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INTEGRATED SLOPE STABILITY ANALYSIS (SSA) WITH TRANSIENT GROUNDWATER FINITE ELEMENT ANALYSIS FOR EMBANKMENT STABILITY

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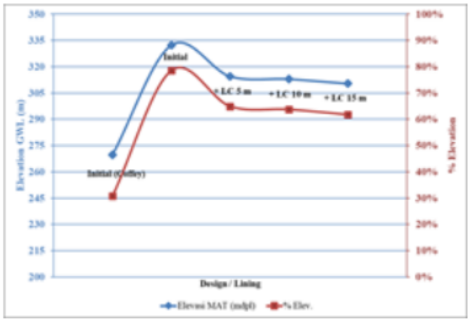


Abstract

The subsurface hydrological conditions greatly affect the slope stability of a material. The presence of water in a material increases the pore pressure, causing a reduction in the strength of the material to withstand the loads borne by the slope. The water for the tailing storage facility comes from liquid waste (slurry). Water from the tailings can seep into the embankment if it is not properly coated with an impermeable layer or if the impermeable layer is not functioning properly. In the TSF design, the hydrogeological conditions need to be well studied to estimate the potential seepage and flow in the embankment material. In addition, monitoring of hydrogeological conditions both in the embankment and the area around the TSF is needed to measure the distribution and flow patterns of water. The study was conducted to evaluate the slope stability that has been done in the previous TSF design. In this study, slope stability analysis will be carried out based on the TSF hydrogeological parameters obtained using the transient groundwater finite element analysis method. Moreover, the study is aimed at optimizing geometric parameters and stabilizing embankments based on existing geomechanical and hydrogeological conditions. The research results were geometric parameters and stabilization efforts of the TSF constituent components.

Keywords: dam; embankment; evaluation; facility; hydrogeology; seepage; transient; tailing

1.0 INTRODUCTION

Tailing Storage Facility (TSF) dam is one of the largest structures built to accommodate mining residue. Embankments are constructed with a fraction of the tailings [1]. Although there are some similarities to water dams, there are very significant differences. Fundamental differences in the function of the dam itself are represented in the aspects of design objectives, engineering and environmental criteria, construction processes, and operations [2]. Contact between beds is a weak zone, and at the contact of rock bedding, it is usually found a thin layer that can trigger instability of slope. Slope stability of low-wall is affected by bedding contact between two rocks [3]. Bedding contact is usually in the form of clay which has high plasticity, thus it will separate two different beds. Overstress occurs due to difference in bedding ratio between the top and the bottom. The smaller the bedding ratio, the smaller the safety factor produced [4]. Since the rock bedding has a weak zone, it may cause failure at the toe.

TSFs often represent the environmental vulnerability associated with mining operations [5]. The peak period of dam failure occurred in 1960-1980 with an incidence of 50 cases/decade; in the following decades it decreased to 20 cases/decade [6]. TSF reliability is the lowest among other soil structures [7]. Dam failure susceptibility is generally caused by the following factors: (i) dyke construction with residual material from mining operations; (ii) the increasing of the dam sequentially as the effluent water content increases; (iii) lack of regulation in design criteria; (iv) high post-mining maintenance costs [8]. Based on the above factors, the main reason for failure is due to "unusual rain" and bad management [6].

In construction planning, it is necessary to pay attention to environmental safety aspects including the location and distance as far as possible from vital objects such as operational facilities and residences to ensure accidents with severe impacts do not occur. Environmental risks in the disposal process include dam safety, as well as operational issues related to the potential contamination of acid mine drainage. Transparency of the safety and environmental security situation associated with dams need to be ensured to increase awareness and preparedness. Then, mitigate the impacts that can occur to anticipate accidents [9, 10].

In analyzing the slope stability of the Tailing Storage Facility (TSF), one of the main components in it is the hydrogeological parameter. Hydrogeological conditions which include position, behavior, dynamics, and interaction of groundwater with materials which play a major role in embankment stability [11-22].

It has long been known that the observed pore pressure data correlates well with several types of dam failures [23]. Hydraulic complexity can have an impact on water flow in the material [24]. There are at least 4 main factors that affect the value of hydraulic conductivity such as rock mass, lithology, depth, and material fill (gouge) in the existing hydraulic system [26]. Changes in groundwater level and mixing with the material in a medium can affect the strength of the rock to bear the load [27].

The earliest attempts to apply the finite element method to hydrogeology were made in the mid-1960s and well implemented in the early 1970s. This method is a useful tool in solving the problem of subsurface water flow in a complex scope [28]. Some of the main applications of FEM in subsurface hydrogeology to stress analysis problems operate on systems in equilibrium conditions. Likewise, the use of FEM for underground water flow problems and seepage in steady state. Initial attempts to apply the FEM method to steady-state heat flow, steady state seepage problems on anisotropic and heterogeneous mediums, followed by applications for seepage on the free surface [28].

Estimation on soil behavior parameters and their relationship to conductivity can be obtained from the groundwater characteristics relationship curve in a nonlinear equation. This equation is based on the assumption that the shape of the water characteristic curve depends on the pore size distribution of the soil [29]. In solving problems, a large system is divided into smaller and simpler parts known as finite elements, which are then compiled into a larger system of equations that model all problems [30].

The slope stability analysis carried out previously has not calculated the hydrogeological parameters in the TSF constituent components. The assumption in the analysis is that there is no flow in the embankment, but the flow is in the contact area under the embankment material. The nature of the embankment material which is drier than the saturated tailings, will tend to have a greater conductivity value for similar materials [31]. This allows for potential flow within the embankment. The groundwater level has a strong influence on the water content, pore pressure, and the shear strength of the material [32]. The presence of water in the embankment can react physically (changes in water content) and chemically with the material, especially if there is an unstable clay mineral. This reaction has the potential to reduce the strength of the material [33].

This causes the previous slope stability analysis that has been carried out tends to be dubious. This study was conducted to assess and evaluate the TSF slope stability analysis that had been carried out previously. It is hoped that with a more careful evaluation of hydrogeological conditions, the results of the analysis of slope stability and optimization of the TSF safety factor (FoS) in this study can reflect actual conditions in the field and be more reliable for the basis of decision making.

2.0 METHODOLOGY

The evaluation study is carried out by analyzing the physical and mechanical parameters of the TSF constituent components used in the previous slope stability analysis. The geometric parameters and physical criteria of the TSF used in the analysis are shown in Figure 1. The geometric boundaries of the TSF constituent components are obtained by digitizing directly in the figure. The error tolerance in digitizing the geometry is less than 1 m for a range of 600 m. Thus, it can be said that the coordinates of the geometric boundaries are likely to be the same or resemble each other. For parameters that are not stated or defined in the previous analysis and the analysis report is determined independently in this study.

Slope stability analysis in this study was carried out using the Limit Equilibrium Method (LEM) with the Spencer calculation method. The spencer calculation method was chosen because it takes into account the balance of force and momentum in the slice [34]. Hydrogeological parameters were simulated using the Transient Groundwater Finite Element Analysis (T-GFEA) method. This method is very useful in estimating the behavior of complex groundwater flows in the material in a time-dependent manner [35, 36].

Slope stability analysis was performed simultaneously with hydrogeological analysis. This is necessary so that the analysis can be carried out comprehensively including aspects of hydrogeology and slope stability embankment; as in some cases of stability analysis of bank slope [37]; stratovolcano flank collapse [38]; earth dam Jatigede [39]; slope embankment koga dam [38]. The criteria in the analysis are defined in order to optimize the safety of the TSF, such as providing an impermeable layer, sloping embankment, and simulating retaining toe as a TSF support component. In this study, all analyzes were carried out using Rocscience: Slide 6.0 software.

3.0 RESULTS AND DISCUSSION

3.1. Material Properties

The physical, mechanical, and hydraulic properties used in the analysis in this study are shown in Table 1. Considering that the material for the tailings dam embankment for TSF is a material that will experience "wetting", it tends to have a greater conductivity value than tailings material which has decreased moisture content (drying) for similar materials [31]. Since the material for the embankment (wetting - solid waste) is assumed to be in a compacted state, the K value is considered the same for the two materials. However, the material model will be determined differently (wetting and drying waste) in the analysis, following the material model according to [31].

Clay material (CH-MH) which has a moisture content of 29.6% NWC is used as packed pile and basement. The more saturated material with a moisture content of 47.7% was assumed to be tailings. The tailings material is considered to be oversaturated with respect to supernanthan (stagnant) water. The tailings material is considered to be oversaturated with respect to supernanthan (stagnant) water. The groundwater level over time will be modeled using the transient groundwater finite element analysis method

Table 1 Material properties

Material Type	Bulk Density (kN/m³)	Effective Strength Parameter			Ea** (kPa)	Poisson's Ratio**	Hidraulic Conductivity (m/s)	Note
		Cohesion c' (kPa)	Friction Angle φ' (degrees)	Tensil Strength (kPa)**				
Deposited Tailings (Drying)	18	0	25	0.00	3844.49	0.200	10^{-7}	Upper bound
Compacted Clayey Mine Waste	20	5	25	10.72	5200.78	0.224	10^{-7}	Wetting
Waste	22	0	38	0.00	66429.35	0.224	10-7	Drying
Foundation Clay (CH)	17	5	30	8.66	6093.24	0.224	5×10^{-8}	lower bound
Foundation	20	200	30	346.41	10679.91	0.224	5×10^{-8}	lower bound

3.2. Underdrainage System Ineffectiveness

In evaluating the stability of the TSF slope, the underdrainage system in the TSF proved ineffective in the dewatering process of the tailings material. Drainage is blocked due to suspension and colloid particles. Thus, the underdrainage criterion was ignored in the evaluation. Instead, the analysis will simulate a more impermeable layer at the contact boundary between the tailings and the embankment (tailings dam). The material with a lower hydraulic conductivity value than the embankment lining material is expected to be able to inhibit groundwater infiltration, considering that hydraulic conductivity affects the infiltration rate and groundwater seepage [41].

3.3. Transient Groundwater Finite Element Analysis (T-GFEA) Parameters

The parameters used for the T-GFEA are shown in Table 2. The percentage value of water "recovery" is used as the basis for the assumption of the percent reduction in water content followed by a drop in water level (drawdown) due to water flowing from the TSF system at a certain time due to settlement of the material. The "undrained" criterion is defined as the drawdown for the portion of the tailings away from the embankment. Meanwhile, the "drained" criterion is determined for the part of the tailings that is close to the embankment (beach), simulating drying by sunlight and seepage of water through the embankment. This criterion is mentioned in the reports for the tailings settlement and drying tests, but was not used in the previous analysis.

Table 2 Parameters used for T-GFEA analysis

Initial Total Head (t_0)	Range from Dam (m)	Drainage	Settling		Drawdown (m) t_n	Total head @ t_n (m)	Remarks
			Time - t_n (day)	Water Recovery			
360.48	227.932	Undrained	15	25.40%	20.744	339.736	Simulating middle part / far-side from dam
	100.000	Drained	18	12.50%	6.693	353.787	Simulating "Beach" part, near - dam

3.4. Analysis

The analysis carried out in this evaluation study consists of several stages and criteria as follows:

3.4.1. Transient Groundwater Finite Element Analysis (T-GFEA)

Transient Groundwater Finite Element Analysis (T-GFEA) with Slope Stability Analysis (SSA). Up to time (t_n) 6 months or 180 days.

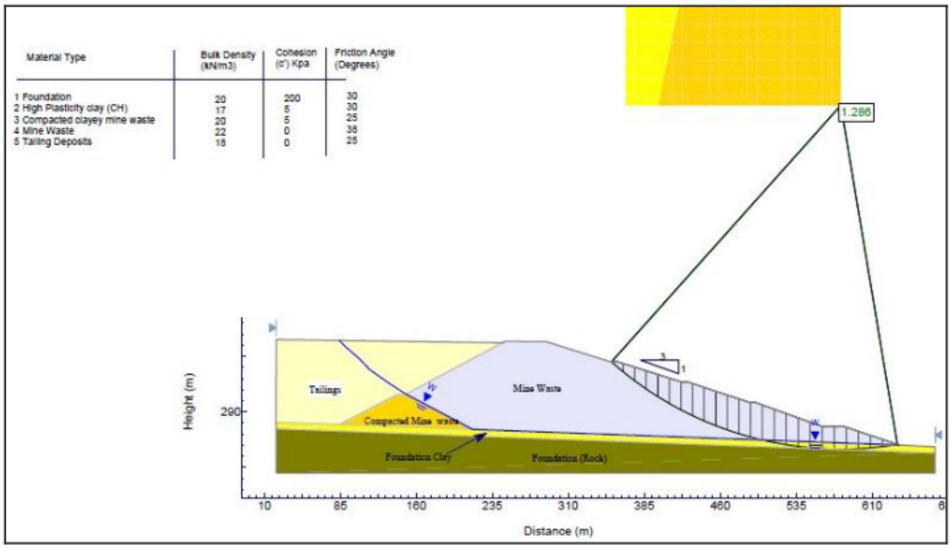
3.4.2. Hydrogeological management efforts

Simulation of a layer of clay material which is more impermeable to the contact between the embankment and the tailings. The thicknesses applied were 5 m (+LC 5), 10 m (+LC 10), and 15 m (+LC 15), with hydraulic conductivity values of 10-13 m/s.

3.4.3 Stabilization efforts including

Efforts to apply retaining wall / toe with vertical thickness or height of 20 m and 30 m. This criterion targets Groundwater Flow at the end of the embankment. In addition, a reduction of the slope (10) was also carried out from 140 to 130.

Figure 1 shows the analysis of the previous (initial) slope stability with the predetermined GW. It appears that the condition of the tailings material in the previous analysis is a saturated condition, but the condition of the groundwater table to the embankment is simulated to be under the gray embankment material (mine waste) on contact with the compacted mine waste.



Material Type	Bulk Density (kN/m3)	Cohesion (c') Kpa	Friction Angle (Degrees)
1 Foundation	20	200	30
2 High Plasticity clay (CH)	17	5	30
3 Compacted clayey mine waste	20	5	25
4 Mine Waste	22	0	38
5 Tailing Deposits	18	0	25

Figure 1 The criteria used as the basis for evaluating the previous analysis

Figure 2 is an example of the results of slope stability analysis using hydrogeological parameters obtained by the transient groundwater finite element analysis method at (tn) 6 months or 180 days. The flow pattern is shown by the flow vector and the groundwater level flowing through the embankment. The difference in position can be observed in the two sections. The groundwater level condition in the initial analysis (predetermined GW) in Figure 1 is much lower than in Figure 2. The pore pressure distribution is getting closer to 0 at a position closer to the groundwater level. The higher the ground water level in a material, the pore pressure due to the ground water level will be greater at a point of the same height in the material.

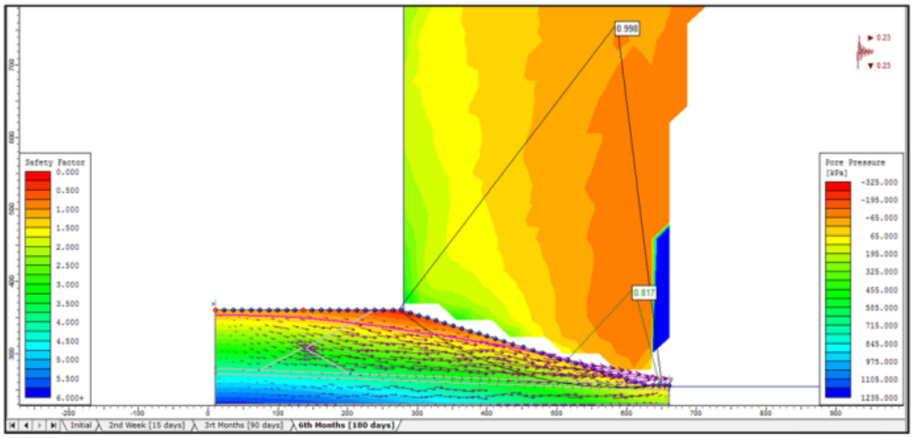


Figure 2 Slope stability analysis with T-GFEA, tn 180 days

The rate of subsidence in the groundwater table reflects the natural settlement and consolidation processes that occur in the material body. This parameter refers to the laboratory test mentioned in the previous report. The groundwater distribution analysis in Figure 1 seems to ignore the conductivity of the embankment, or seems impermeable. Compared to previous analysis reports, the groundwater level tends to be higher due to water flow in the embankment. Thus, the total head pressure and pore pressure increase which can lead to destabilization of the embankment.

The difference in hydrogeological parameters between the previous analysis and the analysis in this study is very significant which has an impact on FoS obtained from the results of the slope stability analysis. The previous analysis resulted in a FoS of 1.286 while the analysis in this study obtained a FoS of 0.998 for an overall slope of 140 for an embankment height of about 103.4 m. It should be noted that there is a smaller FoS value in the toe of the embankment, which is 0.818. This occurs due to the saturation of the groundwater level in that section.

The simplest effort for stabilization is to reduce the steepness of the slope which reduces the load on the slope. Simple reinforcement by providing a retaining wall / toe at the toe of the embankment at the level of the groundwater that comes out on the surface is also possible. Basically, these methods are carried out to withstand the existing stress by increasing the resistance force. Other measures can be made to reduce the influence of water or groundwater levels on the embankment body. Actually, the most effective way is to remove water from the inside with a drainage system as a depressuration effort. However, based on previous studies underdrainage systems or similar systems will not work efficiently. Efforts by applying more impermeable materials can be carried out as an effort to manage hydrogeological parameters, in this case groundwater originating from tailings. The next part of the analysis and submission will be presented at a time of tn 6 months (180 days).

Various hydrogeological conditions were simulated by applying an impermeable material to the contact between the embankment and the tailings. Water is simulated flowing through the contact area between the basement and the embankment. The more impermeable material forces the water flow to move through the weak area (contact zone) so that filling into the embankment body can be reduced. Table 3 contains a summary of the groundwater level parameters with a variety of effort criteria for hydrogeological management from the results of the T-GFEA analysis.

The depth of the MAT listed in the table is measured vertically from the crest embankment. The elevation percentage value is calculated based on the division of the MAT elevation (MAT-base model design elevation) to the vertical range of the model (crest-base model design elevation).

Table 3 Summary of groundwater level data at initial conditions and during application of a more impermeable material

Crest Elevation	Base Model Design	Criteria	Depth GWL	Elevation GWL (m.dpl)	% Elev.	GWL MAT	% Draw Down
360.5	229.45	Initial (Predetermined GW)	90.76	269.74	30.74%	-	-
		Initial (GFEA)	28.155	332.345	78.52%	100.00%	0.00%
		+ LC 5 m	45.959	314.541	64.93%	82.70%	17.30%
		+ LC 10 m	47.51	312.99	63.75%	81.19%	18.81%
		+ LC 15 m	50.105	310.395	61.77%	78.67%	21.33%

Figure 3 shows a visualization of the variation in groundwater level and elevation percent of the MAT against various predetermined criteria. There is a significant difference between the initial conditions used in the previous analysis and the analysis in this study.

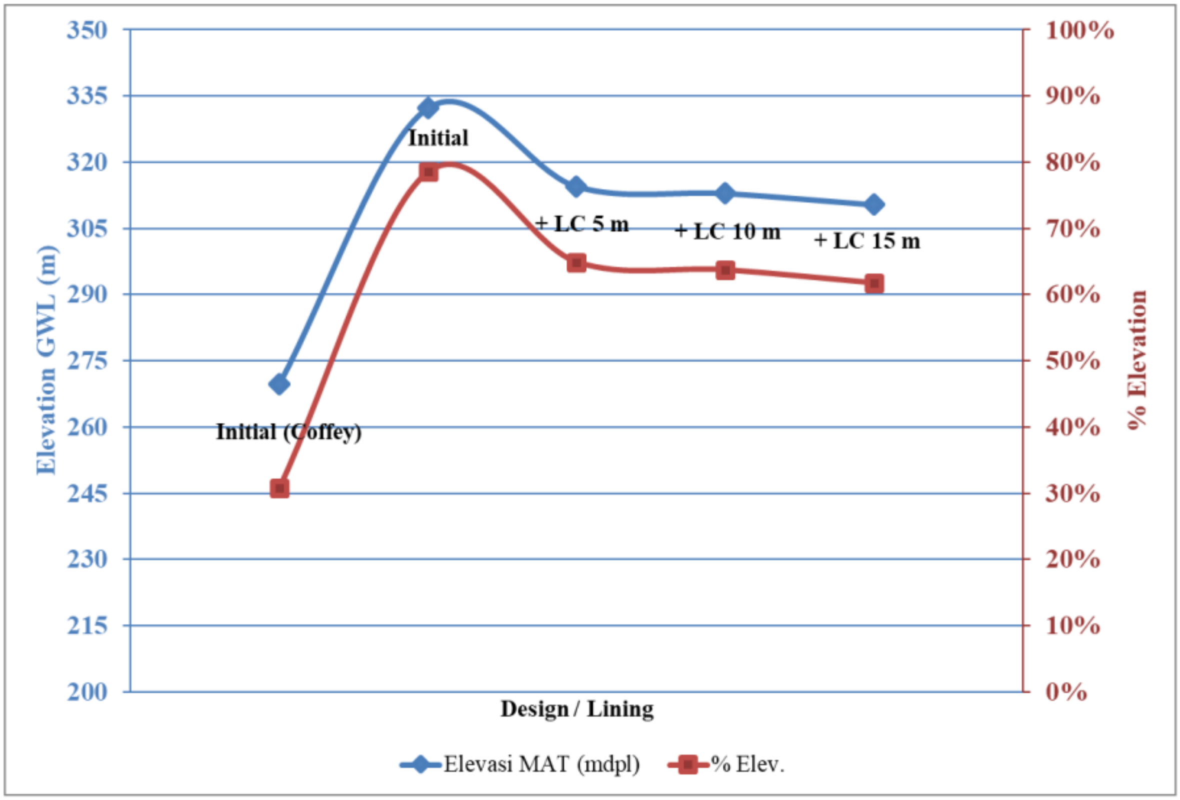


Figure 3 Visualization of variations in the Mat with different design criteria

The MAT ratio is the ratio at the initial position of this study. MAT that is below the initial MAT has a smaller ratio. The percentage reduction (%) is calculated by the equation (% decrease = (1-MAT ratio) * 100). This value is calculated based on the MAT ratio when the clay lining material is applied to the initial MAT (without lining).

Plotting the percentage value of the MAT ratio against the lining thickness criterion of the clay material (D) with a conductivity value of 10-13 is shown in Fig. 4. From the plotting, an equation with a coefficient of determination (R2) of $R^2 = 0.9943$ can be obtained, namely:

$$\text{MAT Ratio} = (0.8661\ D^{(-0.031)}) * 100\% \quad (1)$$

The percentage reduction is the reduction from the ratio of 100% (initial) to a certain MAT ratio. The equation is as follows:

$$\%\text{reduction} = (1-0.8661 D^{(-0.031)}) * 100\% \quad (2)$$

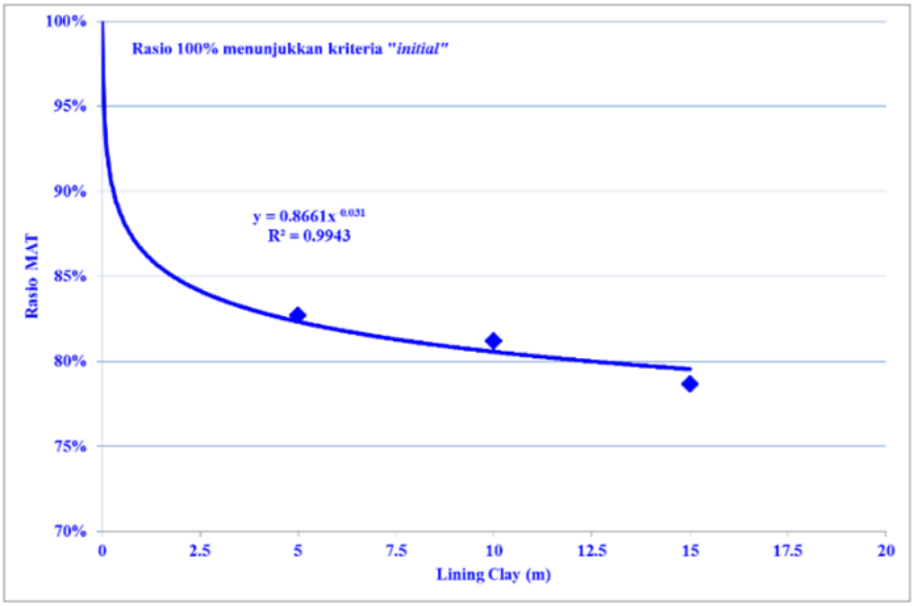


Figure 4 Visualization of variations in the Mat with different design criteria

This value from the function above is analytical, based on the input parameters used in the analysis mentioned above. Thus, differences with actual conditions in the field can still occur. However, if the characteristics in the field resemble the criteria in the analysis, then the above functions can be used as references in planning and evaluation in monitoring hydrogeological conditions.

The analysis for the stabilization and optimization of the TSF embankment (tailing dam) was carried out with the criteria and results as listed in Table 4. Slope stability analysis was carried out simultaneously with T-GFEA analysis with Rocscience software: Slide 6.0. Embankment stabilization cannot only be done by tapping the slopes or adding retaining walls / toe, but requires a combination with control of the ground water level in the embankment body. This statement is also shown in the analysis results in the following table.

Table 4 Summary of the results of embankment stabilization and optimization analysis

Stage	Time - t_n (day)	Criteria		K. Lining Material (m/s)	FoS		Remarks
					overall	toe	
6th Month	180	Initial Design			0.998	0.818	Unstable
		Lining 5 m Clay		K = 10-13	1.146	0.849	Toe Unstable
		Lining 10 m Clay		K = 10-13	1.159	0.858	Toe Unstable
		Lining 15 m Clay		K = 10-13	1.161	0.865	Toe Unstable
		Lining 5 m Clay	slope embankment 14°--> 13°		1.209	0.886	Toe Unstable
		Initial Design	retaining wall / toe 20 m		1.183	0.900	Toe Unstable
		Initial Design	retaining wall / toe 30 m		1.276	1.005	Toe Critical
		Lining 5 m Clay	retaining wall / toe 20 m	K = 10-13	1.255	1.140	Stable
		Lining 5 m Clay	retaining wall / toe 30 m	K = 10-13	1.396 (Global min.)		Stable

4.0 CONCLUSIONS

The underdrainage system in the TSF will be ineffective in the dewatering process of the tailings material. Efforts are needed to manage the hydrogeological parameters related to the groundwater level in the embankment material. In general, the above functions apply to TSF constituent clay components with a hydraulic conductivity of 10-7 m/s, and lining materials with a hydraulic conductivity of 10-13 m/s. The function of the drawdown percentage equation for the required lining material thickness (D) is as follows:

$$\%reduction = (1-0.8661D^{(-0.031)}) *100\% \quad (3)$$

The optimum stability criterion is to add a more impermeable lining of the clay material to a thickness of 5 m and to support the retaining wall / toe with a thickness of 20-30 m.

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