Deterministic and Probabilistic Assessments of the Slope Stability of Kota Bunyi Dam, Pengkalan Hulu, Perak

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Abstract. This paper analyses the stability of the design and construction of Kota Bunyi (KB) tailings dam of Rahman Hydraulic Tin Mine which is located at Kelian Intan, Pengkalan Hulu Perak. The stability assessment of KB tailings dam was conducted using 2D Limit Equilibrium Methods analysis software, Slide 6.0 from Rocscience Inc. using two different approaches – the deterministic and probability approaches. In the analyses, it was found that the upstream and downstream factors of safety (FOS) obtained through deterministic analysis are satisfactory as compared to the recommended minimum FOS for both normal operating freeboard and flood freeboard conditions. In addition, both of the normal and lognormal reliability index values obtained from overall slope surface analysis are twofold the minimum recommended value, which indicate the satisfactory level of safety of KB tailings dam slope.

1. Introduction
Mining produces a very large amount of tailings in its operation which might include slurry with high content of slimes, water and also coarse sandy tailings. In a proper tailings management, the tailings dam is divided into a several partitions called tailings ponds. Usually, at the very front side of tailings pond that is connected to processing plant tailings outlet is allocated for the settlement of coarse sandy tailings. Further distance from the outlet, the smaller size of tailings materials fill the other ponds as the particles flow under the influence of water flow current and gravity. This tailings flow happens in Rahman Hydraulic Tin Mine (RHT) Sdn Bhd, currently the largest producer of tin ore in Malaysia. RHT has been in operation for more than a century and recognised as the oldest hard rock tin mine in Malaysia [1, 2]. Thus, this paper presents the analysis of stability of Kota Bunyi (KB) tailings dam using different types of limit equilibrium methods (LEM) of slices in both deterministic and probabilistic approaches.

1.1 Site Geology
RHT is located at Kelian Intan which is a sub-district of Pengkalan Hulu at the northern part of Perak, Malaysia. Geologically, beneath the Kelian Intan is the Kroh formation which is one of Baling Group formations and represented by Early Silurian to Devonian marine sediments [2, 3]. These marine sediments consist of black shale, sub-mature arenite, calcareous shale and limestone [2, 3, 4].

The dominant lithofacies of Kroh Formation is argillaceous facies that composed of dark-grey black shale and mudstone which have experienced a local low-grade metamorphism by igneous rock intrusion underlying the formation and turned into metasedimentary rocks such as slate, phyllite,
hornsfsels, metamudstone and quartzmica schist [2, 3]. The KB tailings dam covered around 0.15 square kilometres and is located at the north east of RHT mining lease area. Based on previous subsurface investigation work [5], underlain the dam is highly fractured slate and layers of hard material with Standard Penetration Test value greater than 50. Slate dominantly made up the northern area of study which has heavily-jointed structure while at the southern area; residual soil mostly can be seen.

1.2 Design of Kota Bunyih Dam

Based on the general cross-section of KB tailings dam as shown in Figure 1, it can be seen that the dam is constructed on top of original ground that consists of weathered and highly fractured metasedimentary rocks. Here, the KB tailings dam embankments are made of three different layers of embankments – starter dam, existing tailings dam, and the new dam of which their construction is staged over the life of the impoundment.

By comparing types of construction method for raised embankment as classified by Vick [6], KB tailings dam is classified as the centreline embankment, as fill was placed onto the beach and also onto the downstream slope of the existing starter dam that makes the embankment rising vertically upward. In further detail, the downstream slope of KB tailings dam is divided into eight benches in which every bench has a 3 m width and 6 m height with a bench slope angle of 27 degrees. The design parameters of benches produce an overall slope angle of 22 degrees that span along 140 m width. On the other hand, the upstream slope consists of a single bench that inclined at 34 degrees from the horizontal with the top width of 10 m.

The stability of KB tailings dam is enhanced by constructing a few safety features such as rock toe with geotextile filter, impermeable blanket covering the upstream slope, impermeable soil covering the downstream slope and discharge spillway.

![Figure 1. The general cross-section of KB tailings dam.](image)

1.3 Limit Equilibrium Methods

Limit equilibrium method (LEM) of slices and strength reduction method (SRM) by finite element analysis are two of the slope stability analysis methods that are widely nowadays. In general, SRM produced a slightly higher factor of safety (FOS) as compared to those by LEM for most cases [7]. However, in most cases, both of the methods have produced similar critical slip surfaces (CSS), but this condition is only applied if the cohesive strength is low. Even though there are minor differences in both of the methods, both of them generally show a good agreement in the results produced which indicates that the use of either one of them is satisfactory [7].
Thus, LEM is chosen as a slope stability analysis method in this paper due to the low cohesive strength (soil) nature of the case study area. Along the slip surface in LEM, linear Mohr-Coulomb failure criterion is applied to determine the shear strength ($\tau_f$) of soil. Once the soil mass is divided into several number of slices, free body is drawn for each of the slice to determine the FOS. The ratio of shear strength available ($\tau_f$) to the shear stress mobilised ($\tau$) is then taken to determine the FOS of a slope as shown in Eq. (1):

$$FOS = \frac{\tau_f}{\tau} = \frac{c' + \sigma \tan \phi'}{\tau}$$ (1)

Some assumptions need to be made in order to make the problem determinate and in deriving the FOS. Usually, the most common assumptions to make the problem determinate are the location of the acting normal force on the base of the slice and consideration on the inter-slice forces [8, 9].

2. Methodology
The analysis methods used were Ordinary, Bishop Simplified, Janbu Simplified, Spencer and Morgenstern-Price (MP) with half-sine inter-slice force function. It has to be noted that the implementation of General Limit Equilibrium (GLE) in Slide is essentially equivalent to the Morgenstern-Price method [10]. These analysis methods of slices were selected based on the reasons that they are widely used in slope stability analysis despite the fact that they possess different equilibrium conditions and assumptions.

In this paper, steady-state FEA is chosen as the groundwater analysis method. In applying this groundwater analysis method, the KB tailings dam model was meshed and discretized using 6-noded triangles as the mesh element type with 3000 approximate number of elements. A high number of elements were set to obtain an accurate solution especially in the case of a thin material boundary in the steady-state FEA [7].

For probabilistic analysis, it was set similarly to the deterministic analysis except that probabilistic analysis is conducted only for downstream slope under normal operating condition. In probabilistic analysis, Latin Hypercube was used as the sampling method of random variables with 1000 number of samples instead of Monte Carlo as the former is able to produce a comparable result to the latter with a lesser samples and a smoother sampling of probability distributions [10]. After defining the analysis type, cohesion, friction angle and unit weight of materials were selected as the random variables with normal statistical distribution.

3. Results and Discussion
3.1 Deterministic analysis
The deterministic analysis of KB tailings dam was conducted using the mean value of parameters which are shown in Table 1. This analysis is conducted to search for the FOS that related to CSS of the slope for every method of slices chosen. In this deterministic analysis, there are two cases whereby different freeboard levels of the ponded water were considered. Case A considered a normal operating freeboard level of 1.84 m while case B considered a flood freeboard level of 0.3 m. Both of these cases were considered to investigate the effect of freeboard level towards the FOS for both upstream and downstream slope. Based on Table 2, it can be seen that cases A and B, investigated using LEM gave FOS greater than 1.5. According to Duncan & Wright [11] and Jansen [12], these FOS are satisfactory as they recommended the minimum FOS for long-term steady seepage for upstream and downstream slope designs are both limited to 1.5.

By comparing the FOS produced by LEM in flood condition to the normal operating condition for both upstream and downstream slopes, the flood condition does not affecting the FOS of the downstream slope. This pattern was proven by the same CSS and FOS obtained for both cases. For the downstream CSS produced by the LEM for both cases, there is no significant difference can be seen in terms of their positions and sizes. All of the CSS produced are similar for which the left CSS endpoints are located around the top crest of the dam while the right endpoints are located around the
lower part of seventh bench slope. This condition could be due to the effect of impermeable earth blankets that do not allow groundwater to penetrate across the existing tailings dam and new dam even though the level of ponded water is high. If there is no earth blanket covering the upstream slope of KB tailings dam, the chance for the downstream slope to fail is high. This is because groundwater seeps through the existing tailings dam and new dam which causing the rising of water table. If the CSS is in contact with water table, the existing pore pressure at the CSS will become higher and this pressure will separate the soil grains apart. This condition results in the reduction of normal forces and friction resistance at the base of slice which eventually fail the slope.

| Materials                  | \( \gamma \) (kN/m³) | \( c' \) (kPa) | \( \phi' \) (°) | \( K_s \) (m/s) | Model Properties (Soil Type) |
|----------------------------|------------------------|----------------|----------------|----------------|-----------------------------|
| Original Ground            | 18.5                   | 0              | 35             | 1.00E-07       | General                    |
| Starter Dam                | 18.5                   | 5              | 31             | 1.00E-07       | Silt                       |
| Existing Tailings Dam      | 18.5                   | 0              | 33             | 1.00E-06       | Sand                       |
| Existing Earth Blanket     | 13.0                   | 1              | 16             | 1.00E-09       | Clay                       |
| New Earth Blanket          | 18.0                   | 5              | 28             | 1.00E-09       | Clay                       |
| New Dam                    | 18.5                   | 0              | 33             | 1.00E-05       | Sand                       |
| Natural Hill               | 18.5                   | 0              | 33             | 1.00E-07       | Clay                       |
| Slime                      | 13.0                   | 1              | 16             | 1.00E-09       | Clay                       |
| Soil Cover                 | 18.0                   | 5              | 28             | 1.00E-09       | Clay                       |
| Rock Toe                   | 25.5                   | 0              | 45             | 1.00           | General                    |

Table 2. The upstream and downstream slopes FOS obtained from both cases A and B

| Conditions    | Ordinary | Bishop Simplified | Janbu Simplified | Spencer | GLE / MP |
|---------------|----------|-------------------|------------------|---------|----------|
| Case A        |          |                   |                  |         |          |
| Downstream slope | 1.63699  | 1.65722           | 1.63660          | 1.65222 | 1.65478  |
| Upstream slope | 1.72636  | 1.85739           | 1.67771          | 1.85103 | 1.85115  |
| Case B        |          |                   |                  |         |          |
| Downstream slope | 1.63699  | 1.65722           | 1.63660          | 1.65221 | 1.65499  |
| Upstream slope | 2.68439  | 2.83445           | 2.60868          | 2.82455 | 2.82476  |

In studying the effect of freeboard towards water table, it was found that both of the cases have resulted in very similar water tables which only differ in terms of water discharged at the rock toe. The water tables of both of the cases do not make their ways across the earth blankets to the middle body of KB tailings dam directly, but it only cross the dam horizontally at the lower part of the starter dam towards the rock toe at \( 3.0757e^{-9} \) m³/s and \( 3.3852e^{-8} \) m³/s respectively. This is due to the effect of impermeable earth blankets that do not permit the seeping of water which eventually lowers the level of water tables in the dam. In terms of water discharged, the rate is proportional to the level of ponded water, however, the discharges are very nominal.

3.2 Probabilistic analysis

The probabilistic analysis is only conducted to determine the reliability of the KB tailings dam downstream slope that operating at a normal condition. In details, there are two main CSS analyses that carried out in overall slope probabilistic analysis based on Rocscience [10]; the overall slope surface analysis and the critical probabilistic surface analysis. The critical deterministic surface analysis is also carried out in probabilistic analysis.
Based on the summary of probabilistic results of KB tailings dam in Table 3, all the mean FOS have comply the minimum recommended value required for long-term steady seepage downstream slope designs. It is also noticed that the critical probabilistic surfaces analysis of Janbu Simplified, Spencer and GLE/MP have produced two surfaces that correspond to the normal and lognormal FOS distributions. On the other hand, there are two FOS limit used in determining the probability of failure – the probability of failure when FOS < 1.0 and FOS < 1.5. In this stability assessment, the former is automatically computed for all of the surface analyses while the latter is determined by sampling the exact value of FOS at 1.5 from cumulative probability plot and only available for overall slope surface analysis. It is also can be seen that, there is zero probability of failure when FOS < 1.0 for all surface analyses. This means that from all of the number of samples, there is none of the sample has FOS < 1.0. However, for the case of probability of failure when FOS < 1.5, Bishop Simplified method gave the lowest by having 8.539 percent of its FOS samples less than 1.5. This probability of failure is relatively low and considered acceptable although there is no universal acceptable values implemented [10, 11].

There are two reliability indices in probabilistic analysis that are computed assuming normal and lognormal distribution of the FOS. According to Rocscience [10], FOS is often best fit by a lognormal instead of a normal distribution because lognormal distribution is best used with variables that have non-zero values. Generally, in order to ensure a safe slope design, a reliability index of at least 3 is recommended [10]. Based on the summary of probabilistic results of KB tailings dam in Table 3, it is noticed that only four reliability index values are less than 3. Moreover, these reliability index values are from normally-distributed FOS and were given by critical probabilistic surface analysis. In the meantime, all of the reliability indices for critical deterministic surface analysis exceed the minimum recommended value and also surpass the indices given by critical probabilistic surface analysis. Still, the indices given by critical deterministic surface analysis do not represent the KB tailings dam slope reliability. In a more representative overall slope surface analysis, it can be seen that both of the normal and lognormal reliability index values are twofold the minimum recommended value which indicate the high level of safety of KB tailings dam slope.

Table 3. The summary of probabilistic results of KB tailings dam.

| LEM       | Surface Analysis  | Mean FOS | $P_f$ at FOS < 1.0 (%) | $P_f$ at FOS < 1.5 (%) | $\beta$ | $\beta_{LN}$ |
|-----------|-------------------|----------|-----------------------|------------------------|--------|--------------|
| Ordinary  | Overall Slope     | 1.577    | 0.000                 | 17.370                 | 7.005  | 8.702        |
|           | Critical Probabilistic | 105.174 | 0.000                 | N/A                    | 0.910  | 4.823        |
|           | Critical Deterministic | 1.640   | 0.000                 | N/A                    | 5.388  | 6.803        |
| Bishop    | Overall Slope     | 1.643    | 0.000                 | 8.539                  | 6.146  | 7.774        |
| Simplified | Critical Probabilistic | 110.782 | 0.000                 | N/A                    | 1.373  | 6.945        |
|           | Critical Deterministic | 1.660   | 0.000                 | N/A                    | 5.564  | 7.066        |
| Janbu     | Overall Slope     | 1.588    | 0.000                 | 15.620                 | 6.776  | 8.442        |
| Simplified | Critical Probabilistic | 43.957* / 1.658** | 0.000                 | N/A                    | 4.204  | 6.743        |
|           | Critical Deterministic | 1.639   | 0.000                 | N/A                    | 5.392  | 6.807        |
| Spencer   | Overall Slope     | 1.639    | 0.000                 | 9.227                  | 6.105  | 7.713        |
|           | Critical Probabilistic | 71.516* / 1.669** | 0.000                 | N/A                    | 2.926  | 6.914        |
|           | Critical Deterministic | 1.656   | 0.000                 | N/A                    | 5.513  | 6.992        |
| GLE/MP    | Overall Slope     | 1.640    | 0.000                 | 9.255                  | 6.081  | 7.685        |
|           | Critical Probabilistic | 79.340* / 1.670** | 0.000                 | N/A                    | 2.285  | 6.869        |
|           | Critical Deterministic | 1.657   | 0.000                 | N/A                    | 5.509  | 6.990        |

* Critical probabilistic surface related to normal distribution
** Critical probabilistic surface related to lognormal distribution
N/A Not available
4. Conclusion
This paper analysed the stability of the design and construction of KB tailings dam, using different types of limit equilibrium methods of slices in both deterministic and probabilistic analyses. It was found that the upstream and downstream FOS obtained through deterministic analysis are satisfactory as compared to the minimum recommended FOS under both normal operating freeboard and flood freeboard conditions. In terms of reliability indices, both of the normal and lognormal reliability index values from overall slope surface analysis are twofold the minimum recommended value, which indicate the high level of safety of KB tailings dam slope.

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