Groundwater Flow Modeling for Pit Wall Stability and Floor Heave Analyses: A Case Study of Mae Moh Mine

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Abstract

Mae Moh mine is a large open-pit coal mine located in Lampang province, Thailand. The mine has been operated by EGAT since 1955 and supplies up to 45,000 tons of lignite daily to feed EGAT's power plant. Groundwater is a common problem for mine operations. Poor control of groundwater movement will have a negative impact on the safety, efficiency, and economic situation of mining. This research aims to simulate groundwater systems in mining areas for groundwater management to help prevent the problems of pit wall instability and floor heave from groundwater pressure. The groundwater model uses the 3D GMS® software, which is the finite-difference groundwater flow model to simulate the groundwater system. The geological, hydrological, hydrogeological data are collected and analyzed before putting into the conceptual model. After that, the conceptual model is translated into a numerical model, the model simulates in a transient state, and calibration runs. The calibration process is performed until the piezometric levels from the model are consistent with the results from observation wells measurements. The slope stability in the C1 west wall pit is analyzed, and the floor heave is also evaluated. The instability of slope and floor heave conditions are defined. The calibrated model is used to predict the range of depletion of the groundwater table. The calibration results show that the accuracy of the groundwater flow model is 98.64%; the comparison of contour lines between measured heads and calculated heads provides good results. The simulation results suggest that to ensure safe mining from slope instability and floor heave, the dewatering requires, from 2021 to 2049, an average of 5,153 cubic meters per day. With this prediction, the groundwater level will be depressed to be lower than the lowest pit floor every year until the final stage plan in the year 2049.

Keywords: *Groundwater flow modeling, Pit wall stability, Floor heave, Mae Moh mine*

1. Introduction

Mae Moh mine (Figure 1) is a large open-pit coal mine located in Mae Moh Basin, in Lampang province, Thailand. The mine has been operated by the Electricity Generating Authority of Thailand (EGAT) since 1955 and supplies up to 45,000 tons of lignite daily to feed EGAT's power plant. Groundwater is a common problem for mine operation, especially while developing the deep pit below groundwater level. Poor control of groundwater movement will have a negative impact on the safety, efficiency, and economic situation of mining. This research aims to simulate groundwater systems in mining areas for groundwater management to help prevent the problems of pit wall instability and floor heave from groundwater pressure.

The model uses the 3-D GMS® software (Groundwater Modeling System), which is the finite-difference groundwater flow model to simulate the groundwater system of basement formation aquifer in mining areas. The geological, hydrological, hydrogeological data are collected and analyzed before putting into the conceptual model. After that, the conceptual model is translated into a numerical model, as well as the boundary conditions, initial conditions, aquifer parameters, and hydrologic stresses are assigned. The model simulates in a transient state and calibration runs emphasize material parameters, groundwater head boundary, and water balance. The measurements from observation wells are used in the calibration process. The parameter sensitivity analysis is also carried out. The calibration process and sensitivity analysis are performed until the piezometric levels from the model are consistent with the results from observation wells measurements. The slope stability in the C1 west wall pit is analyzed using the limit equilibrium method. The floor heave is evaluated as well. The instability of slope and floor heave conditions are defined. The calibrated model is used to predict the range of depletion of the groundwater table. The planning for dewatering of each mine stage until the year 2049 is suggested.

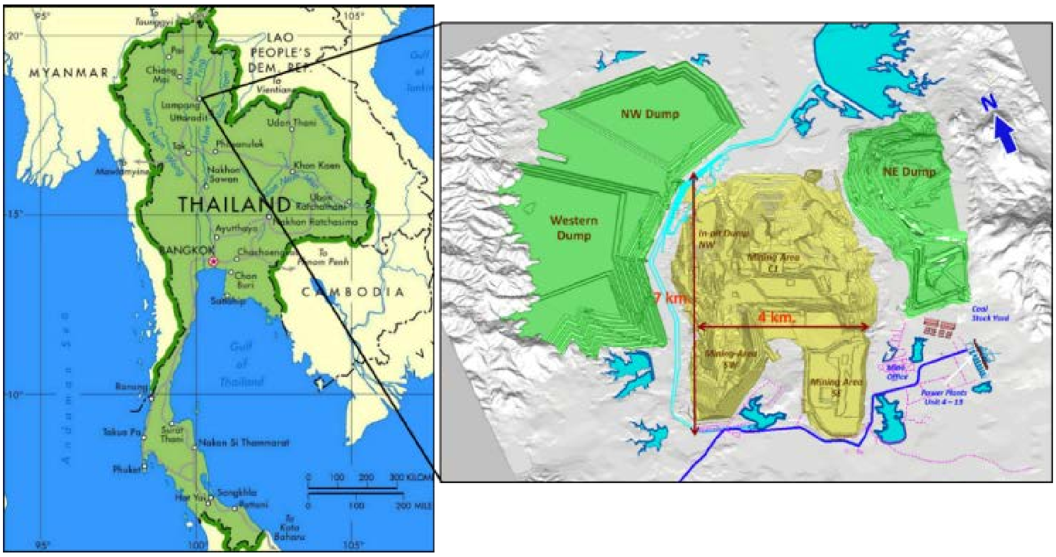


Figure 1 Mae Moh mine location

2. Objectives

1) To simulate and analyze the groundwater characteristics around the mine pit area

2) To determine and evaluate the slope stability and floor heave problems due to high groundwater pressure in the pit

3) To apply the groundwater flow model for predicting the dewatering management in a long-term mine planning design

3. Materials and Methods

3.1 Collecting previous data

Previous geological data, hydrological data, geohydrology data, and other selected data in the study area were collected, then interpreted for creating a database to analyze the pit wall stability in the C1 west wall area and the floor heave problem. After that, a 3D groundwater flow model was set up.

3.2 Slope stability problem

Slope failure and slope instabilities are a spectacle of the soil or rock movement that impacts mining operation. Slope failure occurs when the downward movements of a material depend on geologic condition, condition of soil strength, external loads, and pore water pressure (Prakash, 2009). Therefore, different processes can lead to the reduction in the shear strengths of soil mass, increased pore pressure, cracking, swelling, leaching, and strain softening. In addition to these reasons, other factors contributing to the failure of slope include properties of rock mass, slope geometry, state of stress, temperature, and erosion (Duncan et al., 2014). There are several types of slope failure depending on the geological conditions, groundwater level, and slope geometry. The common characteristics of failure in the homogeneous soil are rotational and translation slips of which slips surface is a circular failure and plane failure, respectively. Besides, low wall failure in opencast coal mines the most common failure is wedge failure cause in coal deposit basin is permeated with geological discontinuity (Prakash, 2009).

The method of a slice is based on the limit equilibrium method (LEM), the factor of safety that is a factor by which the shear strength of the soil would have to be divided to bring the slope into a state of barely stable equilibrium (Charles, 1999) is defined as Equation 1.

$$\text{Facter of safety}=\frac{c'A+\left[W\cos\Psi_p - U - V\sin\Psi_p\right]\tan\phi'}{\left[W\sin\Psi_p + V\cos\Psi_p\right]} \tag{1}$$

c'	The effective cohesive strength of failure surface
ϕ'	Effective internal angle of friction
W	Weight of the unstable block
A	Area of the failure surface
V	Driving water force
U	Uplift water force
Ψ_p	Dip of the sliding plane

LEM was conducted for non-circular slip surface using the General Limit Equilibrium (GLE)/Morgenstern-Price method (1965). The procedure assumes that the shear forces between slices are related to the normal forces. For comparison, and to make sure slip surface with minimum FS are identified, block, auto-refine, and path search options were applied, with failure surface optimization.

Groundwater pressure for slope stability analysis in the C1 West-wall area using R_u coefficient (Murthy, 2003), was desirable to express the pore-water pressure conditions using a simple single parameter, R_u, which is calculated as:

$$R_u=\frac{u}{\gamma z} \tag{2}$$

Where u is the pore-water pressure (pore-water pressure is represented by the unit weight of water γ_w multiply by groundwater head h_w), γ is the unit weight of claystone in Mae Moh coal mine, which is equal 19.5 kN/m^3 (Von et al., 2006) and z is the depth below ground. The denominator (γz) is also known as the overburden stress.

In the analysis of slope stability in the C1 West-wall, groundwater head varies from 0 to 1 of depth below ground, resulting in R_u being 0.0 to 0.513.

R_u coefficient between 0.0 to 0.513 can be specified for each soil type to define pore pressure. The R_u coefficient simply models the pore pressure as a fraction of the vertical earth pressure for each column in the sliding mass.

LEM will be used to analyze pit wall stability in the C1 west wall area against groundwater pressure by Rocscience-Slide® 2D slope stability software for evaluating the safety factor or probability of failure (factor of safety less than 1.0). The evaluation slope stability process is separated into 3 parts, the first part uses AutoCAD® software to convert the cross-section of the mine plan in the C1 west wall area into Rocscience-Slide® 2D software. The second part analyzes the stability of slip surfaces using limit equilibrium methods by Slide® 2D software. The third part approximates failure boundary and rocks mass failure in each stage plan by AutoCAD® software.

3.3 Floor heave problem

The floor heave problem against groundwater pressure will be analyzed from the current stage plan until the final stage by using a simple weight balance model. The factor of safety equal to overburden load divided by groundwater pressure. Groundwater pressure act as a driving force and overburden load is resisting force from Equation 3 (Fraser et al., 1979). It is generally accepted that the overburden load is represented by the unit weight of overlying materials γ_s multiply by the thickness of the overlying materials h_s, and the groundwater is represented by the unit weight of water γ_w multiply by groundwater head h_w (Equation 4), in this equation, we assume side friction equal to zero. By the calculation, if the groundwater pressure overcomes the load of the overlying layer of an aquifer, it's meant that unstable or the pit floor heave problem can occur or factor of safety less than 1.0.

The evaluation floor heave process is separated into 4 parts. The first part uses Rhinoceros® software to convert the topography of the mine plan in each stage plan in linear data from AutoCAD® software into points for contour plotting in Surfer® software. The second part uses Surfer® software to create contour lines of groundwater level from Basement Formation, the elevation of top basement aquifer, and topography of mine plan in each stage plan. The third part uses Microsoft Excel® software to calculate the factor of safety ratio. The fourth part uses Surfer® to create contour lines factor of safety in each stage plan, including the year 2020, 2023, 2026, 2032, 2038, and 2049 (final stage).

$$\text{Factor of safety}=\frac{\text{Overburden Load}}{\text{Groundwater Pressure}} \quad (3)$$

$$\text{Factor of safety}=\frac{\gamma_s h_s}{\gamma_w h_w} \quad (4)$$

3.4 Groundwater Flow Model

The most important transmission property of geologic formations, hydraulic conductivity (K) usually exhibits significant variations through space within a geologic formation. It may also vary with the direction of measurement at a given location point in a geologic formation. These two properties are given below prior to the derivation of groundwater flow equations. The first property is known as heterogeneity, while the second property is known as anisotropy. The geologic processes that produce various geological environments/settings are responsible for the prevalence of these two properties in geologic formations, including aquifers. Following is the governing equation of groundwater flow (Todd et al., 2005).

$$K_x\frac{\partial^2 h}{\partial x^2}+K_y\frac{\partial^2 h}{\partial y^2}+K_z\frac{\partial^2 h}{\partial z^2}\pm W=S_s\frac{\partial h}{\partial t} \quad (5)$$

K_x,K_y,K_z	Aquifer hydraulic conductivities in the X-, Y- and Z-directions
S_s	Specific storage of the aquifer
h	Hydraulic head in the aquifer
t	Time
W	The volumetric source rate and/or sink rate per unit volume of the confined

The finite difference method is a numerical method, which can be used for solving partial differential groundwater equations, making predictions, and improving the process of understanding the hydraulic head solution results, flow system, and storage (Anderson et al., 1992). The prediction of quantities of interest (dependent variables) is based upon an equation or series of equations that describe system behavior under a set of assumed simplifications.

Groundwater model calibration is usually carried out to ensure that the model can reasonably well mimic the groundwater flow system, fit the field piezometric heads (Arlai et al., 2012). In the past, model calibration was achieved by using trial-and-error adjustment of parameter values to match the measured hydraulic heads. However, with the advanced development of computer programming, the model calibration is done using automatic parameter estimation codes such as PEST (Doherty et al., 1994). The automatic model calibration allows a systematic adjustment of parameter values to achieve a reliable model outcome.

The groundwater model used is based on the MODFLOW (Modular Three-Dimensional Finite-Difference Ground-Water Flow Model) is a 3D multi-layer, cell-centered, finite difference, saturated flow model. Setting up a 3D groundwater flow model using GMS® software (Groundwater Modeling System) and is specially designed to model groundwater flow in open pit Mae Moh mine area.

Work flow for groundwater modeling is shown in Figure 2. The Groundwater Flow Model has been developed, calibrate, and predictive simulations of the groundwater flow and groundwater table for the Mae Moh mine in each stage plan.

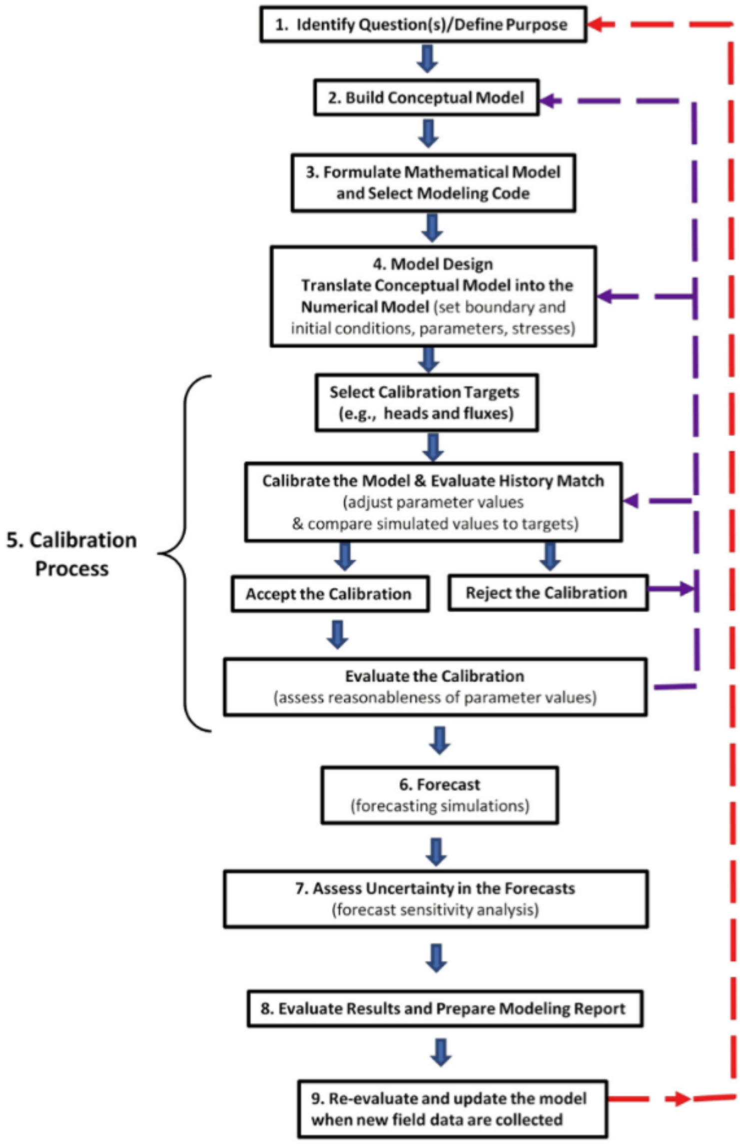


Figure 2 Work flow for groundwater modeling (Anderson et al., 1992)

3.5 Dewatering plan

Plan to dewater and depressurize continuously the whole Mae Moh mine life using groundwater flow modeling to optimize dewatering strategies to ensure safe mining conditions and predict the range of the depletion of the groundwater table.

4. Results and Discussion

The results of the study are separated into 4 parts consisting of geology and hydrogeology, analysis of slope stability at the C1 west wall, the floor heave analysis, and setting up of a 3D groundwater flow model. Then, the groundwater flow model was used to reduce groundwater pressure to avoid problems with slope stability at the C1 west wall and floor heave of the Mae Moh coal mine in the future.

4.1 Geology and Hydrogeology

The geology of the Mae Moh basin is the Tertiary basin situated in the mountainous region of northern Thailand, as also shown in Figure 3. A geological map and cross-sectional A-A'-A'' and B-B'-B'' of the Mae Moh basin are shown in Figures 4, 5, and 6, respectively, and the three major geological units are shown in Figure 7 (Dames, and Moore, 1995).

(1) Post-Tertiary: This consists of gravel deposit at the bottom and alluvium deposit at the top. The thickness of this formation varies from less than 1 to 10 meters. In the southern part, basalt sheet overlay on Tertiary sediments.

(2) Tertiary: Tertiary Formation overlay the basement of Triassic rocks, which can be separated into three formations as follows;

  a. Huai Luang Formation (HL): Almost all are claystone, siltstone, and mudstone with some lenses of sandstone and conglomerate. The thickness of this formation varies from less than 5 to 250 meters of Mae Moh basin.

  b. Na Khaem Formation (NK): This formation consists of grey to greenish-grey, high calcareous rock and fossil of coal. The thickness of this formation varies from less than 250 to 400 meters.

  c. Huai King Formation (HK): This formation contacts with Triassic basement rock. It consists of mudstone, siltstone, sandstone, conglomeratic sandstone, and conglomerate. The thickness of the Huai King Formation varies from less than 15 meters on the eastern to 150 meters on the western of this basin.

(3) Triassic: Beneath the Tertiary and consist of marine Triassic rocks, which are exposed on the west and east side of the basin. There are:

  a. Doi Long Formation (TR4): has limited exposure at the northeast of the mine and consists of limestone.

  b. Hong Hoi Formation (TR3): is the most widespread formation of shale, sandstone, and bedded limestone.

  c. Pha Kan Formation (TR2): is exposed to northwest, southwest, and south of the pit, which consists of massive limestone.

  d. Phra That Formation (TR1): overlies the volcanic of the Permo-Triassic. It consists of basal conglomerates and limestone.

The tectonic model explaining the formation of these basins is described either as pull-apart basins associated with strike-slip faulting or extension and changing stress system related to the Tertiary-aged escape tectonics of Southeast Asia (Morley, 2002).

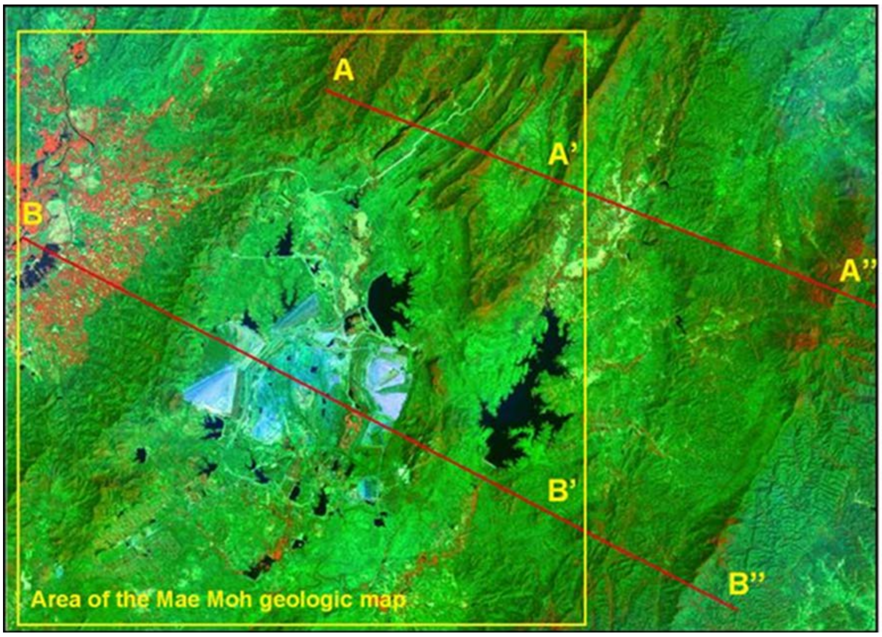


Figure 3 Landsat image of Mae Moh basin and location of cross-section A-A'-A'' and B-B'-B'' (GTSC, 2011)

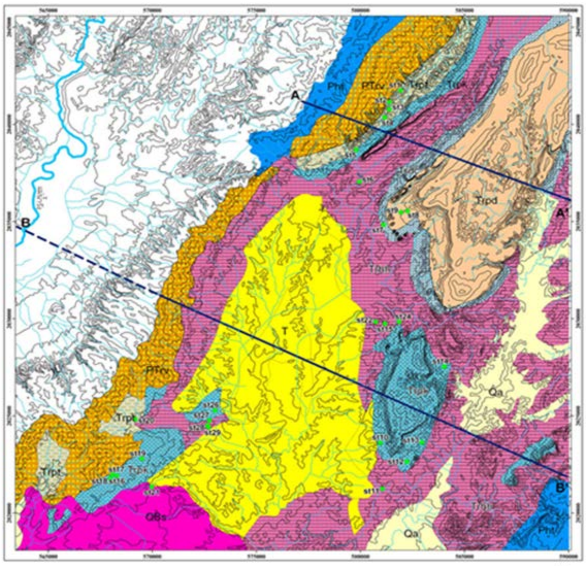


Figure 4 Geological map of Mae Moh basin and location of cross-section A-A' and B-B' (GTSC, 2011)

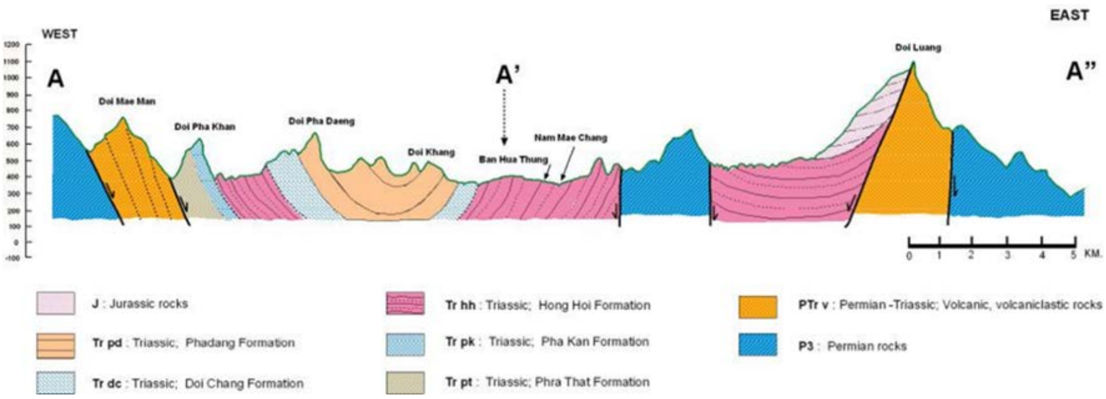


Figure 5 Cross-section A-A'-A'' (GTSC, 2011)

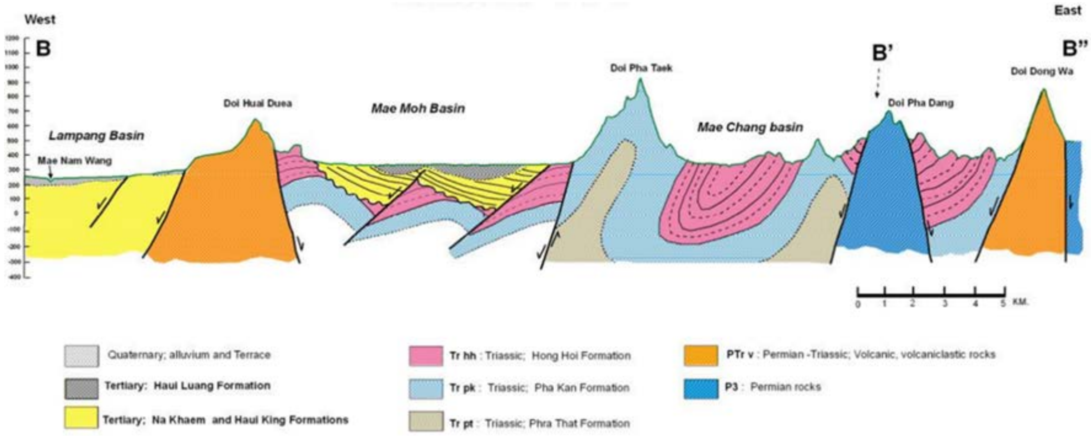


Figure 6 Cross-section B-B'-B'' (GTSC, 2011)

Hydrogeology of Mae Moh Basin, Dames, and Moore describes that there appear to be two main aquifer systems in the mine area (Figure 7).

(1) Basal Tertiary Aquifer system: As Huai King formation represents a potential aquifer system although it is a thin layer in the western.

(2) Triassic Bedrock Aquifer System: This aquifer is a result of secondary structures such as weathering, karst, joints, fractures, and faults. Doi Chang Formation (Basement Tr4) and Hong Hoi Formation (Basement Tr3) have been targeted as the main potential aquifer (Dames and Moore 1995, Dames and Moore 1998).

The deep groundwater flow system flow from northern, western and eastern direction to main mine pit (GTSC, 2011). Hydraulic parameters were determined based on the results of those tests conducted by EGAT.

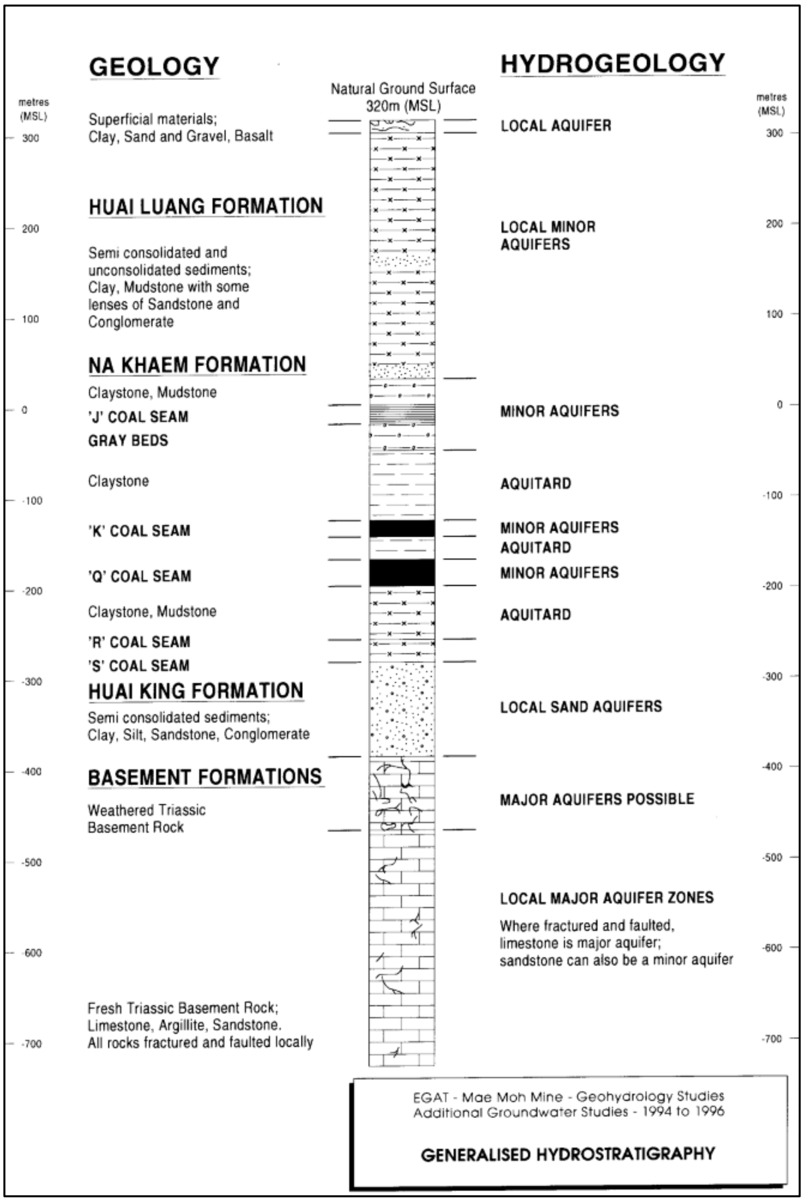


Figure 7 Schematic of the stratigraphic column (Dames and Moore, 1995)

4.2 Analyze slope stability at C1 west wall

Analysis cross-section N11 to N18 in C1 west wall, in this area have complex fault blocks, result in the pit slope is steep due to the western fault line intersect with the eastern fault line. Make separated coal layer and each part has a different dip angle. Therefore, in some areas, bedding dip direction out of the pit slope but in some areas bedding dip directly into the pit slope with an angle between 6-15 degrees, causing different stability problems. Besides, some sets of major eastern faults have displacements greater than 250 meters (Figure 8) with a dip angle of approximately 65 degrees, which coal layers have slipped downward deeper. Therefore, it is necessary to reduce the pit slope approximately 264 meters high, from the level of +236 to -28 m.MSL., the overall slope angle of approximately 17.0 degrees (1.00V: 3.27H).

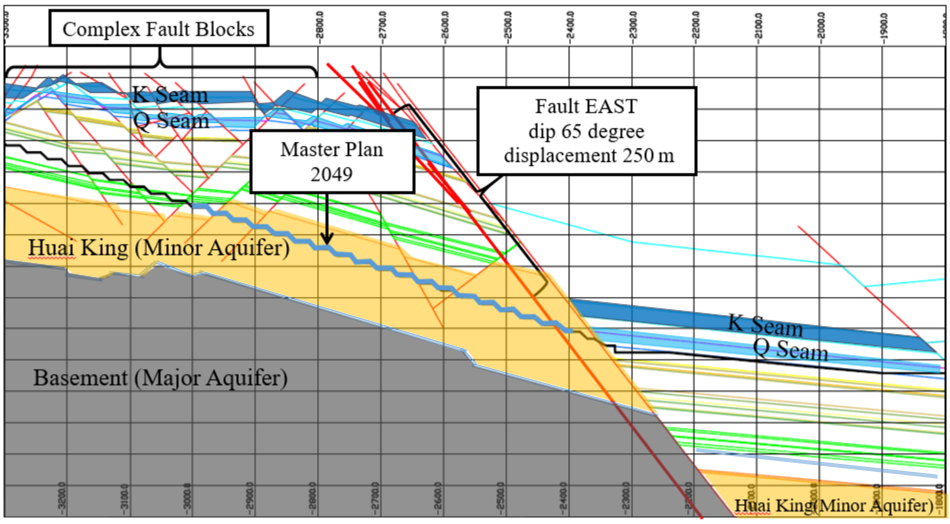


Figure 8 Major eastern fault and complex fault blocks

Analysis slope stability in the C1 West-wall area indicated that in the year 2026 there has the potential to occur slope stability problems against groundwater pressure (factor of safety less than 1), as shown in Figure 9 and failure boundary in 2026 in Figure 10. Approximately 4.3 million cubic meters of rock mass will begin to fail when the digging-unloading price is 80 baht / BCM., the damage value is 344 million baht. The volume of the mass slide will increase with the failure boundary extent until the end of the mining operation in 2049.

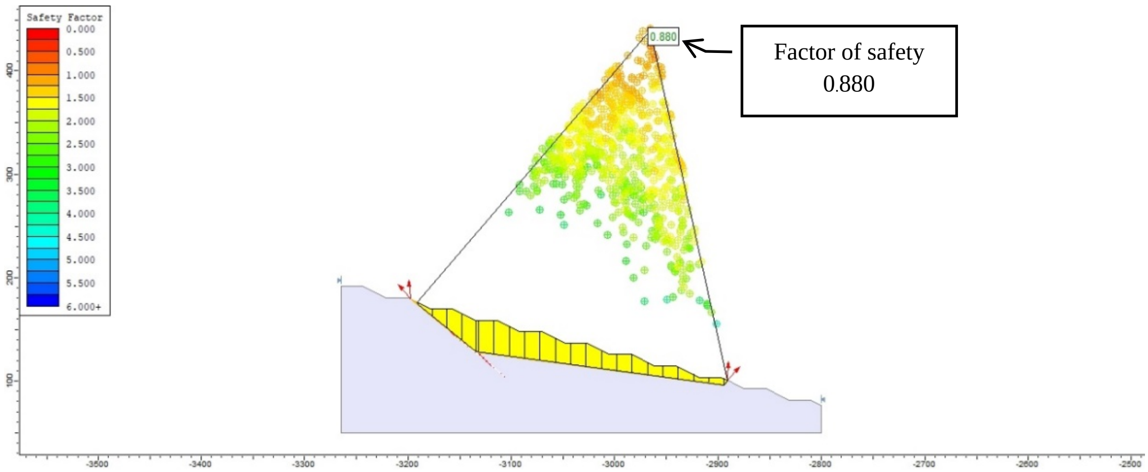


Figure 9 Failure block at section N11

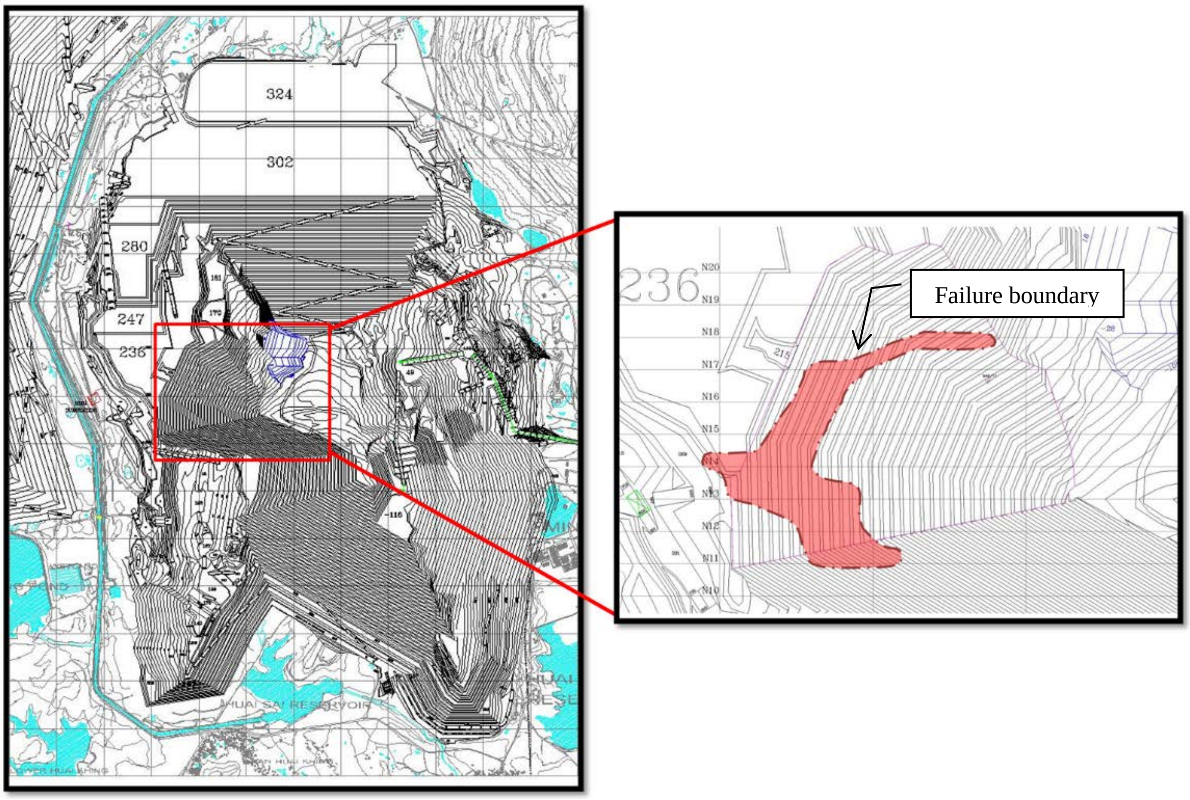


Figure 10 Failure boundary in 2026

The complexity of geostructures and a series of fault lines make different stability problems at different times, which the problems according to each section line are shown in Table 1.

Table 1 Summarizes the factor of safety values from stability analysis results

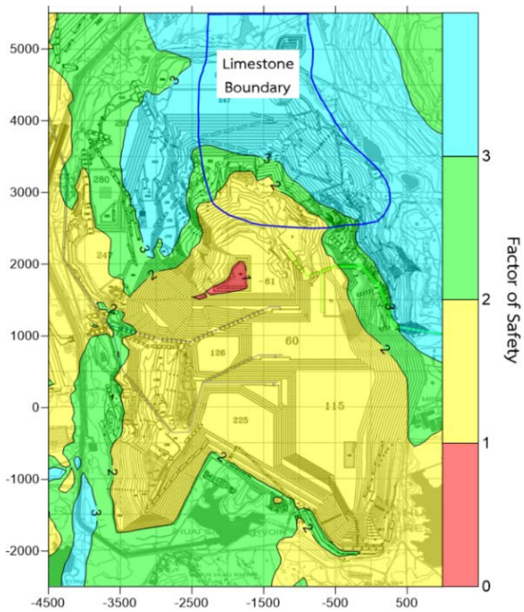
Section	Block No.	Dry (R_u 0.00)	Groundwater pressure		Stage Plan (Year)
			R_u 0.125	Full Sat. (R_u 0.513)	
N11	1	1.025	0.880		2026
N13	1	0.764			2026
	2	0.805			2026
	3	0.738			2026
N14	1	1.062	0.974		2020
	2	0.980			2020
N15	1	0.739			2020
	2	0.862			2023
N16	1	1.189	1.056	0.784	2023
N17	1	0.827			2026
	2	0.929			2026
N18	1	1.590	1.402	0.996	2026

The results in Table 1 indicated that most of the section will collapse even though there is no groundwater pressure involved (R_u 0.00). In such an event, soil or coal must be left to support. However, some section will collapse with increasing groundwater pressure (R_u 0.125 to R_u 0.513). Therefore, it is necessary to dewater and depressurize until it does not affect the stability of the pit slope.

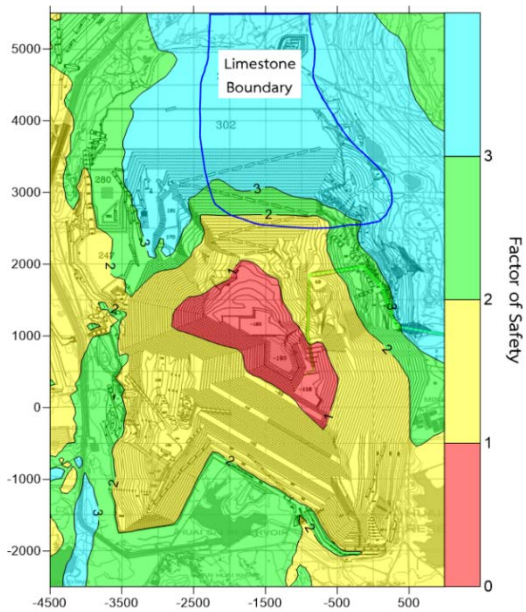
4.3 Floor heave analysis

Evaluation floor heave is based on the factor of safety ratio between the weight of the soil mass above the pressurized aquifers and the groundwater levels above the aquifers (Fraser, 1979). In the process of analyses floor heave problem of the Mae Moh mine, various parameters are required, including Master Plan versions revised long term mine plan of contracts 10 and 11 in 2020, 2023, 2026, 2032, 2038, and 2049, top Basement Formation (Dames, and Moore, 1995), groundwater levels from basement aquifer on January 31, 2021, and unit weight of claystone, Nakham Formations, which is aquitard and placed over Basement Formation, which is equal 1.89 kg/m^3 (modified from Von et al., 2006), by this calculation, the density value was reduced by 5% due to stress relief, blasting, unknown discontinuities and deterioration of claystone, resulting in the unit weight of claystone used in the calculation is 1.80 kg/m^3

The results revealed that the critical area or factor of safety less than 1.0 in each stage plan will begin in the year 2038 show in Figure 11 (A) and the critical area is also small at the central pit area, the problems area is wider until the end of the mining operation in 2049 (final stage plan) shown in Figure 11 (B) and should be focused at the same area. Because, in the future mine operation, the thickness of the overlying layer becomes thinner. So, the critical area of floor heave problems will expand more if the groundwater water level is not depressurized. The groundwater dewatering and depressurization system can be installed, excess groundwater pressure under the mine can be reduced and many of the above potential problems can be mitigated continuously until the end of Mae Moh mine's life.



(A)



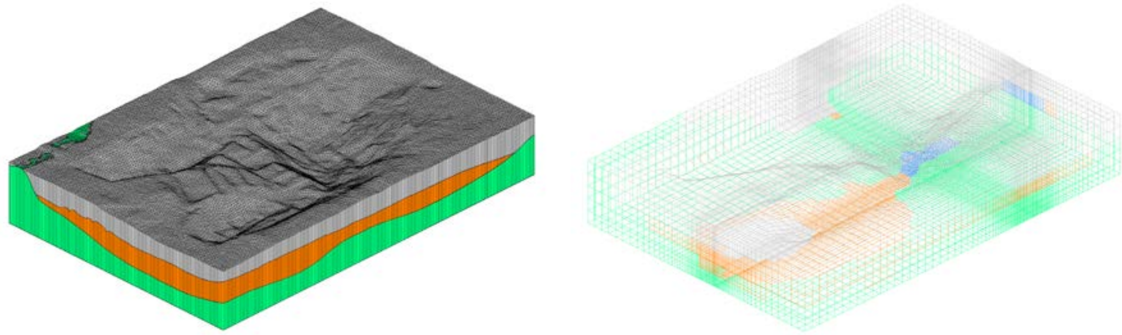
(B)

Figure 11 Contour line factor of safety (A) Year 2038 (B) Year 2049

4.4 Groundwater Flow Modeling

The groundwater flow model of the Mae Moh Basin has been run using the Groundwater Modeling System® (GMS) model. The GMS software has been used during model development, calibration, and predictive simulations. The model surrounds an area of dimension 44 km^2 and has a perimeter of 27 km., 4 geological units consist of Basement Tr3 Formation, Basement Tr4 Formation, Huai King Formation, and

Nakham Formation. The finite-difference grid 101 rows (N-S), 74 columns (E-W), 5 layers (depth) consist of 45,900 nodes and 37,370 cells. Orientation NNE-SSW; parallel to Mae Moh mine grid. Depth the model extends to an elevation of -300 m.MSL., east-west boundary coincides with groundwater divides under ranges defining basin boundary, north-south boundaries-generally based on topography and groundwater divides. Figure 12 shows the conceptual model and numerical model of the Mae Moh mine groundwater flow model.



(A) (B)

Figure 12 Mae Moh mine groundwater flow model (A) conceptual model (B) numerical model

To ensure that the groundwater model gives a good result, calibration runs have been carried out. The chosen calibration period is 49 months from January 1, 2017, to February 1, 2021, for the calibration length of 5 days. This time step length is sufficiently short to give accurate results for the 5 days mean of groundwater levels and dewatering water quantities. After calibration time (February 1, 2021) set time steps length 365 days or every 1 year until 2049 for predictive simulation.

Transient observation data at 10 observation wells will be imported. The model has already been parameterized into different zones of horizontal hydraulic conductivity (K_x), horizontal anisotropy (K_x/K_y), vertical anisotropy (K_x/K_z), specific yield (S_y), and specific storage (S_s) for all aquifers. The model will be run with the current parameter values to see how well the model matches the pump test. Then PEST® (Doherty, 1994) will optimize the parameter values. Finally, pilot points will be plotted with the parameters to see if it is possible to improve the match between the simulated and field-observed values.

If an observed value has been assigned to MODFLOW, the calibration error at each time step can be plotted using a "calibration target." A set of calibration targets provides useful feedback on the magnitude, direction (high, low), and spatial distribution of the calibration error. The components of a calibration target are illustrated in the following Figure 13 (Aquaveo, 2019). The center of the target corresponds to the observed value. The top of the target corresponds to the observed value plus 2 meters interval and the bottom corresponds to the observed value minus 2 meters interval. The colored bar represents the error. If the bar lies entirely within the target, the color bar is drawn in green. If the bar is outside the target, but the error is less than 200%, the bar is drawn in yellow. If the error is greater than 200%, the bar is drawn in red.

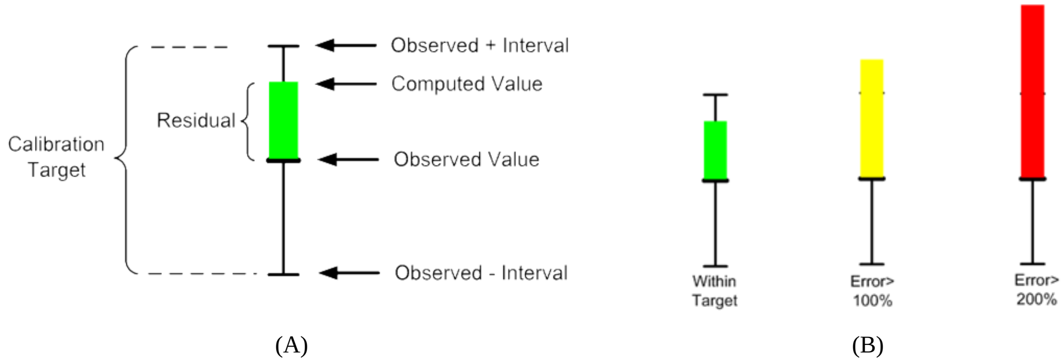


Figure 13 The components of a calibration target (Aquaveo, 2019) (A) calibration target and (B) observation target error bars

A time series plot is used to display the time variation of one or more scalar datasets associated with a given point inside a model solution. Besides, if transient calibration data has been defined, a band can be shown, which represents a time-variant calibration target. The sample of comparison between the measured and calculated heads in PA15 observation well from January 1, 2017, to February 1, 2021, is shown in Figure 14.

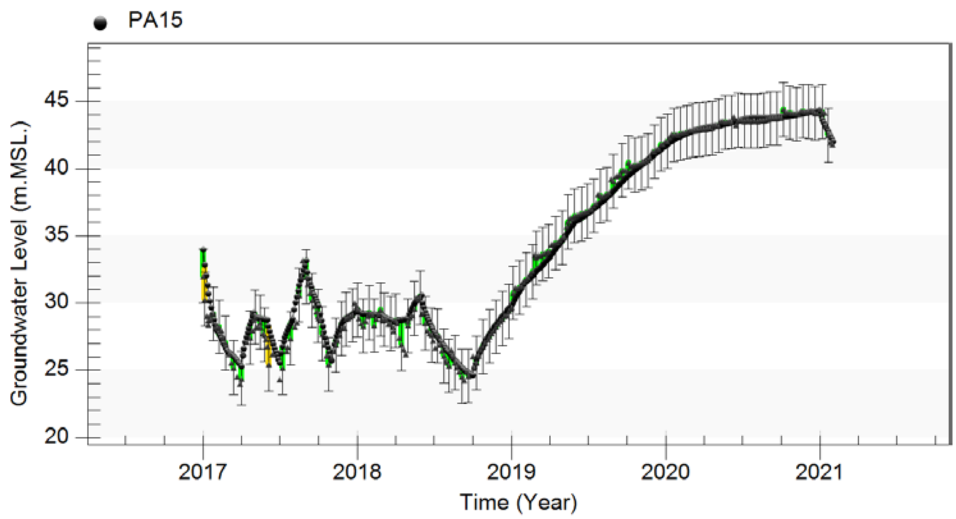
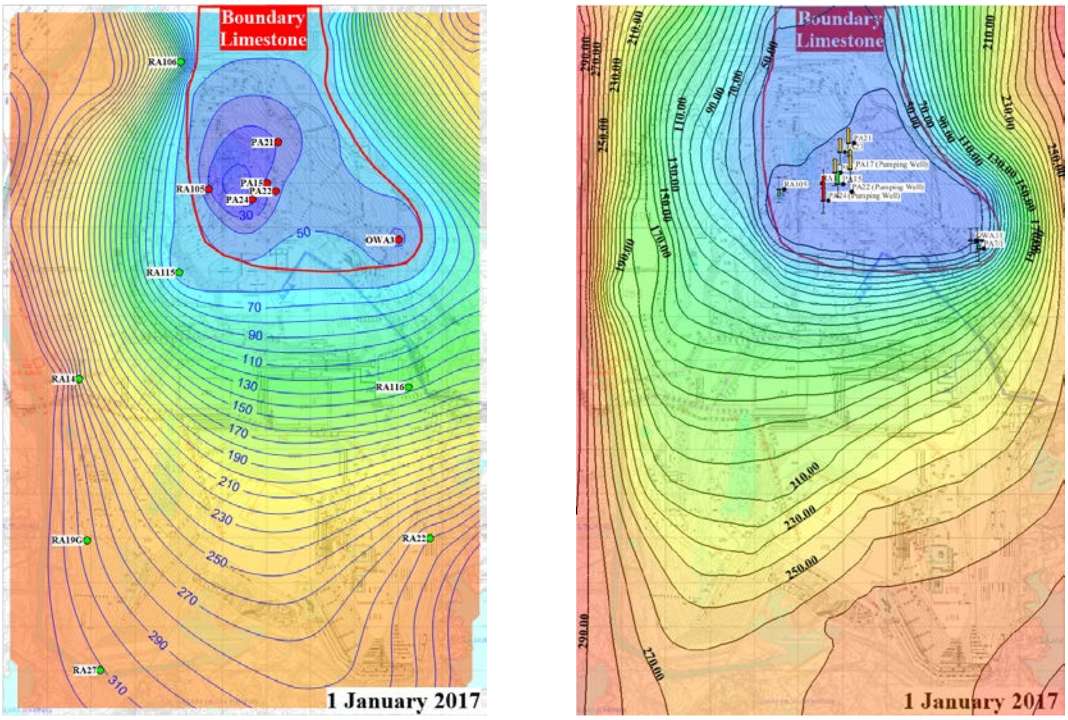


Figure 14 Comparison between the measured and calculated heads in PA15 observation well

Comparisons of contour lines of groundwater levels between measures and calculated in each year during the calibration period (4 Years) were found to be consistent, such as the comparison of contour lines of groundwater levels on January 1, 2017, as shown in Figure 15.



(A) (B)

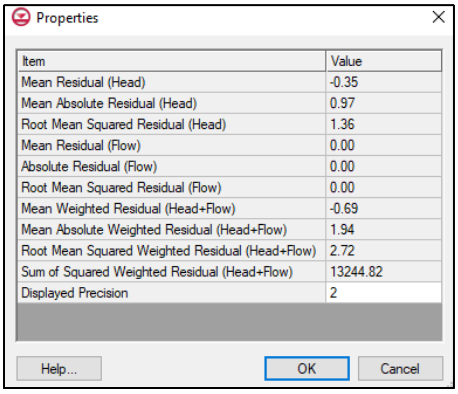
Figure 15 Comparison contour line of groundwater levels between (A) measure and (B) calculated

The quantify of quality of the calibration the following formula (Braxein, 2007) is used

$$RMS = \sqrt{\frac{\sum_{i=1}^{n}(h_c - h_m)^2}{n}} \tag{6}$$

n Number of the data points
h_c Computed groundwater heads
h_m Measured groundwater heads

The RMS (Root Mean Square) of ground water levels (Head) between measured groundwater heads (10 observation wells) and computer groundwater heads in calibration times for the final calculation is 1.36 are shown in Figure 16, which lead to an accuracy of 98.64%.



Properties

Item	Value
Mean Residual (Head)	-0.35
Mean Absolute Residual (Head)	0.97
Root Mean Squared Residual (Head)	1.36
Mean Residual (Flow)	0.00
Absolute Residual (Flow)	0.00
Root Mean Squared Residual (Flow)	0.00
Mean Weighted Residual (Head+Flow)	-0.69
Mean Absolute Weighted Residual (Head+Flow)	1.94
Root Mean Squared Weighted Residual (Head+Flow)	2.72
Sum of Squared Weighted Residual (Head+Flow)	13244.82
Displayed Precision	2

Help... OK Cancel

Figure 16 Error summary of Groundwater Flow Modeling

Groundwater flow model simulation from 2017 until the end of 2049 and the detailed water balance every time step is shown in Figure 17. The data revealed that the most inflow from GHB boundary (constant head) and storativity, groundwater discharge from groundwater system by pumping wells is the most outflow and small part outflow from constant head and storativity.

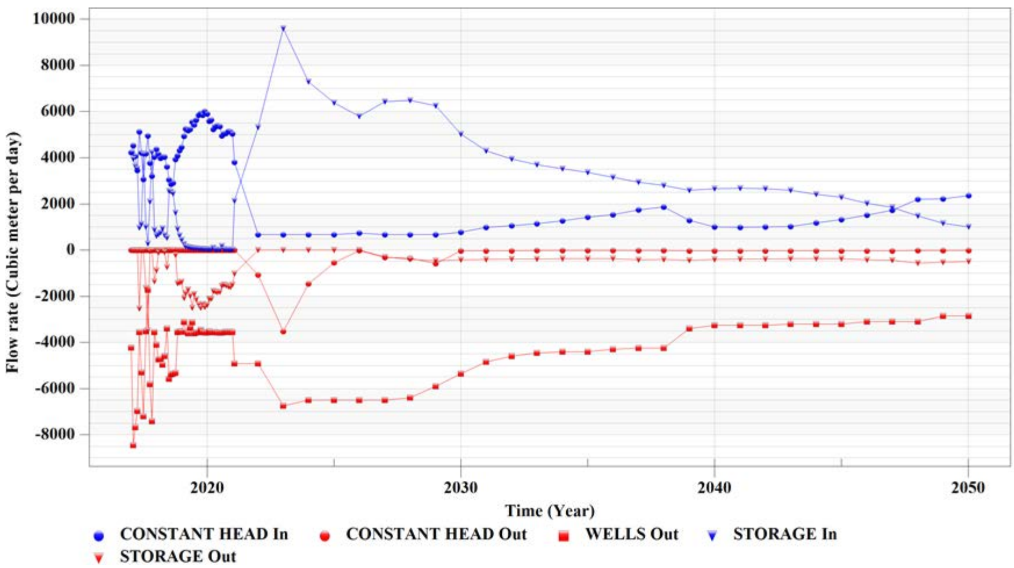


Figure 17 Water balance every time step

Table 2 shows the resulting dewatering requirement, total water balance, and target drawdown of each year.

Table 2 Dewatering requirement, total water balance, and target drawdown in each year

Year	Flowrate				Target Drawdown	
	Total In (m^3/day)	**Total Out (m^3/day)**	**In-Out (m^3/day)**	**Percent Discrepancy**	**Lowest pit floor (MSL.)**	**GWL. From model (MSL.)**
2017	4,232	4,230	1.45	0.034	32.00	31.98
2018	4,986	4,986	-0.12	-0.002	29.50	29.34
2019	4,907	4,907	0.09	0.002	29.66	29.76
2020	5,948	5,948	0.02	0.000	42.03	41.76
2021	5,057	5,055	2.60	0.051	44.23	44.14
2022	5,984	5,985	-0.69	-0.011	41.80	17.69
2023	10,278	10,280	-1.52	-0.015	41.80	-22.27
2024	7,971	7,973	-2.04	-0.026	-21.00	-35.97
2025	7,047	7,048	-1.31	-0.019	-21.00	-43.72
2026	6,525	6,526	-0.81	-0.012	-21.00	-49.84
2027	7,112	7,114	-1.64	-0.023	-28.00	-64.69
2028	7,155	7,157	-1.69	-0.024	-28.00	-80.61
2029	6,927	6,928	-0.69	-0.010	-28.00	-94.47
2030	5,798	5,800	-2.20	-0.038	-94.00	-98.43
2031	5,277	5,278	-1.17	-0.022	-94.00	-99.40
2032	5,013	5,013	-0.03	-0.001	-94.00	-99.75
2033	4,853	4,855	-2.52	-0.052	-94.00	-100.24
2034	4,800	4,800	-0.52	-0.011	-94.00	-101.19
2035	4,791	4,795	-3.66	-0.076	-94.00	-102.52
2036	4,686	4,687	-0.64	-0.014	-94.00	-103.27
2037	4,667	4,668	-1.38	-0.030	-94.00	-104.92
2038	3,868	3,871	-2.37	-0.061	-94.00	-106.11
2039	3,678	3,677	0.37	0.010	-94.00	-107.15
2040	3,667	3,667	0.05	0.001	-94.00	-111.19
2041	3,661	3,662	-0.54	-0.015	-94.00	-117.52
2042	3,603	3,604	-0.62	-0.017	-116.00	-124.25
2043	3,599	3,599	0.27	0.007	-116.00	-130.97
2044	3,610	3,611	-0.42	-0.012	-116.00	-139.16
2045	3,554	3,554	-0.34	-0.009	-138.00	-151.18
2046	3,576	3,576	-0.07	-0.002	-138.00	-164.22
2047	3,689	3,690	-0.02	0.000	-138.00	-178.07
2048	3,395	3,395	0.00	0.000	-171.00	-189.89
2049	3,353	3,352	0.00	0.000	-193.00	-194.48
Average flow out from 2021 to 2049 (m^3/day)		5,153				

The results suggest that to ensure safe mining in the floor heave and slope stability conditions, future dewatering requires, from 2021 to 2049, an average of 5,153 cubic meters per day, or 1.88 million cubic meters per year. With this prediction, groundwater levels will be lower than the lowest pit floor every year until the final stage plan in 2049.

5. Conclusion

The hydrogeology of the Mae Moh basin is complex, especially within the Basement formations. Within the recent and the Pleistocene deposits, minor unconfined aquifers are present. The Na Khaem formation is generally classified as aquitards containing little recoverable groundwater. The Huai King formation, once regarded as a minor aquifer zone, features only minor fine-grained sand aquifers with relatively low permeability and limited extent. Within the Triassic deposit, the Basement formations are made up of the most significant aquifers, especially in the limestone (Basement Tr4 formation) in the north of the basin. These aquifers occur as a result of secondary structures (i.e. fault zone) and appear relatively permeable. The sandstone and argillites (Basement Tr3 formation) appear to have only minor aquifer zones.

At some critical thickness of rock cover above the aquifers underlying the Mae Moh mine pit, the potential for rock heave exists. If there is a reduction in groundwater pressure in the aquifers through pumping and/or an occurrence of floor rupture, the associated groundwater inflow has the potential to severely impact slope stability and mining efficiency. According to the analysis of the mine wall stability in the C1 West Wall area, slope stability problems against groundwater pressure is also likely to occur in 2026; critical areas of floor heave problems are expected to begin from 2038 to 2049 as the degree of problem areas become greater.

Upon the completion of groundwater flow modeling simulations of aquifer depressurization, the model is in a full 3D version and appears to be a realistic predictive method, to be utilized for simulating aquifer depressurization. As the model is large and very complex, it provides, to a great extent, correct order-of-magnitude predictions. The most important groundwater recharge zones at the basin are considered the limestone (Basement Tr4 formation), which outcrops around the northern basin boundaries. Groundwater potentiometric levels in the Basement formations decrease towards the center of the basin; however, they were originally above the ground surface in the central basin area. The groundwater flow patterns indicate that groundwater at the basin moves southward and through common outlets. The development and calibration of the groundwater flow model for the Mae Moh mine fulfill the requirements. Also, according to the agreed calculation of accuracy, the accuracy of the model is 98.64%; the comparison of contour lines between measured heads and calculated heads provides good results.

Flowing production wells located in the Basement Tr4 boundary will be the main method to achieve mine depressurization. The simulation throughout the year 2049 suggests that the dewatering requirements average 5,153 cubic meters per day, or 1.88 million cubic meters per year, for depressurization to ensure safe conditions. As for the slope stability problems in the C1 West Wall and floor heave problems, the groundwater dewatering and depressurization systems can be installed in production wells. With this preparation, excess groundwater pressure under the mine floor can be reduced; and, hence, many of the aforesaid potential problems can be alleviated in a continued manner till the termination of the Mae Moh mine operation in 2049.

6. Recommendations

Recommendations derived from the study are detailed below.

(1) These flowing wells and the associated groundwater level response should be considered a long-term flow recession test. Also, monitoring and recording procedures with respect to a flow rate of underground water at each pumping well and a change (response) of the underground water levels in each observation well during mine depressurization through the end of mining operation should be carried out regularly.
(2) The data from the depressurization system should be analyzed regularly to define depressurization progress and to refine future mine depressurization requirements.
(3) Any further geological drilling programs should be utilized and incorporated into a survey of the Basement Tr4 boundary.
(4) The input of new observation wells for the simulation according to the planned mine stages, in the future may decide to install additional piezometers as mine depressurization proceeds and/or existing piezometers need replacement.
(5) If piezometer data mismatch the calculated groundwater heights, checking is required.
(6) More flow testing at each stage and a measure of aquifer recovery should be taken into account. Also, undertaking staged flow testing and allowing adequate recovery periods are necessitated, to determine a potential change in flow rate and hydraulic properties.
(7) An aquifer pressure security and target level system should be established.
(8) During mine depressurization, a regular monitoring schedule of groundwater levels, flow rates, and groundwater sampling should be maintained.

(9) Groundwater samples should be submitted to the Mae Moh laboratory for analysis
(10) The groundwater model should be updated and run regularly.

7. Suggestions for Future Plan

From this study, future drilling and testing programs will help support the decision-making in further installing piezometers and production wells to determine the following issues.

(1) A degree of horizontal hydraulic connection between the argillite/sandstone (Basement Tr3 formation) and the limestone (Basement Tr4 formation)
(2) The drawdown in the argillite/sandstone (Basement Tr3 formation) whilst pumps in the production wells in the limestone (Basement Tr4 formation) is being operated
(3) Long-term chemistry of groundwater in the limestone
(4) A degree of vertical hydraulic connection between the Basement formations and overlying rocks
(5) A necessity for installing horizontal drains to reduce water pressure in slope, ensure good drainage, and minimize risk likelihood of major slope failure in the C1 West Wall area
(6) Empirical long-term aquifer parameters
(7) The regional effects of depressurization
(8) The hydrogeology of Mae Moh basin; and, in particular, the occurrence and hydraulic characters of major permeable structures in the limestone (Basement Tr4 formation)

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