condition of the slope, there is no failure in every point. that conclude the condition of the slope is stable based on the probability of failure, the factor of safety, and field condition.

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|                      | Section 1a | Section 1b | Section 2 | Section 3a | Section 3b | Section 4 | Section 5 | Section 6 | Section 7a | Section 7b | Section 8 |
|----------------------|------------|------------|-----------|------------|------------|-----------|-----------|-----------|------------|------------|-----------|
| **Azimut**           |            |            | Section Azimut 2, 4 |            |            | Section Azimut 5 |            |            |            |            |            | Section Azimut 235 |
|                      |            |            | Section Azimut 1 |            |            | Section Azimut 60 |            |            |            |            |            | Section Azimut 285 |
| Ci remai Fault       |            |            | Kerinci Fault |            |            | Kerinci Fault |            |            |            |            |            | Kerinci Fault |
| Ferry Fault          |            |            | Ferry Splay Fault |            |            | Ferry Fault |            |            |            |            |            | Ferry Splay Fault |
| K atim Fault         |            |            | K atim Splay Fault |            |            | Yuli Fault |            |            |            |            |            | Yuli Fault |
| Ferry Fault          |            |            | Ferry Fault |            |            | Ferry Fault |            |            |            |            |            | Ferry Fault |
| Charly Fault         |            |            | Charly Fault |            |            | Charly Fault |            |            |            |            |            | Charly Fault |
| Perigi Fault         |            |            | Perigi Fault |            |            | Perigi Fault |            |            |            |            |            | Perigi Fault |
| SW#2 Fault           |            |            | SW#2 Fault |            |            | SW#2 Fault |            |            |            |            |            | SW#2 Fault |
| SW#5 Fault           |            |            | SW#5 Fault |            |            | SW#5 Fault |            |            |            |            |            | SW#5 Fault |
| SW#3 Fault           |            |            | SW#3 Fault |            |            | SW#3 Fault |            |            |            |            |            | SW#3 Fault |
| Kelud Fault          |            |            | Kelud Fault |            |            | Kelud Fault |            |            |            |            |            | Kelud Fault |
| Kelud Splay Fault    |            |            | Kelud Splay Fault |            |            | Kelud Splay Fault |            |            |            |            |            | Kelud Splay Fault |
| **Ψs**               | 5          | 5          | 5          | 5          | 5          | 5          | 5          | 5          | 5          | 5          | 5          | 5 |
| **Ψp**               | 25         | 25         | 25         | 25         | 25         | 25         | 25         | 25         | 25         | 25         | 25         | 25   |
| **Ψf**               | 41         | 41         | 41         | 41         | 41         | 41         | 41         | 41         | 41         | 41         | 41         | 41   |
| **Φ**                | 30         | 30         | 30         | 30         | 30         | 30         | 30         | 30         | 30         | 30         | 30         | 30   |
| **Γa**               | 9.82       | 9.82       | 9.82       | 9.82       | 9.82       | 9.82       | 9.82       | 9.82       | 9.82       | 9.82       | 9.82       | 9.82 |
| **Γr**               | 27         | 27         | 27         | 27         | 27         | 27         | 27         | 27         | 27         | 27         | 27         | 27   |
| **Z**                | 89.46      | 114.46     | 35         | 53         | 71         | 56.37      | 57.7       | 76.33      | 47         | 140.42     | 85.02      | 46.12   |
| **Zw**               | 0          | 0          | 0          | 0          | 0          | 0          | 0          | 0          | 0          | 0          | 0          | 0    |
| **H**                | 159.35     | 159.35     | 105.28     | 105.28     | 105.28     | 136.2      | 133        | 133        | 238        | 218.39     | 192.16     | 111.63   |
| **B**                | 0          | 0          | 40         | 13.1       | 0          | 0          | 43.59      | 0          | 150        | 0          | 0          | 53.33   |
| **C**                | 112        | 112        | 112        | 112        | 112        | 154        | 129        | 129        | 129        | 118        | 159        | 187    |
| **FK**               | 1,245      | 1,248      | 1,449      | 1,507      | 1,251      | 1,04       | 1,11       | 1,12       | 1,35       | 1,243      | 1,053      | 1,46   |

Table 4. Results of Mathematical Calculation Slope Safety Factor for Plane Failure