NUMERICAL MODELLING AND SLOPE STABILITY ANALYSIS FOR OPTIMIZING OPEN PIT COAL MINE AT BINUANG SOUTH KALIMANTAN

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ABSTRACT

The objective of the numerical modelling study and slope stability analysis using the finite element method (FEM) is to determine the optimum pit slope design. Many simulations were carried out by varying the overall pit slopes and the depth of the open pit coal mines. The pit slope with a safe condition in stability and a reasonable waste-coal ratio was chosen as the optimum pit slope design. According to the result of this study, some revisions on the existing pit slope design are needed. It is also recommended to develop a monitoring system, especially for instability monitoring and groundwater level fluctuations behind the slope surfaces that could threaten the slope stability.

Keywords : Slope stability analysis, numerical modelling, finite element method (FEM), overall pit slope, optimum pit slope design

1. INTRODUCTION

The main objective of this numerical study and slope stability analysis is to check the slope stability of the open pit coal mine according to the existing pit plan is quite stable at least for projecting the life time of the mine, and also to determine the optimum pit slope design by numerical modelling and simulation study. Many variations of overall pit slopes and the depths with the same geotechnical parameter inputs were simulated during this study.

The slope model with the safety factor of 1.3 to 2.0 and the waste-coal ratio less than the economic stripping ratio that can be received by the management (SR is less than 12 for the mining area) was expressed as an optimum pit slope.

The optimum pit slope model obtained from this study was recommended as the ultimate pit slope design and will be used as a reference for the operation of the open pit coal mine in the future. This study is expected to be a typical model that can be developed to support the implementation of conservation principle in coal mining in Indonesia.

2. METHODS

Methods in this study consist of firstly, literature study, including the secondary data collection from technical reports and related former researches, such as geological maps, topographical or situation maps, geological log maps, core log data, geotechnical data from laboratory test, and pit plan maps. Secondly, field investigation includes the observation and taking photograph of the rock mass conditions in the slope surfaces represents overburden, interburden and coal seams of high wall as well as low-wall of the open pit mine. Geotechnical rock descriptions was done during observation (Singkal, 1986) by collecting the strength index, rock quality designation (RQD), joint spacing, joint conditions of the rock mass, and ground water conditions. Core samples were also collected from 4 geotechnical cores drilling program (GT.01, GT.02, GT.03 and GT.04), and then were used for laboratory testing. Thirdly, geotechnical data processing covers the statistical data setting and characterization of the rock masses of overburden, interburden, and coal seams by using Roclab software based on all of the data were obtained from the investigation and the existing secondary data. Fourthly, performing the numerical modelling study and slope stability analysis by using the finite element method (FEM). The modelling was done on three cross-sections of the pit slopes representing the coal mine slope of the Karet Tiga and the Sarang Burung area in Binuang region, South Kalimantan. Slope modelling was made by various combinations of the depth and the overall pit slope for the high and low-wall sides. The mine digging operation was simulated by dividing it into some stages of the digging to find out the optimum pit slope model.

3. GEOLOGICAL CONDITION OF MINE AREA

There are four minor faults known in the two mine areas, with strikes of N295°E, N147°E, N170°E, N180°E, and two other minor faults with strike of N 310-320° E and N 60-110° E in various dips that were almost vertical. It is known that a regional asymmetries folding structure, the west wing, has a deeper dip than that of the east wing. It is also found a minor anticline and syncline as illustrated in the Figures 1 and 2. The coal seam in that area is known as Tanjung Formation. In general, there are three coal seams in that area with strikes of N 174° E to N 222° E and the dip between 15° and 16°. The rock masses are seamy (Figure 3), the dips are generally between 20° and 30°.

The geotechnical data that obtained from the laboratory test and site investigation were processed by using the Roclab software, and their results are resumed in Tables 1 and 2.

Figure 1. Structure condition in the investigated area

Figure 2. Location of geotechnical investigation at the low-wall

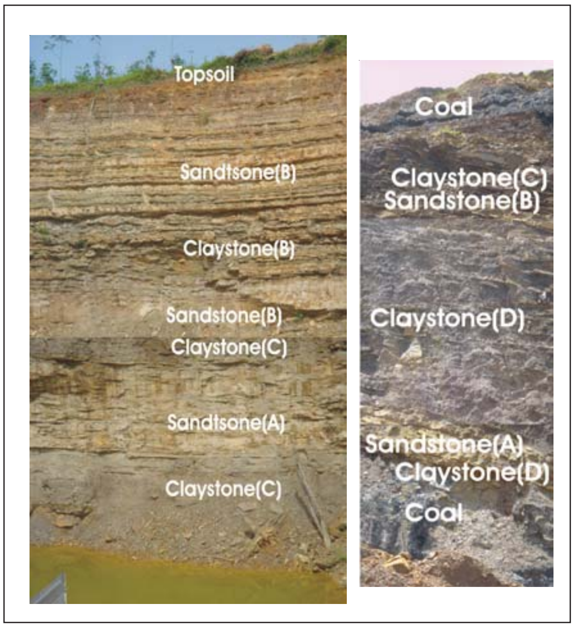

Figure 3. Stratigraphy of the rock mass at the high wall of the mine out area

4. NUMERICAL MODELLING AND SLOPE STABILITY ANALYSIS

Pit slope modelling is a representation of open pit slope that will be analysed by inputting the geometrical factors, kind of rock materials, limitation and orientation of discontinuities, physical and mechanical properties of rock mass of the pit slope, in-situ stress condition, loading conditions, and limit conditions, so that it could represent the real condition as near as possible. The geo- metry of the models, the depth and the overall pit slopes, influences the waste-coal ratio (or stripping ratio, SR), that is the ratio between waste volume that has to be removed and the coal tonnages that can be mined. From the economic and safety point of

Content

Table 1. Geotechnical processing data of the Karet Tiga mine (Suratha *et al*, 2006)

No	Kind of rock	γ (ton/m^3)	σ_t (MPa.)	σ_c (MPa.)	E (MPa.)	μ	Φp (degree)	Cp (MPa.)	Φr (degree)	Cr (MPa.)
1	Claystone	2.071	0.03	0.33	103	0.28	35	0.11	29	0.08
2	Sandstone	2.205	0.19	1.86	391	0.29	30	0.27	24	0.20
3	Siltstone	2.486	1.70	17.02	4375	0.28	37	0.25	32	0.19
4	Sandstone	2.359	1.47	14.66	2565	0.28	30	0.31	24	0.23
5	Claystone	2.554	0.38	3.75	725	0.29	31	0.06	25	0.04
6	Coal	2.373	0.21	2.14	478	0.21	26	0.21	23	0.16
7	Claystone	2.392	0.15	1.46	473	0.21	24	0.23	18	0.17
8	Sandstone	2.309	1.23	12.30	3606	0.23	25	0.70	20	0.53
9	Siltstone	2.467	1.42	14.16	2727	0.27	27	0.54	20	0.40
10	C-claystone	2.221	0.45	4.53	1771	0.32	16	0.33	11	0.24
11	Claystone	2.684	2.56	25.60	4240	0.28	35	0.16	34	0.12
12	Sandstone	2.286	1.08	10.80	5706	0.28	32	0.28	29	0.18

Table 2. Geotechnical processing data of Sarang Burung mine (Suratha *et al*, 2006)

No	Kind of rock	γ (ton/m^3)	σ_t (MPa.)	σ_c (MPa.)	E (MPa.)	μ	Φp (degree)	Cp (MPa.)	Φr (degree)	Cr (MPa.)
1	Claystone-1	2.071	0.03	0.33	103	0.28	35	0.11	29	0.08
2	Sandstone-1	2.242	0.437	4.37	1091	0.31	30	0.10	22	0.07
3	Claystone-2	2.174	0.66	6.62	2027	0.26	32	0.17	26	0.13
4	Sandstone-2	2.218	0.06	0.56	1589	0.31	29	0.55	20	0.41
5	Claystone-3	2.253	0.72	7.23	2112	0.20	34	0.21	27	0.16
6	Coal	2.373	0.21	2.14	478	0.21	32	0.21	23	0.16
7	Claystone-4	2.233	0.59	5.9	1384	0.27	33	0.16	26	0.12
8	Siltstone	2.337	0.80	7.99	1215	0.24	40	0.22	32	0.17
9	Sandstone-3	2.046	0.76	7.58	2004	0.21	30	0.59	21	0.44

Where:

- γ, *density of rock mass,*
- σ_t, *tensile strength,*
- σ_c, *compressive strength,*
- E, *Young modulus,*
- μ, *Poisson's ratio,*
- *Cp, peak cohesion,*
- Φp, *peak internal of friction angle,*
- Φr, *residual internal of friction angle*
- *Cr, residual cohesion.*

view, the SR and the safety factor of the slope are very important factors in determining the optimum pit slope design.

There were two main activities in this study, the numerical modelling and slope stability analysis by using the FEM. Generally, there are five steps in the numerical modelling, the development of static's system model, selection of the rock mass constitutive, modelling of the load and in-situ stress as input, setting the limits of the model, limit condition, and validation of the model.

The main aim of the slope stability analysis is to identify the stability condition of the open pit slopes that is developed according to the pit plan design either for the Karet Tiga or the Sarang Burung locations. In general, slope stability is effected by five main factors, they are; slope geometry (consisting of the depth and the dip of slope), rock mass strength, orientation of discontinuities corresponding to the orientation of the pit slope, groundwater condition particularly the groundwater level in the rock mass slope, and external factors, such as vibration from earthquake, blasting activities, and external load of the system (Hoek and Bray, 1981; International for Rock Mechanics, 1975).

4.1 Static System Modelling

The static system modelling is a representation of the cross section structure of the pit slope with taking the forces, kinds and configuration of rock materials and their geotechnical properties, rock mass structures or discontinuities, and geometrical system of the model. The static system modelling uses the principal of plane strain analysis or two dimensional model analyses. The strain that has the direction perpendicular to the model area (or Y-axis) was neglected or assumed to be zero. It means that the length of the model to the Y-direction is unlimited. Therefore the strain analysis was only done to the X and Z directions.

In this study, it was developed three and four models representing the mine area of the Karet Tiga and the Sarang Burung respectively. To the all of the seven models, there were made some simulations by varying the overall pit slopes and the depth of the mine opening to find out the overall optimum pit slope.

For example, two of the statics system models representing as the Karet Tiga and the Sarang Burung mine areas are illustrated in Figures 4 and 5 respectively (Suratha *et al*, 2006).

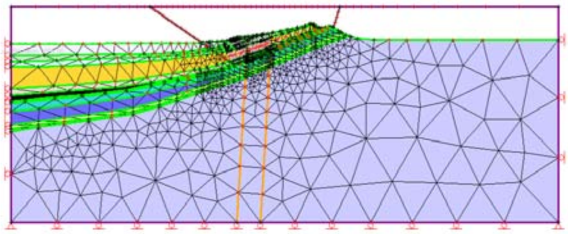

Figure 4. The static system model of the pit slope section 23 of the Karet Tiga area

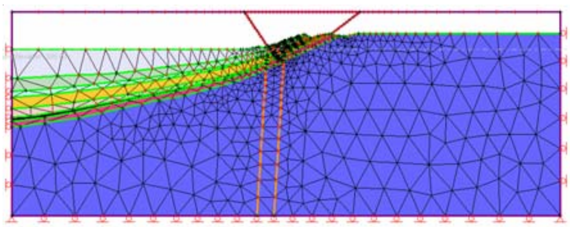

Figure 5. The static system model of the pit slope section-07 of the Sarang Burung area

4.2 Constitutive Model of Rock Mass

Rock mass behaviour modelling is to choose the specific characteristics of the rock mass that have to be taken into consideration for slope models according to the real rock mass condition as near as possible. In this modelling, the rock mass was assumed as elastic-plastic material. Hence, it was possible to analyze the model with the assumption of elastic behavior until the plastic limit condition. Therefore, the Mohr-Coulomb criteria of failure can be adopted in determining the stability factor of the models for overburden, interburden, coal seam, and underburden rock seam as well.

4.3 Input Parameter

Input parameters for all of the seams of the rock slope models were taken from the rock mass data characterization during site investigations and laboratory test. Some professional judgments were also involved to rationalize the input parameter based on the theoretical approach and experiences.

The summary of the input parameters for the FEM modelling can be seen in Table 3. For the Karet Tiga mine area, the material type numbers of 1 to 5 are representing the high-wall side, and numbers of 7 to 12 are representing the low-wall side. For the Sarong Burung mine area, material type numbers of 1 to 5 are representing the high-wall side, and numbers of 7 to 9 are representing the low-wall side.

4.4 In-situ Stress

In this study, it was assumed that the load was only coming from the earth gravitation. There was no external static load, and there was also no dynamics load taken into calculation, because the South Kalimantan region is located in the safe area from earth quake.

The gravitational load depends on the depth beneath of the surface. Theoretically, the stress at any point in the model can be calculated as follows:

$\sigma_z = r.g.h$
$\sigma_h = k.\ \sigma_z = \mu/(1-\mu).\ \sigma_z$

Where;

σ_z = vertical stress
h = depth from surface

Content

Table 3. Input parameters for the FEM slope model

No	Kind of material	Unit weight (γ) (MN/m^3)	Tensile strength (σ_t) (MPa)	Young Modulus (E) (MPa)	Poisson's ratio (μ)	Friction angle(Φ) (degree)	Cohesion (c) (MPa)
A. KARET 3							
1	Claystone-1	0.01925	0.38	150	0.35	30	0.10
2	Sandstone-1	0.02086	0.20	450	0.35	30	0.25
3	Siltstone-1	0.02467	1.20	3	0.32	34	0.25
4	Sandstone-2	0.02044	1.30	2,8	0.28	33	0.30
5	Claystone-2	0.02538	0.30	650	0.29	29	0.15
6	Coal	0.01300	1.20	477	0.28	24	0.15
7	Claystone-3	0.02350	0.30	450	0.28	22	0.20
8	Sandstone-3	0.02309	0.30	3	0.23	27	0.60
9	Siltstone-2	0.02467	1.50	2,2	0.34	26	0.30
10	C-Claystone	0.02211	0.35	1,5	0.34	20	0.30
11	Claystone-4	0.02684	0.90	4	0.28	31	0.35
12	Sandstone-4	0.02286	1.50	3,6	0.28	33	0.32
B. SARANG BURUNG							
1	Claystone-1	0.02071	0.10	190	0.28	28	0.11
2	Sandstone-1	0.02442	0.50	1	0.28	30	0.13
3	Claystone-2	0.02174	0.50	1,6	0.28	28	0.10
4	Sandstone-2	0.02218	0.06	1,5	0.31	30	0.50
5	Claystone-3	0.02253	0.40	1,6	0.28	30	0.20
6	Coal	0.01300	0.21	478	0.28	32	0.21
7	Claystone-4	0.02233	0.30	1,2	0.28	30	0.16
8	Siiltstone	0.02337	0.50	2	0.28	30	0.40
9	Sandstone-3	0.02046	0.50	2	0.28	30	0.40

σ_h = horizontal stress
k = stress factor
r = rock density
μ = Poisson's ratio
g = gravity acceleration

4.5 Limit Conditions

Limit condition is defined as a condition of displacement or velocity at the limits of the model. At the left side and the right side of the model, it was assumed that there was no more horizontal displacement will happened ($m_x = 0$), and vertical displacement is allowed (m_z ¹ 0). On the other hand, at the bottom side of the model it was assumed that there was no more vertical displacement will happened ($m_z = 0$), and horizontal displacement is allowed (m_x ¹ 0). At the corner points of the bottom line of the model were assumed as the fixed points ($m_x = m_z = 0$).

4.6 Validation of the Model

Validation of the model is an effort to check that the model was valid according to the design concept of the modelling covering the geometry of the static system model, kind and their limits of the rock seams in the model, geotechnical parameters of rock mass of the model, and stress distribution among the model either vertically and or horizontally. It was carried out by the process of consolidation or execution the FEM software to the model. The vertical stress at any point of the model obtained from the execution can be checked to the theoretical vertical stress.

4.7 Slope Stability Analysis

All of the pit slope models of the Karat Tiga and the Sarong Burung mine areas were analyzed by using the FEM. From the result of the software execution, the stress distributions, displacements, and safety factor curves of the models entirely can be known. It means that the value of stress, displacement, and safety factor at any point of any element or mesh in the model can be known.

In context of slope stability analysis, safety factor (SF) distribution is used as an indicator to determine the stability condition of mine slope opening. Theoretically, every element in the slope model will be stable if the strength to the stress ratio at that element is greater than one, or the safety factor is greater than one (SF > 1.0). It can also be expressed that the safety factor is a ratio between the strength at any element in the model and the stress acted on that element, in accordance with the criteria of failure of the rock mass. The stability evaluation can be carried out based on the distribution of stress and safety factor at every element in the model, in order to be able to evaluate the stability of the entire pit slopes of the mine. Interpretation can then be made by examining the distribution of safety factor particularly at the surrounding of the toe of the slope model with the highest stress even for high and or low-wall sides.

4.8 Simulation for Pit Slope Optimization

The optimum pit slope was determined by performing a simulation study. Some of the pit slope models were simulated by varying overall pit slope and depth of the mine opening with representative geotechnical data inputs according to each location.

As an illustration, one example of the simulation in this modelling study was taken from the Karet Tiga pit section 11. The depth of mine opening from top surface of low-wall was varied from 20, 40, 50, 60, and 130 m. The overall pit slopes of the high wall side were also simulated from 40 °, 45 °, 50 °, 55 °, and 60 °. From this simulation, it can be concluded that the mine depth of 125 m according to the existing pit plan is valid and can be implemented. The optimum pit slope is 50 °, and safety factor, SF is between 1.3 and 1.57. It is shown that some elements of the model have safety factor of almost near one (SF= 1.04). Nevertheless, it can be concluded that the overall slope model as a whole system is still in a stable condition. Figures 6 and 7 show the typical results of the FEM modelling and analysis of this study (Suratha *et al*, 2006).

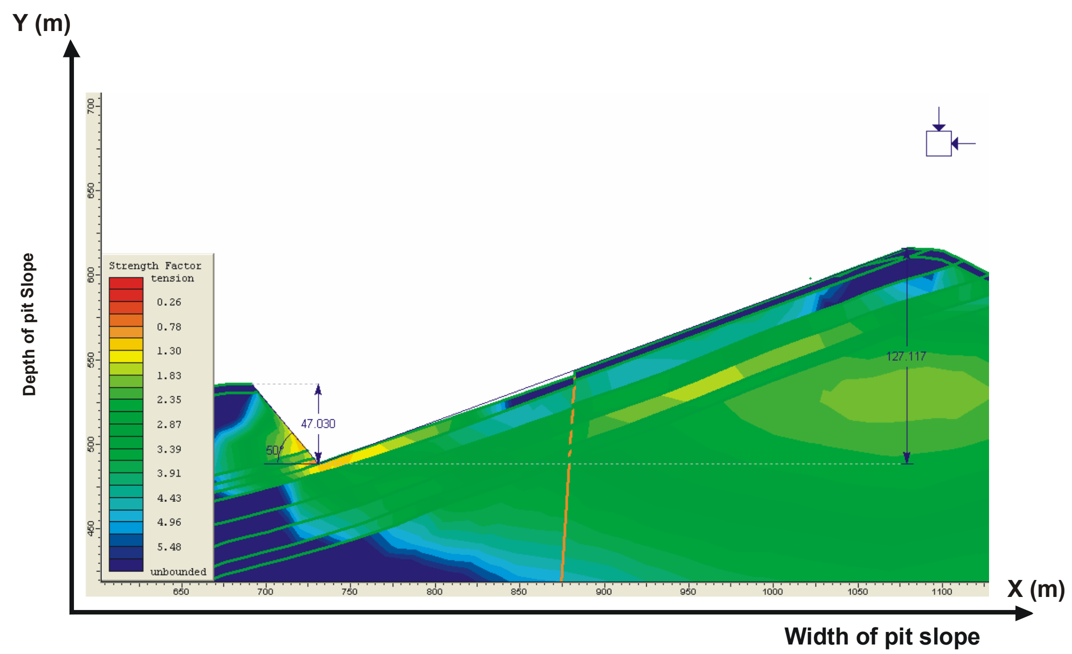

Figure 6. Geometrical pit slope model of the Karet Tiga pit, section 11

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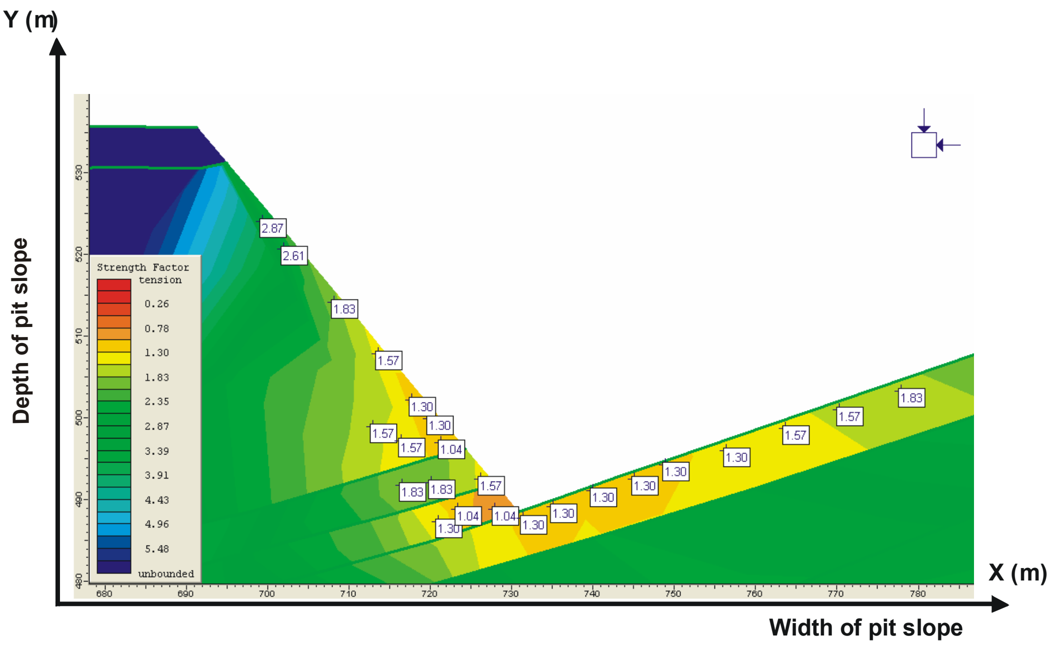

Figure 7. Safety factor distribution of the Karet Tiga pit, section 11

Table 4. Resume of numerical modelling and slope stability analysis

No	Cross-section	Low-wall		High-wall				
		Height (m)	Safety Factor	Height (m)	Slopes (degree)	Safety Factor	Distance from original pit limit (m)	Stripping Ratio
A. Karet Tiga								
1	**S-11**	**125**	**1.30**	**45**	**50**	**1.30**	**0**	**8.8**
2	S-23	95	1.30	55	40	1.30	40	13.6
3	S-31	110	1.30	45	40	1.30	30	9.6
B. Sarang Burung								
1	**S-07**	**80**	**1.30**	**40**	**50**	**1.57**	**0**	**13.8**
2	S-16	115	1.30	50	50	1.30	0	11.6
3	S-26	50	1.30	40	40	1.30	90	7.93
4	S-33	100	1.30	45	40	1.30	20	16.0

The resume of the numerical modelling study and the slope stability analysis by using the FEM for all of the models are summarized in Table 4.

5. DISCUSSION

The slope wall at the low-wall side is quite steep between 20º and 30º. There is a thin seam (2.5 - 5.0 m) of claystone at the beneath the coal seam and at above a thick and strong sand-stone. In the contact plane, there is a filing material of clay as a sliding plane.

Even though the slope stability analysis result shows a stable condition, either for high and or low-wall sides, a good care should be done to the possibility of groundwater that can be seep into the contact plane, particularly in the rainy season. In this condition, the low-wall slope failure is potentially happened. Hence, good care and anticipated action plan should be carried out.

The most simple and cheap ways to be conducted is by making some of horizontal drill holes at the slope surfaces that have indication of water seepage. The perforated PVC pipe with diameter of 2-3 inches and 4 – 8 m in length can be slotted into the horizontal drill holes for groundwater drainage.

The waste-coal ratio changes by changing the crest position at the pit limit of the existing pit plan. The stripping ratios for the Karet Tiga pit models are 8.8, 13.6 and 9.6, and that for the Sarong Burung pit are 13.8, 11.6, 7.93, and 16.0. These ratios can be used as a reference in making a revision of the existing pit slope plans.

Even though the optimum pit slopes have been determined, the important thing that has to be remembered is the rock mass in the earth is heterogenic, discontinue, and anisotropic material. The rock mass conditions are varied. So, the analysis results and technical calculations on this paper may not accurate. Hence, the development of the slope monitoring system is needed. The slope instability indications such as tension-cracks, and slope displacements in the slope surfaces can be monitored. Groundwater seepages could directly be monitored in the slope surface, and the fluctuation of groundwater levels in the rock mass could also be monitored in the boreholes by installing piezometers. The interpretation of the monitoring results is an important thing.

From this, the earlier remedial actions can be recommended. In principle, the remedial actions to avoid the slope failure are reducing the groundwater level, reducing the pit slopes in the limits of the acceptable waste-coal ratio, and or revising the pit slope and its depth design based on geotechnical study.

6. CONCLUSIONS

To achieve the optimum overall pit slope design, the existing pit plans should be revised. For open pit mine in the Karet Tiga, the maximum overall pit slope at high wall side is 40º to 50º, the wall height is 45 m to 55 m, the depth from the peak of low-wall crest is 95 m to 125 m, and the crest at the up pit limit should be moved forward to 30 m to 40 m (Figure 8).

For open pit mine in the Sarong Burung, the maximum overall pit slope at high wall side is 40 ° to 50º, the wall height is 40 m to 50 m, the depth from the peak of low-wall crest varies from 50 m to 115 m, and the crest at the up pit limit section 33 should be 20 m moved forward, and 90 m at section 26. There are no need revisions for other sections (Figure 9).

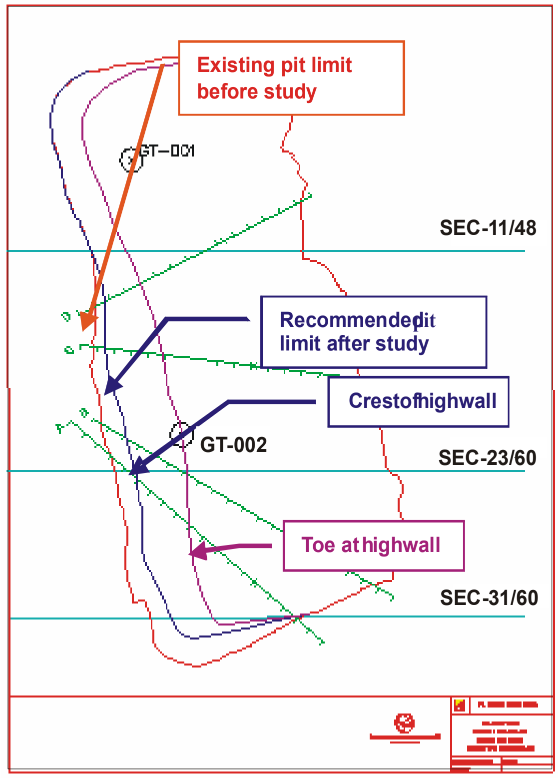

Figure 8. Recommendation for pit slope design at the Karet Tiga area

The overall pit slope condition after revision is believed to be stable during the life time of the mine operation.

It is recommended to develop a monitoring system for slope instability indications and groundwater seepages by doing a regular and direct inspection during the life time of the mine.

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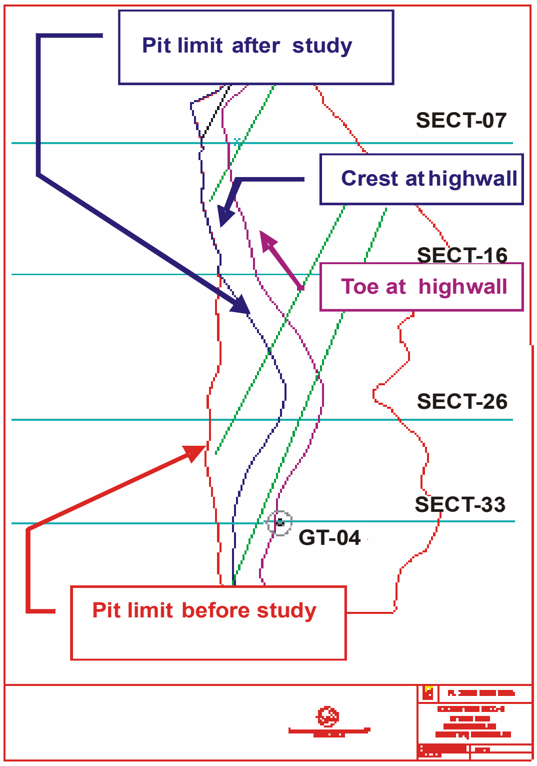

Figure 9. Recommendation for pit slope design at the Sarang Burung area

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