Open Pit Slope Design of Barapukuria Coal Mine Using Limit Equilibrium Methods of Slope Stability Analysis

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Abstract- The Barapukuria Coal basin is situated in the north-western part of Bangladesh. The Barapukuria coal basin is expected to be a potential zone for exploitation of coal by open pit mining method. This study proposes an adequate slope design of open pit coal mine at Barapukuria coal basin. Failure of slope is a common phenomenon in open pit mine. So, prior to mine operation it is necessary to fix the slope angle, bench height and berm width in terms of safety and economic viability. This article outlines the slope angle design using Limit Equilibrium Methods of Slope Stability Analysis.

Keywords- Open pit mine, Coal basin, Slope Stability, Limit Equilibrium Method and Economic viability

I. OPEN PIT SLOPE CONFIGURATION

The slope of the pit wall is one of the major elements which affects the size and shape of the pit. The pit slope is usually measured in degrees from the horizontal plane and it may vary depending on the rock quality. The pit slope helps to determine the amount of waste for the exploration of coal that must be removed.

Pit walls need to remain stable as long as mining activity is done in that area for the safety of people and machineries. The stability of the pit walls should be analyzed as carefully as possible. The major factors to evaluate the proper slope angles of pit walls are rock strength, faults, joints, presence of water, and other geologic information. The pit walls should be set as steep as possible to minimize the strip ratio. The overall pit slope used for design must be flatter to allow for the road system in the ultimate pit. The configuration of an open pit slope is based on three spatial scales (Figure 1)

Bench configuration: Bench configuration is defined by bench height, width, and face angle;

The interramp angle: The interramp angle is defined by the bench configuration; and

The overall slope angle: The overall slope angle is defined by interramp sections separated by haul roads or mining levels.

II. METHOD OF STUDY

The method of study involves geotechnical study of rock samples for determination of cohesion, angle of friction, rock unit weight etc. For the design of slope two computer programs has used which are XSTABL and pgfan05.
Determination of the slope design angles for the proposed Barapukuria open pits five representative walls are taken (Figure 2). In this design sector the specific critical walls were selected for two dimension limit equilibrium stability analyses.

**Figure 2: Pit Wall Orientation Used for Overall Slope Design in Barapukuria Coalfield.**

### A. Open Pit Slope Design

For the slope design of the proposed Barapukuria coal mine deterministic design method is used. In deterministic design method we choose Limit Equilibrium Method (LEM) in which most used methods are Bishop simplified method of slice (Bishop, 1955) and Progressive failure method (Khan, et. al, 2002).

Limit Equilibrium Methods (LEM): Limit equilibrium analysis is a simplification of the more rigorous limit theory in continuum mechanics, and has such become the method of choice for routine slope stability analysis in soil mechanics as well as in design of open pit mine slope. In limit equilibrium analysis, an assumption of the slip-line field is made, usually as a geometrically fairly simple failure surface. The shear strength of the material is normally described by the Mohr-Coulomb yield criterion ($S = C' + \sigma' \tan \phi'$)

Where, $S =$ shear strength of material, $C'$ = Cohesive strength of the material, $\sigma'$ = Normal stress, $\phi'$ = Angle of friction.

In limit equilibrium methods, postulate that the slope might fail by a mass of Soil Sliding on a failure surface. At the moment of failure, the shear strength fully mobilized and the overall slope and each part of it are in static equilibrium. The shear strength of soil is normally given by the Mohr-coulomb failure criterion.

$$S = C' + \sigma' \tan \phi'$$

In the simplest form of limit equilibrium analysis, only the equilibrium of forces is satisfied. The sum of the forces acting to induce sliding of parts of the slope is compared with the sum of the forces available to resist failure. The ratio between these two sums is defined as the factor of safety ($F$):

$$F = \frac{\sum (\text{Resisting Forces})}{\sum (\text{Disturbing Forces})}$$

1. **Bishop’s Simplified Method of Slices**: In Bishop’s simplified method of slices failure is assumed to occur by rotation of a block of soil on a cylindrical slip surface centered on a point, which is the overall center of the slip surface (Figure 3). By examine overall moment equilibrium about the center and expression for the factor of safety is obtained. It is assumed that the inter-slice forces are horizontal.

**Figure 3: Force Diagram for n-th Slice**

In this method the slope is divided into a number of vertical slices. A large number of slices is used the base of each slice may be approximated by a straight line and the slice weight may be calculated as: $W = \gamma bh$
Where, \( W = \text{Slice weight} \), \( \gamma = \text{unit weight of slice} \), \( b = \text{width of slice} \), \( h = \text{height of slice} \).

The total unit weight is used for both total and effective stress analyses, as it is equilibrium against total boundary forces.

The horizontal inter-slice forces include both soil and water components, but the vertical inter-slice forces are soil shear forces only. By resolving forces vertically and summing moments of each slice about the circle center, Bishop was able to drive the following formula:

\[
F = \frac{\sum [l \cdot b + (W - ub) \tan \varphi] - \frac{1}{m}}{\sum W \sin \alpha}
\]

Where, \( m_\alpha = \cos \alpha + \frac{\sin \alpha \tan \varphi'}{F} \), \( C' = \text{Cohesion} \), \( \varphi' = \text{Angle of friction} \), \( u = \text{Pore water pressure} \).

2. **Progressive Failure Method**: An actual failed slope generally exhibits the behavior of progressive failure; local yielding or failure initiated at some points gradually develops and finally leads to overall failure of the slope along a slip surface. Therefore a realistic analysis of slope stability should include the effect of such a process of progressive failure.

\[
E_{i+1} = E_i \left[ \frac{A_2 - \lambda f(x) A_4}{A_1 - \lambda f(x) A_3} \right] + \left[ \frac{A_5 - A_6}{A_1 - \lambda f(x) A_3} \right]
\]

Where, \( A_1 = m_2 \sin \delta_i + m_1 \cos \delta_i \), \( A_2 = m_2 \sin \delta_i + m_1 \cos \delta_i \), \( A_3 = m_2 \cos \delta_i + m_1 \sin \delta_i \), \( A_4 = m_2 \cos \delta_i - m_1 \sin \delta_i \), \( A_5 = (m_2 \sin \alpha - m_1 \cos \alpha) \times \left( \frac{\sin \alpha \tan \varphi_i}{F_i} + \frac{C_i b_i}{F_i \cos \alpha_i} \right) + W_i m_2 \), \( A_6 = k_i W_i m_1 = \frac{\sin \alpha_i \tan \varphi_i}{F_i} + \cos \alpha_i \), \( m_2 = \frac{\cos \alpha_i \tan \varphi_i}{F_i} - \sin \alpha_i \).

And the equation of moment equilibrium is \( M_i \mid \lambda \mid F_i \) = 0

Over all Factor of safety: An overall factor between the sum of \( F_{\text{overall}} \) may defied by the ratio between the sum of the mobilized shear forces (T) and the sum of the available shear strengths (\( R_p \) and \( R_s \)) along the entire slip surface.

\[
F_{\text{overall}} = \frac{\sum_{n=1}^{m} R_{p}}{T} \sum_{n=1}^{m} R_{t}
\]

Where, \( m \) is the number of slices with residual strength among the total slices (n).

### III. RESULT

A. **Bench Face Slope Angle Design**

The bench face angles are designed according to the geological formations of the Barapukuria area. Each formation has a definite angle of slope, which is showing in Table I.
TABLE I
RESULTS OF BENCH FACE DESIGN ANGLE

<table>
<thead>
<tr>
<th>Form</th>
<th>Material Properties</th>
<th>Recommended Bench Face Angle (°)</th>
<th>Factor of Safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>Madhupur Clay</td>
<td>C': 36.28 KPa, ϕ': 27°, γ_m: 17.65 KPa/m³, γ_c: 22.56 KPa/m³</td>
<td>77</td>
<td>1.497</td>
</tr>
<tr>
<td>Upper Dupi Tila</td>
<td>C': 27.3 KPa, ϕ': 38°, γ_m: 18.75 KPa/m³, γ_c: 25.21 KPa/m³</td>
<td>75</td>
<td>1.498</td>
</tr>
<tr>
<td>Lower Dupi Tila</td>
<td>C': 58.3 KPa, ϕ': 25.9°, γ_m: 18.24 KPa/m³, γ_c: 21.68 KPa/m³</td>
<td>82</td>
<td>1.501</td>
</tr>
<tr>
<td>Gondwana</td>
<td>C': 45.2 KPa, ϕ': 30°, γ_m: 22.56 KPa/m³, γ_c: 23.76 KPa/m³</td>
<td>77</td>
<td>1.508</td>
</tr>
</tbody>
</table>

B. Overall Slope Angle Design

The results of the overall slope design in five sections are shown in Table II and graphically in Figure 5.

TABLE II
RESULTS OF OVERALL PIT SLOPE DESIGN

<table>
<thead>
<tr>
<th>Section</th>
<th>Slope Height (m)</th>
<th>Material Properties</th>
<th>Recommended Overall Slope Angle (°)</th>
<th>Factor of Safety Simplified Bishop Method (Bishop, 1955)</th>
<th>Factor of Safety Progressive Failure Method (Khan et. al., 2002)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1A1</td>
<td>300</td>
<td>C': 27.3 KPa, ϕ': 38°, γ_m: 18.75 KPa/m³, γ_c: 25.21 KPa/m³</td>
<td>29</td>
<td>1.801</td>
<td>1.84</td>
</tr>
<tr>
<td>A2A2</td>
<td>350</td>
<td>C': 27.3 KPa, ϕ': 38°, γ_m: 18.75 KPa/m³, γ_c: 25.21 KPa/m³</td>
<td>27</td>
<td>1.817</td>
<td>1.846</td>
</tr>
<tr>
<td>A3A3</td>
<td>400</td>
<td>C': 27.3 KPa, ϕ': 38°, γ_m: 18.75 KPa/m³, γ_c: 25.21 KPa/m³</td>
<td>22</td>
<td>1.802</td>
<td>1.823</td>
</tr>
<tr>
<td>A4A4</td>
<td>450</td>
<td>C': 27.3 KPa, ϕ': 38°, γ_m: 18.75 KPa/m³, γ_c: 25.21 KPa/m³</td>
<td>18</td>
<td>1.836</td>
<td>1.887</td>
</tr>
<tr>
<td>A5A5</td>
<td>275</td>
<td>C': 27.3 KPa, ϕ': 38°, γ_m: 18.75 KPa/m³, γ_c: 25.21 KPa/m³</td>
<td>30</td>
<td>1.829</td>
<td>1.872</td>
</tr>
</tbody>
</table>

C. Pit Wall Design Sector

Pit wall design sector includes the combination of three scale i.e. bench face, interramp and overall slope angles along a definite section. For the design of pit walls of the proposed Barapukuria open pit mine, five representative sections are selected along which the design approach are applied. In this case, assumed berm width (L) is 12m and ramp or step out distance is 22m. The bench face angles are plotted according to the recommended angles of the geotechnical units. The interramp height is taken 100m for safely mine operation. The pit wall configurations are illustrated in Figure 6.

Figure 5: Overall slope angle along A1A1/Section

Figure 6: Pit Wall Configuration along A1A1/Section including Bench Face, Interralamp and Overall slope angle.
IV. CONCLUSION

The Barapukuria coal basin is expected to be a potential zone for exploration of coal by open pit mining method. As the over burden of coal seam is loose sediments, so before going to mining operation it is necessary to fix the slope angle. This proposes an adequate slope angle by analyzing Limit Equilibrium Methods of Slope Stability Analysis. We always took consideration of Factor of safety more than 1.8 for most critical failure surface. So, the results of the analysis should take in consideration during Barapukuria open pit coal mine design form mine hazards like slope failure or landslides.

REFERENCES
[8] Islam, M.S. 1993, Anatomy and Environment of deposition of the abnormally thick coal seam VI in the Barapukuria basin, Dinajpur,