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Groundwater Flow Modeling and Slope Stability Analysis for Deepening of Mae Moh Open Pit Lignite Mine

A.B.N. Dassanayake[1], N. Phien-wej[2] and P. H. Giao[3]
[1]*University of Moratuwa, Sri Lanka*
[2,3]*Asian Institute of Technology, Bangkok, Thailand*
[1]*E-mail*: abndassanayake@gmail.com

ABSTRACT: This study deals with modeling the groundwater pressure effect and slope stability analysis of C1 pit on deep pit mining of Mae Moh open pit lignite mine, Thailand. Groundwater flow model was constructed and run using Visual Modflow 3D. The groundwater model consists of two aquifers and one aquitard, which were then divided into nine material types for property designation. The predictive simulations were carried out for seven years (2010 to 2017) according to the mine development plan. Results showed that low permeable Argillite underlying the west wall of C1 pit is problematic as low drawdowns were obtained for short term pumping from Argillite formation. Long term pumping schedules must be initiated to lower the potentiometric head within Argillite formation by pumping from limestone under Northeast (NE) pit. Stability of the west wall of the C1 pit for 2017 pit slope was evaluated in terms of the safety factor by the limit equilibrium method. Results obtained in this study indicated that the west wall is susceptible to failure due to water pressure associated with it. To maintain a safe slope, potentiometric head within west wall of C1 pit should be maintained below 170m, MSL.

Keywords: Groundwater flow modeling, slope stability, open pit, Mae Moh mine.

1. INTRODUCTION

The Mae Moh open pit lignite mine, situated in the Lampang province in Northern Thailand, about 600 km Northwest of Bangkok and 27 km Northeast of the Lampang city (Figure 1.1), is one of the biggest open pit lignite mines in the world where deposit covers an area of more than 32 km^2. Its operation started in 1955 and since then production capacity has been increased gradually. Electricity Generating Authority of Thailand (EGAT) owns and operates the Mae Moh mine and its associated power stations, providing the total capacity of 2,400 Megawatts, which represents 20-30% of Thailand's electric power requirement (Punyawadee, 2006).

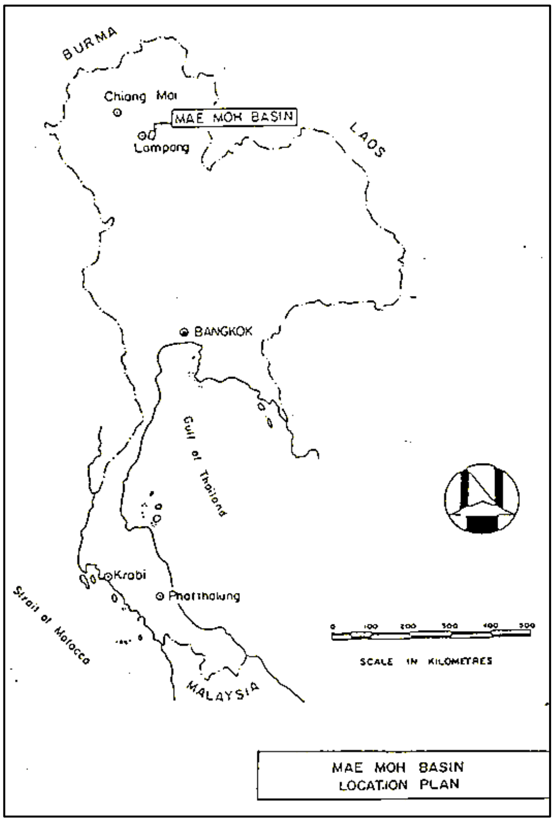


Figure 1.1 Location of Lampang city (ADAB 1985)

In 1986 EGAT decided to increase its electricity generating capacity to meet the incremental demand for the electricity in the country and reduce the country's high dependence on oil imports. This decision has resulted in a requirement for deepening the mine than originally planned, to excavate the lignite coal in the deeper levels. Groundwater investigation was therefore initiated in July 1988 and has indicated that coal measures being mined are underlain by major aquifer systems. The aquifer will require depressurization to ensure that EGAT is able to utilize and extract these coal resources under safe and productive mining condition, especially at deeper levels. At the beginning, groundwater investigations were started within the Northeast (NE) pit and then established several groundwater testing sites spreading over the mine area. According to the mine schedule they pay more attention to one of the central pits, C1 pit (Figures 1.2 and 1.3).

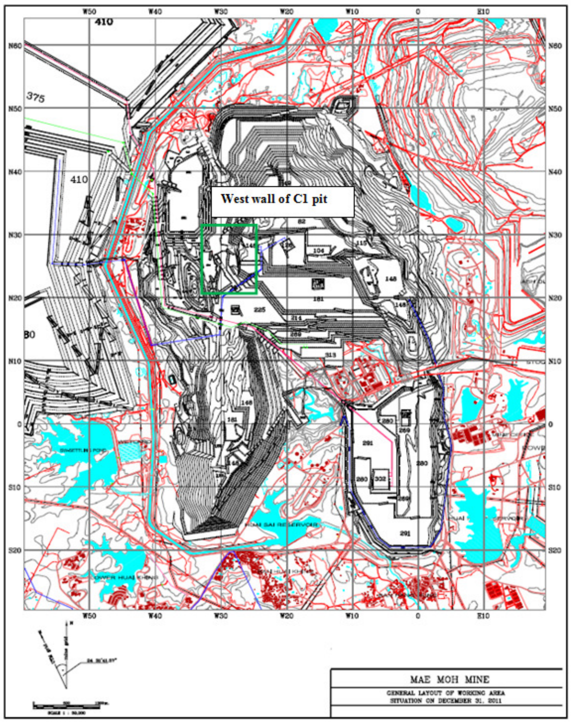


Figure 1.2 Development stage plan year 2011 demarcating study area (Courtesy of EGAT)

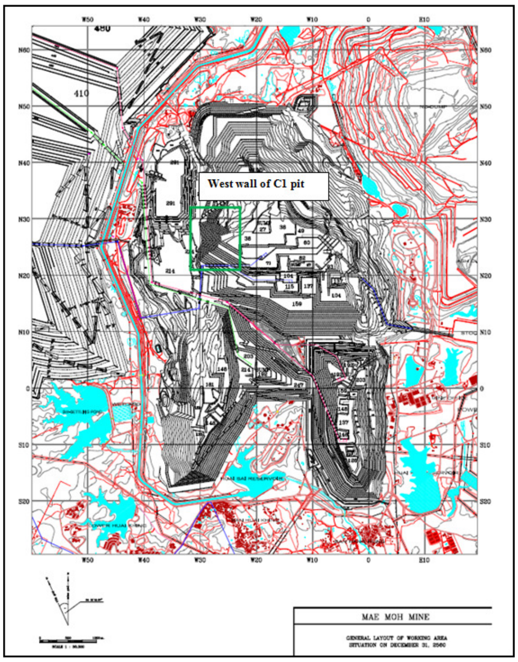


Figure 1.3 Development stage plan year 2017 demarcating study area (Courtesy of EGAT)

Groundwater Investigations, which have been done to date in the Mae Moh mine reveals that there is an increased potential that the groundwater from the Basement formations will affect mining, when the mine is deepened (Dames and Moore 1995, Dames and Moore 1998, Thirapong 2009). Hence it is imperative requirement to understand the groundwater flow behavior under the mine and most significant effects of groundwater; slope instability, floor heaving, trafficability, and pit flooding associated with this proposed deeper mining to design an effective dewatering system.

From initial investigations, it has been found that high grade lignite seams (K and Q seams) are located in the deeper levels and the geological structures associated with the lignite seams are unfavorable. According to the geotechnical investigations, the Basement formation of the Central pit (C1) area mainly consists of Argillite with high water pressure. With deeper mining, groundwater under high pressure within this Basement formation could migrate up through faults. As a result of unfavorable geological structure associated with the groundwater pressure, there could be a potential for slope instability mainly in the west wall of the C1 pit (Figures 1.2 and 1.3). Hence, in this study, the authors aim to model the groundwater flow behavior of Mae Moh mine and investigate possible depressurization methods to confirm the stability of the west wall of C1 pit.

3D groundwater flow model of Mae Moh mine is developed by considering the mine geological stratigraphy and hydrology. The groundwater flow behavior of the basement formation and drawdown response of the Argillite formation beneath the West wall of the C1 pit are studied. In addition, slope stability analysis is carried out in critical locations along the West low wall of the C1 pit by considering the influence of the groundwater pressure.

2. LOCATION AND GEOLOGY OF THE STUDY AREA

The Mae Moh basin is located in northern Thailand at latitude of 18° 18' 21" N and the longitude of 99° 44'02" E. It is approximately 27 km east from Lampang city and 600 km North of Bangkok (Figure 1.1). The Mae Moh basin is an intermountain basin, located on an undulated terrain of a graben (Figure 2.1). It was formed by normal faults of north-south trending (Bunopas and Vella, 1983; Evans, 1989). It covers an area of about 135 km^2 with the maximum width of 8.8 km and length of 18.3 km. The basin is bounded on east and west by steep, rugged sub parallel mountain ranges. These mountain ranges are composed mainly of deformed Permian and Triassic rocks (Figure 2.2). Permo Triassic volcanic rocks dominate the ranges of the west and the Triassic limestone form the ranges of north and east. The Southern boundary of the basin is formed by flat lying Pleistocene basaltic lava (Figures 2.1 and 2.2) (ADAB 1985, Dames and Moore 1995).

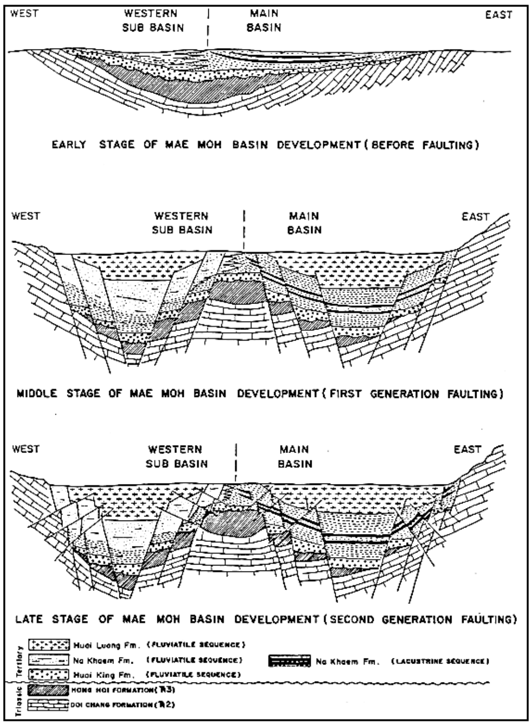


Figure 2.1 Geological Evolution of Mae Moh Basin (after EGAT 1985)

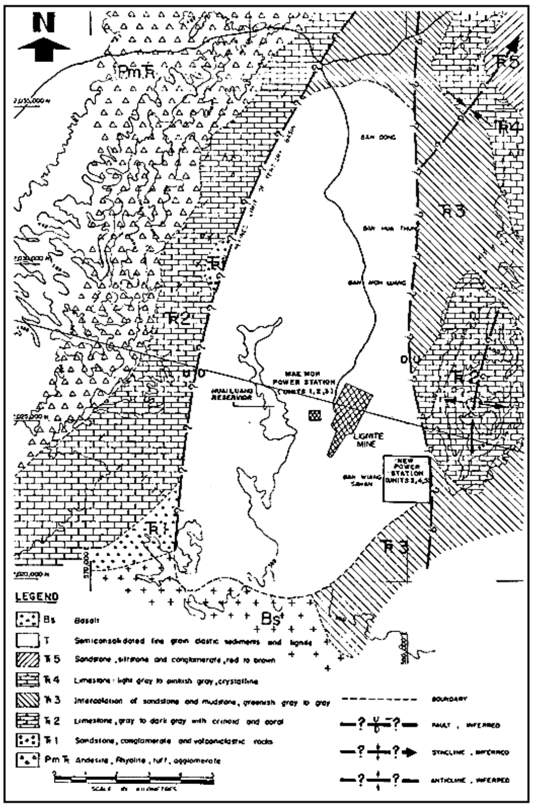


Figure 2.2 Rgional geology of Mae Moh basin (ADAB 1985)

3. GROUNDWATER AND GROUNDWATER RELATED INVESTIGATIONS AND MODE OF SLOPE FAILURES IN MAE MOH MINE

3.1 Groundwater and groundwater related investigations

Groundwater investigations of the Mae Moh mine were initiated by EGAT in 1988 to understand the groundwater occurrence under the mine. During the latter half of 1988, a piezometer (P128) was drilled and completed in the Triassic (basement formation) limestone and confirmed the presence of a confined aquifer with a potentiometric surface elevation of 333 m, MSL or 13 m above the ground surface (Dames and Moore 1995, 1998, Tandicul 1991). This piezometer has given a preliminary indication regarding the requirement of depressurization of the aquifer below the open pit mine. As a consequence of this condition EGAT has initiated two programs of groundwater drilling and testing; Phase 1 and Phase 2 Groundwater Investigations during 1989 to 1991 and 1991 to 1993, respectively, to understand the geohydrology of the mine area and to predict the problems associated with groundwater, during the operational sequence of the mine. Since the completion of phase 2 groundwater investigations and between 1994 and 1996, EGAT has continued to study the hydrogeology of the mine area and surrounding basin by completing additional groundwater testing and drilling programs. In this study the data of those investigations were used to conceptualize the groundwater flow of Mea Moh mine.

3.2 Modes of slope failures in Mea Moh mine

Information on the slope instabilities developed in the Mae Moh mine, especially in the recent excavations is one of the most important sources to design the slopes and also to confirm the safety and to maintain a continuous operational sequence. The combinations of bedding shears (including the Green Zones), normal faults, high groundwater tables and impermeable ground adversely affect the potential stability of both the high and low walls in the Mae Moh mine. The slope failures occurred in Mae Moh mine is recorded by the mine's Geotechnical division. Referring to this information Dight (1994) identified and classified the slope failures of Mae Moh mine into seven failure modes (Figure 3.1): five of these mechanisms involved planer failures and two mechanisms are circular failures.

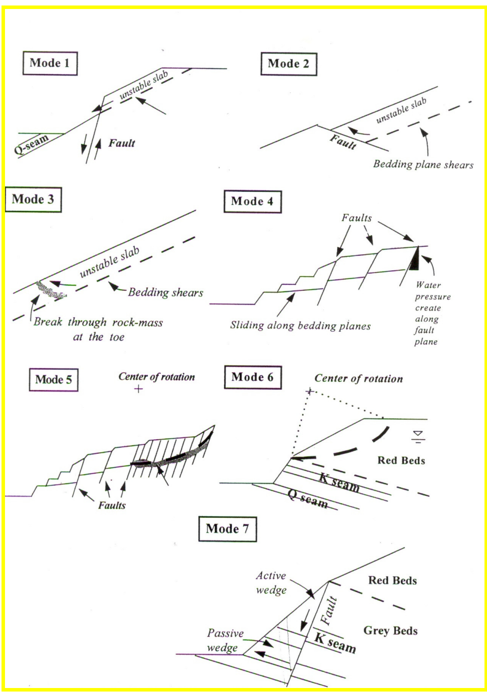


Figure 3.1 Mod of failure at Mae Moh mine (Review Mae Moh Mine Master Plan for Power Plant Units 1-13/EGAT)

4. METHODOLOGY

4.1 GROUNDWATER FLOW MODELING

4.1.1 Aquifer conceptualization and discretization

A conceptual groundwater model was created as a basic graphical representation of the complex natural aquifer system within the Mae Moh basin. The elements of the conceptual model included extents and characteristics of the aquifer system and groundwater flow directions, sources, and sinks. The conceptualization took into consideration the overall objective of the model, the schedule and resources for reaching the objective, and the available hydrogeologic data.

The model area covers a square shaped region of 11 km by 11 km including the open pit mine within the Mae Moh basin (Figure 4.1). The basin is bounded on east and west by steep, rugged sub parallel mountain ranges. In the north, the basin is enclosed by northeast trending mountain range. The surfaces of these ranges are mainly consisting of Triassic limestone. The southern boundary of the basin is not enclosed and is formed by flat lying Pleistocene basaltic lava.

The original ground surface of the Mae Moh basin is flat to gentle rolling consisting of Tertiary rocks and overlying younger sediments. The average elevation of the mining area is about 330 m, MSL. The groundwater flow in the Mae Moh Aquifer system converges from mountain ridges in east and west toward the flat area in the middle of the basin where most of the pumping occurs.

The Mae Moh aquifer system was conceptualized as shown in Figure 4.2. The geology of the model domain has been mainly simplified into 3 Geological Units (Table 4.1): the Basement formation; overlain by the Huai king formation; and superficial layer which consists of Na Khaem formation, Huai Luang formation and geological units above it (Corsiri and Crouch, 1985). Concerning the objective of the model and hydrological and geological data availability, the bottom geological unit was subdivided into 3 layers as upper Basement, lower Basement and bedrock. The top of the basement formations in the model domain undulates between -750 m, MSL and +450 m, MSL.

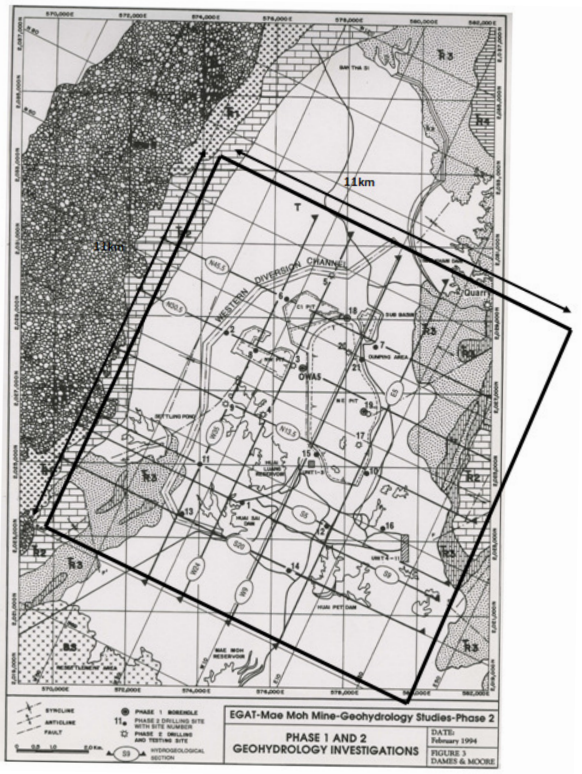


Figure 4.1 Selected area for groundwater Flow model development

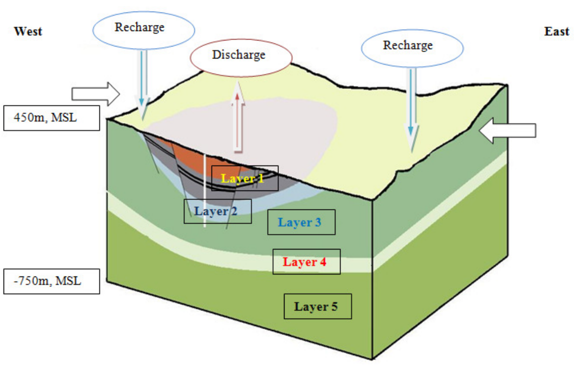


Figure 4.2 Conceptual Groundwater model-Mae Moh mine

Table 4.1 Geological units in conceptual groundwater model

Layer no	Geological Unit	Hydrostratigraphy	Thickness (m)
1	Huai Luange and Na Khaem Formations	Aquitard	5-550
2	Huai King Formation	Aquifer	10-320
3,4	Basement Formation	Aquifer	-
5	Bedrock		-

The conceptual model was developed with the following assumptions:

- The surficial aquifer was divided into zones of coarse material assigned with relatively high hydraulic conductivities and fine material assigned with relatively low hydraulic conductivities.
- A decreasing hydraulic conductivity with increasing depth was assigned to the Basement limestone aquifer.
- The groundwater flow direction of the basin has been assumed by considering the topography of the basin and potentiometric head distribution within the mine area.

The groundwater flow model of the Mae Moh basin was built by using the USGS Visual Modflow (2.7.2 version) finite difference groundwater modeling software (Anderson and Woessner, 1992). The model was designed with 2 aquifers and one aquitard, which were then divided into 5 layers and 9 material types (Table 4.2). The model design was formulated according to the conceptual model which was mainly based on the details employed in the report entitled "Mae Moh Mine Geohydrology Program-Additional groundwater Studies-1994-1996".

The aquifer system within the Mae Moh basin is not confined only to the C1 pit of the Mae Moh mine, but extends through the basin. Hence the model domain was created as 11 km by 11 km grid in the X and Y directions (corresponding to East –West and North-South respectively) covering a large part of the basin as shown in Figure 4.1. The cell size of the model domain was selected as 100 m × 100 m and the cells within the area which covers the C1 pit (Figure 4.3) were then refined to 50 m. As a result of refining, the model having 19,591 cells in one layer (143 rows × 137 columns) and with 5 layers the total of 97,955 cells within the model mesh.

In order to simplify the model, only three geological units have been modeled:

Unit 1-Confining layer-including recent and Pleistocene deposits, Huai Luang formation and Na Khaem Formation
Unit 2-Huai King formation
Unit 3-Basement formation

Dimensions : 11 km (N-S) from 70 N to 40 S; 11km (E-W) from 40E to 70W
Size of the model : 121 km^2
Orientation : Parallel to Mae Moh mine grid (Mae Moh mine grid is oriented on 24° 31'41''Northeast of true north)
Depth : The model extends to an elevation of -750m, MSL
Finite difference mesh : 110 rows (N-S), 110 columns (E-W)

Although model consists of three geological units, nine material types have been used to simulate the basin hydrogeology as in Table 4.2.

Table 4.2 Subdivision of geological units into material types

Material type	Geological units
Material type 1	Huai Luang and Na Kheam formation (low Permeable)
Material type 2	Basement formation – Argillite (low Permeable)
Material type 3	Huai King formation (Permeable)
Material type 4	Basement formation – limestone – under NE pit – Top (Permeable)
Material type 5	Basement formation – limestone East and West basin margins – Top
Material type 6	Basement formation – Sandstone (low Permeable)
Material type 7	Basement formation – limestone – under NE pit – Basal (Permeable)
Material type 8	Basement formation – limestone East and West basin margins – Basal (low Permeable)
Material type 9	Basement formations – Deep, fresh rock (low Permeable)

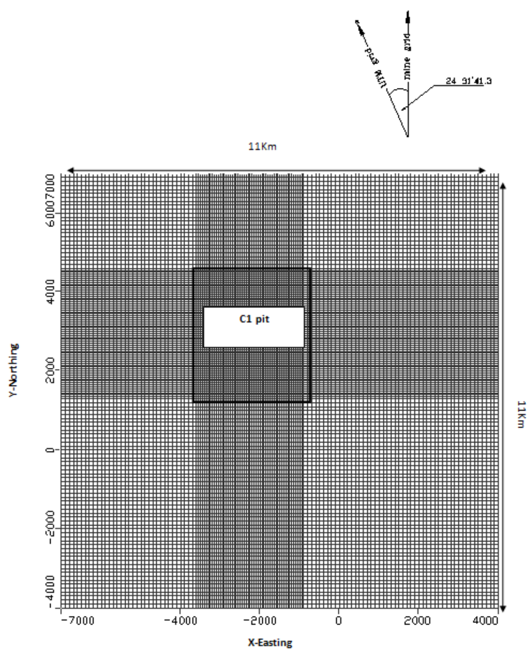


Figure 4.3 Finite Difference Model grid of groundwater flow model

4.1.2 Model parameters and boundary conditions

Aquifer parameters were assigned to appropriate model cells, according to the listed material types in Table 4.2. According to the records of EGAT, in order to determine the aquifer parameters, especially for the Huai King and basement formation, a large number of tests were completed under Phase 2 groundwater investigation program. Also, additional testing was completed during 1994 to 1996 groundwater investigations. The initial modeled hydraulic parameters were determined based on the results of those tests conducted by EGAT (Dames and Moore 1995, Dames and Moore 1998).

The assigned hydraulic conductivity and specific storage values of the material types are shown in Table 4.3. To model, rock permeability with depth in the Basement formation, material type 7, 8 and 9 were used by assuming that permeability decrease with depth. For the groundwater flow model, porosity is not necessary. But in Visual Modflow program, it is required in the mass transport modeling purpose (MT3D) (McDonald and Harbaugh, 1988). Hence, as a default parameter, it was assigned to the model according to the average porosity values of material types.

Table 4.3 Modeled material type and hydraulic parameters (before calibration)

Material Type	Description	Hydraulic conductivity (m/s)				
		Kx (E-W)	Ky (N-S)	Kz	Ss(1/m)	Sy
1	Huai Luang and Na Kheam formation	5.787E-08	1.157E-08	4.629E-09	2.00E-07	0.0005
2	Basement formation – Argillite	6.944E-09	2.314E-09	4.629E-09	5.00E-07	0.005
3	Huai King formation	2.314E-07	4.629E-08	9.259E-09	6.00E-07	0.01
4	Basement formation – limestone – under NE pit – Top	3.472E-05	8.101E-05	4.629E-05	1.00E-06	0.03
5	Basement formation – limestone East and West basin margins – Top	5.787E-06	1.736E-05	9.259E-06	1.00E-06	0.005
6	Basement formation – Sandstone	6.944E-09	2.314E-09	4.629E-09	1.00E-05	0.08
7	Basement formation – limestone – under NE pit – Basal	3.472E-06	8.101E-06	4.629E-06	3.30E-06	0.005
8	Basement formation – limestone East and West basin margins – Basal	5.787E-06	1.157E-06	9.259E-07	3.30E-06	0.001
9	Basement formations – Deep, fresh rock	1.157E-10	5.787E-09	1.157E-10	2.00E-07	5.00E-04

The boundary conditions are a key component of the conceptualization of a groundwater flow system (Franke and Reilly, 1987; Reilly, 2001). Therefore, appropriate boundary conditions were specified for numerical calculations, based on the potentiometric head distribution along the perimeter of the Model domain. Considering the constant head values of the hydrographs of observation bore holes along the perimeter of the model domain, constant head boundary conditions were assigned to the Huai King formation and Basement formation. These conditions are specified in FDM meshes as shown in Figure 4.4.

Groundwater recharge was considered from two sources, rainfall recharge and water bodies within the model domain (Figure 4.5). Rainfall recharge was simulated in the model and assumed that it was only infiltrated into the model in areas where no tertiary sediments are present. Hence, rainfall recharge was assigned to the area of 54 km^2 in the model domain, except tertiary sediments in the central part of the basin as shown in Figure 4.5. An average annual rainfall of 1100 mm/year was taken by analyzing the rainfall data for a period of 8 years (1970-1988) and the rate of infiltration was assumed as 5% of average annual rainfall.

Assumed recharge parameters

Annual rainfall: 1.1 m/year (1100mm/Year)
Percentage of recharge from rainfall: 5%
Catchment area: 54×10^6 km^2

The initial heads of all layers were assigned as zero meters from MSL prior to run the steady state calibration simulation. The resulted heads of steady state calibration were used as initial heads for the transient calibration.

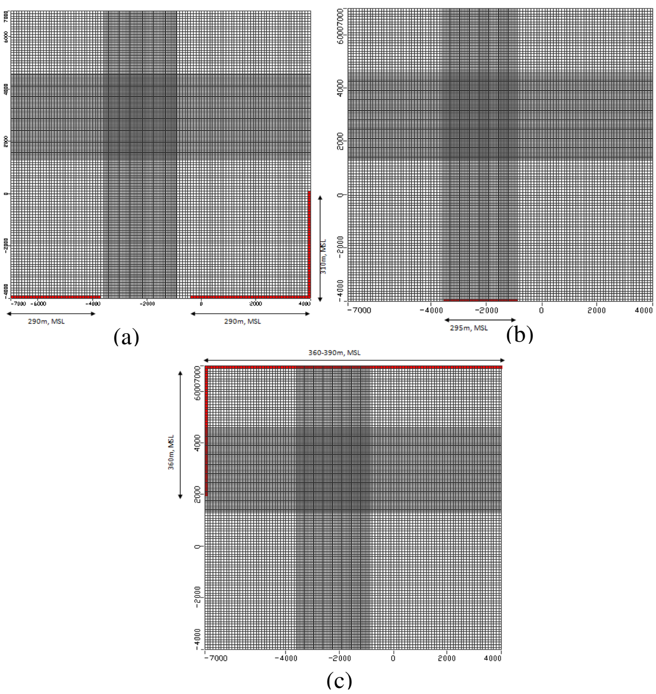


Figure 4.4 Finite Difference Model mesh- Constant Head Boundary condition a) Top of the Huai King Formation b) Bottom of the Huai King Formation c) Basement Formation

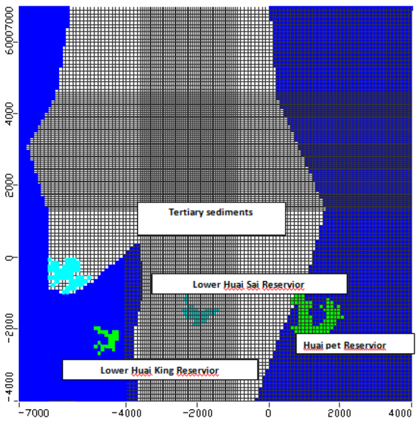


Figure 4.5 Finite Difference Model mesh- Recharge Boundary assigned to the surface except tertiary sediments

4.1.3 Model simulation

In order to determine the groundwater flow behavior and draw down effect of the area consisting Argillite in the basement formation in the C1 pit, a number of simulations were completed using the groundwater flow model. The simulations comprise three categories, calibration simulation, model verification and predictive simulation.

4.1.3.1 Model calibration

Calibration is the process of adjusting or altering model input parameters to achieve a desired degree of correspondence between the model simulation and the actual groundwater flow system (ASTM, 1996). During model calibration, the aim was to achieve the best match of actual and modeled groundwater head distribution of the Mae Moh basin. Model calibration was performed for both steady state condition, and transient condition.

4.1.3.1.1 Steady state calibration

Steady state model calibration was carried out prior to the transient model calibration. This was conducted by using the potentiometric head distribution of 14 observation wells measured during the first half of 1994, within the basin. Visual Modflow 2.7.2 version allows steady state simulation without the need to specify the simulation duration. The initial potentiometric heads for the steady state calibration were assigned as zero. Steady state calibration was achieved by altering the input aquifer parameters and boundary conditions by trial and error method until model simulated observed data into a satisfactory level.

4.1.3.1.2 Transient calibration

The results of the PA12B flow recession test (with a discharge rate of 12,000 m^3/day and was conducted as an additional groundwater test, during 1994-1996) were incorporated in this calibration. The groundwater head distributions resulted from PA12B flow recession test for 176 days during 5th June 1995 to 28th November 1995 were used as the observed heads. Head distributions of four observation bores within the C1 pit area were used as input for the simulation, from bore hydrographs.

PA13 – screened within limestone under NE pit
OA19/2– screened within sandstone and Argilite
RA 9 - screened within Argillite
RA12 – Screened within Argillite

During transient calibration, computed potentiometric heads were compared with the observed heads. Then, the aquifer parameters were modified within a reasonable limit by trial and error method to minimize the difference between the observed and calculated hydrographs. The values of several parameters were not modified simultaneously because if several parameters were modified at the same time, the effect of each parameter could not be identified.

The initial potentiometric heads for transient calibration were achieved by the resulting head distribution of steady state simulation. The acceptance of each calibration was assessed using the specified statistical criteria of Normalized RMS error < 10%, in Visual Modflow.

4.1.4 Model verification

After calibrating the model up to a satisfactory level, it should be verified in order to determine whether the model can be used as a predictive tool. This was achieved by using an observation head data distribution of OA 21/2, OA65 and OA 67 observations bores of PA12B flow recession test with 176 days pumping period and 175 days recovery period, which were not incorporated during the calibration run.

4.1.5 Predictive simulation

Predictive simulations were completed, assuming two configurations in the groundwater model;
(a) No change in the ground surface profile, and
(b) Change in ground surface profile corresponding to proposed excavations,
in order to determine the depressurization requirement for the proposed mining schedule in the year 2017 and the potentiometric head distribution within Argillite in the Basement formation under C1 pit and the response of Argillite to depressurization process for the period of 7 years from 2010 to 2017.

Predictive simulation 1 (Transient simulation) was completed to determine the groundwater head distribution at the end of year 2009 utilizing a groundwater discharge schedule of Mae Moh mine.

Predictive simulation 2A (Transient simulation) was completed to simulate the drawdown effect in the Argillite rock when pumping from the production bores in the limestone. In predictive simulation 2, 3,000 m^3/day was pumped from each bore; PA12B, PA13B and OA64B for 7 years assuming excavation have not been preceded since 1994.

In **Predictive simulation 2B** (Transient simulation) - Same pumping schedule was used by assigning surface elevation of year 2010.

In **Predictive simulation 3A** (Steady state simulation), 3,000 m^3/day was pumped from each bore PA12B, PA13B and OA64B by assigning surface elevation of year 2010.

In **Predictive simulation 3B** (Steady state simulation) 3,000 m^3/day was pumped from each bore PA12B, PA13B and OA64B by assigning surface elevation in the year 2017

Predictive simulation 4 was completed integrating the results of slope stability analysis. From slope stability analysis several unstable locations within the west low wall of C1 pit have been identified. Depressurization was observed by assigning two pumping wells P-ARG 1 and P-ARG 2, within this potentially unstable area. In this simulation 60 m^3/day pumping rate was assigned due to the low permeability condition in the Argillite formation.

4.2 SLOPE STABILITY EVALUATION

4.2.1 Analysis of previous slope failures

Prior to analyze the stability condition of the west low wall of C1 pit, previous slope failures within the Mea Moh mine has been analyzed. The details on previous slope instabilities were collected from the Geotechnical Division of Mae Moh mine, Lanpang.

4.2.2 Slope stability analysis of the west low wall of C1 pit

Eight cross sections;N20 to N 27 within the study area were studied considering the shears, specially the existence of weak green clay layers, faults and interrelationship between them with the mapping exposures of the mine. As a result of the above procedure, critical locations of the area were identified. Stability analysis was conducted analytically considering the limit equilibrium state (Figure 4.6) of the slopes for a dry condition and for varying groundwater elevations. In this analysis, it was assumed that the rock mass is impermeable and the sliding block is rigid, the strength of the sliding block is given by the Mohr coulombs criterion and all forces passing through the centroid of the sliding block. The strength parameters used for the stability analysis of west low wall of C1 pit are illustrated in Table 4.4.

In planar failure, Factor of safety is given by the limit equilibrium analysis as,

Factor of safety = Resisting Force / Driving Force

$$FS = \frac{c'A + \left[W\cos\psi_p - U - V\sin\psi_p\right]\tan\phi'}{\left[W\sin\psi_p + V\cos\psi_p\right]} \quad (1)$$

Effective internal angle of friction	ϕ'
Effective cohesive strength of failure surface	c'
Unit weight of intact rock	γ_r
Unit weight of water	γ_w
Depth of tension crack	Z
Water height in the tension crack	z_w
Weight of unstable block	W
Area of failure surface	A
Driving water force	V
Uplift water force	U
Height of the slope	H
Length to tension crack from slope face	b
Dip of the sliding plane	ψ_p

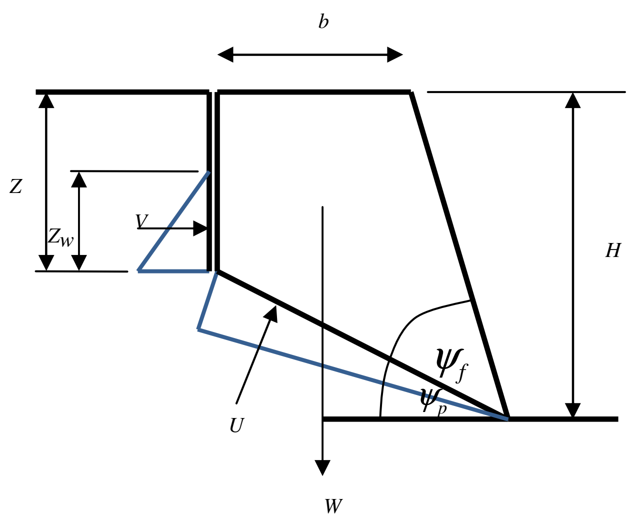


Figure 4.6 Theoretical model of plane slope failure

Table 4.4 Input parameters for slope stability evaluation

Material	Unit Weight (kN/m^3)	Shear strength	
		Cohesion(kN)	Friction angle(°)
Clay stone	19.5	100	25
Fault	20	0	17
Green clay	20	0	12

5. RESULTS AND DISCUSSION

5.1 Groundwater flow modeling

According to the groundwater model domain, the modeled lithological distribution within the Basement formation in the Mae Moh basin is illustrated as below (Figure 5.1).

– The eastern and western margins of the basin are underlain by a mixture of sandstone and limestone.
– Western central portion of the basin is underlain by Argillite Eastern central portion of the basin is underlain by a mixture of sandstone and limestone.
– A large portion of the NE pit is underlain by limestone. Other pit areas are generally underlain by Argillite with minor sandstone.

The initial model hydraulic parameters were based on the results of the pumping tests. These parameters have been varied slightly (within an acceptable range) to achieve the model calibrations (Table 5.1).

The individual high permeability structures which occur in the basement formation could not be modeled because,

– The locations of all the structure were not known.
– Permeability within those structures was unknown.
– Modelling of all of these structures would make the model too complex for practical use.

Limestone generally has a low permeability in 10^{-6}-10^{-9} m/s. But Karstic limestone exhibit 10^{-2} to 10^{-6} m/s permeability due to the development of karsts structure (Freeze and Cherry, 1979). The limestone in the Mae Moh mine is permeable because of the secondary structures which have been developed through limestone formation. Therefore, both the low permeability matrix and the high permeability structures have to be incorporated to model permeability values. Hence the modeled values approximately equivalent to those values obtained from the pumping test.

5.1.1 Model calibration

5.1.1.1 Calibration simulation for steady state condition

In groundwater flow modeling of Mae Moh Basin, model calibration was achieved through trial and error approach until the calculated potentiometric head values matched the observed values to a satisfactory level. Steady state calibration was completed in order to match the observed potentiometric head distribution (assuming non pumping condition) with calculated heads and thus form a realistic set of starting head conditions for all the other model simulations.

Figure 5.2(a) shows the modeled potentiometric head distribution and observed or measured head values with bore numbers, in the Basement formation. As expected in the conceptual model, the simulated groundwater flow towards the center of the basin and then to the south.

Figure 5.2(b) shows the scatter plot of calculated versus observed head values. Scatter plot was produced with observed heads on the horizontal axis and calculated or modeled heads on the vertical axis. The scatter points represent the heads of the observation well data. All the points should occur with a minimum degree of scatter about the line of perfect fit which go through the origin (with 45° angle) for a perfect calibration. The Graph shows that the resulting heads in a reasonable agreement with the observed heads as the data points approximately on the line of 45° and having Normalized RMS error 4.96%, which is less than 10% as specified by the Visual Modflow statistical criteria. Hence the results of the steady state calibration were considered accurate enough for the current level of hydrological knowledge.

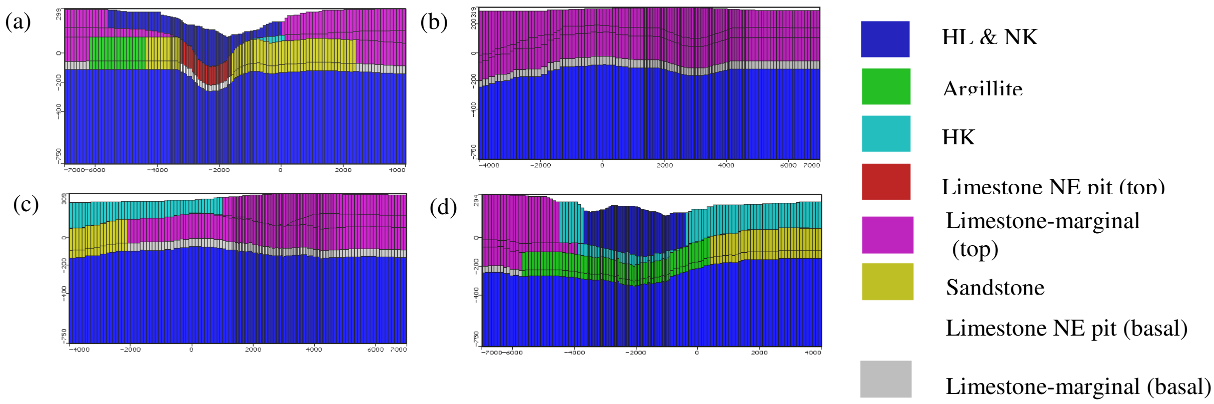
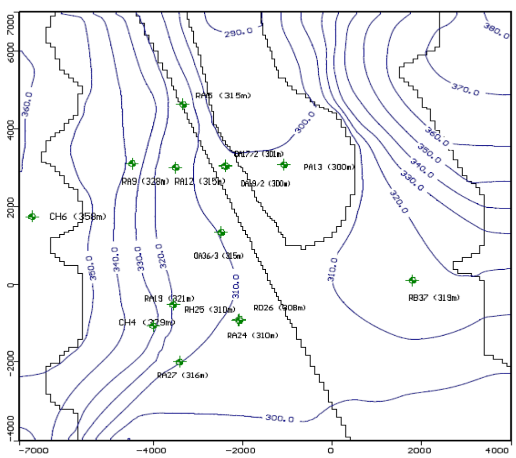


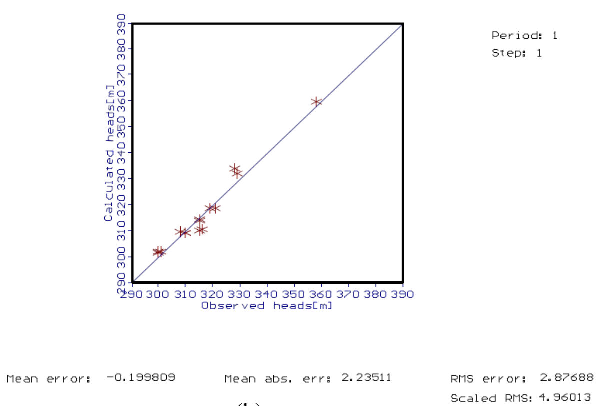
Figure 5.1 (a) Cross section N70 (North boundary of the model) (b) Long section W70 (West boundary of the model) (c) Long section E40 (East boundary of the model) (d) Cross section S40 (South boundary of the model)

Table 5.1 Modeled material type and hydraulic parameters (after calibration)

Material Type	Description	Hydraulic conductivity(m/s)				
		Kx (E-W)	Ky (N-S)	Kz	Ss (1/m)	Sy
1	Huai Luang and Na Kheam formation	5.787E-08	5.78704e-8	4.629E-08	4.00E-07	0.01
2	Basement formation – Argillite	6.944E-09	2.314E-09	4.62963e-8	5.00E-07	0.005
3	Huai King formation	5e-7	5e-7	9.25926e-8	6.00E-07	0.01
4	Basement formation – limestone – under NE pit – Top	0.0000035	0.0000035	4.629E-05	1.00E-06	0.03
5	Basement formation – limestone East and West basin margins – Top	5.8e-7	5.8e-8	0.0000093	3.30E-06	0.005
6	Basement formation – Sandstone	9.4444e-8	9.4444e-8	4.62963e-8	1.00E-05	0.08
7	Basement formation – limestone – under NE pit – Basal	3.5e-7	3.5e-7	0.0000046	3.30E-06	0.005
8	Basement formation – limestone East and West basin margins – Basal	5.787E-06	1.157E-06	9.259E-07	3.30E-06	0.001
9	Basement formations – Deep, fresh rock	1.157E-10	1.15741e-9	1.15741e-10	2.00E-07	5.00E-04



(a)



(b)

Figure 5.2 (a) Ground water flow Modeling-Steady State calibration-Observed and modeled Potentiometric head distribution (b) Ground water flow Modeling-Steady State calibration -scatter plot of calculated verses observed head values

5.1.1.2 Transient calibration

Following steady state calibration, transient calibration was completed to make the model simulation more realistic. The potentiometric head distribution, resulted from steady state calibration was taken as the initial heads for transient calibration simulation (Figure 5.3(a).) This predictive simulation shows a significant regional drawdown in limestone and only minor drawdown in the surrounding Argillite and sandstone (Figure 5.3(b), and (c)). Also, it shows that the drawdown of RA12 and RA9 observation points were slightly different although they were existed within the same formation (Figure 5.4). This was due to the distance effect of those wells from the discharge point or the effect of cone of depression. Hydrographs of the observation wells show reasonable match between the observed and calculated potentiometric head distribution during the simulation period of 176 days. Also, it confirmed from the Normalized RMS error of 7.85% resulted from the transient calibration.

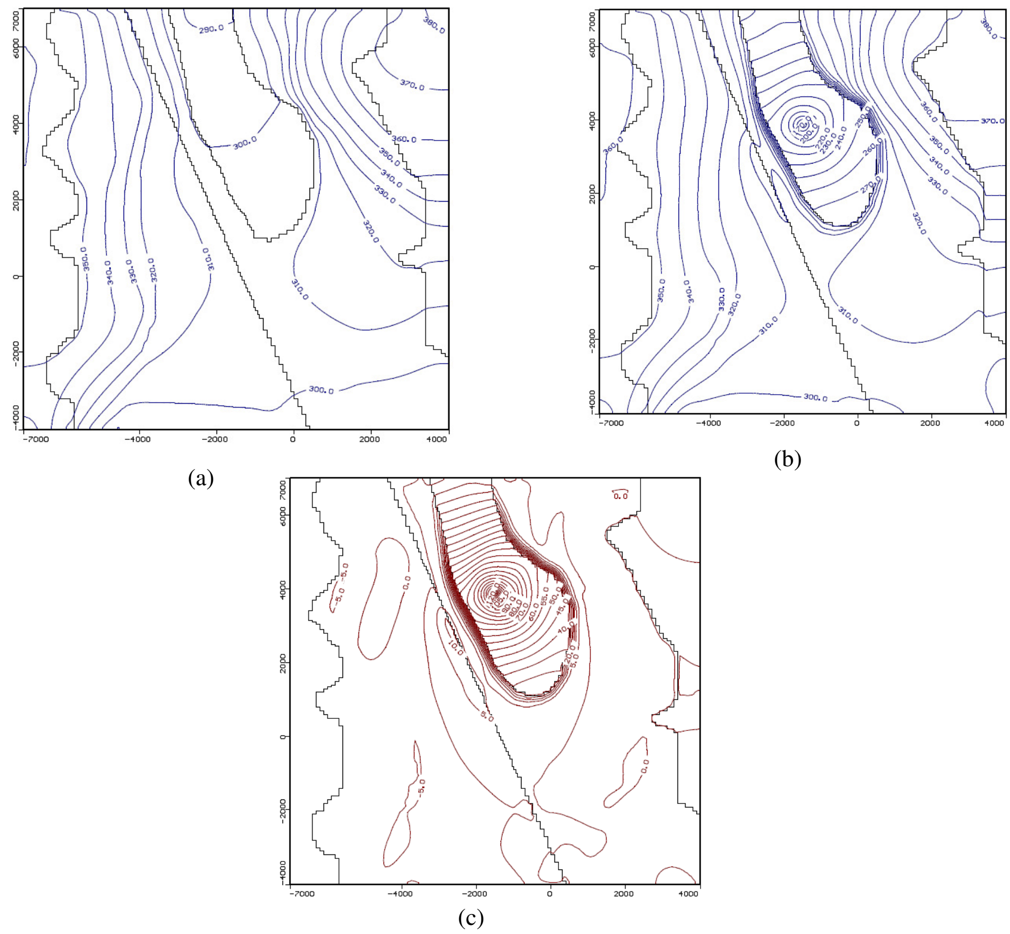


Figure 5.3 Ground water flow Modeling-Transient calibration (a) Initial potentiometric head distribution in Basement formatiom (b) Final potentiometric head distribution in Basement formatiom (c) Draw down of the Basement formation

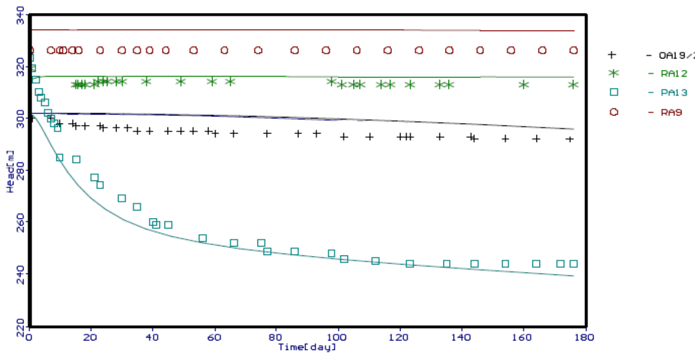


Figure 5.4 Ground water flow Modeling-Transient calibration –Hydrographs of observed and calculated head distribution for 176 days

5.1.2 Model verification

In order to verify the groundwater flow model developed for the Mae Moh basin, the groundwater flow model was tested by using a data set independent of the calibration data. This historical data matching (Figure 5.5) shows that the modeled or model's predicted potentiometric head distribution for the period of time stated in the model verification process is within an acceptable limit.

According to the resulting hydrograph of observation wells namely OA21/2 and OA65 shows good correlation between observed and calculated potentiometric head distribution for both pumping and recovering periods of the PA12B flow recession test. But there is an overestimation of the potentiometric head distribution at OA 67 observation point during recovering period, although it shows a good fit during pumping from PA12/B production bore.

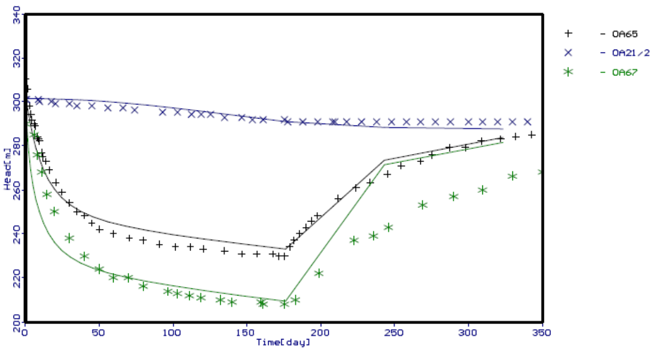


Figure 5.5 Ground water flow Modeling-Model verification –Hydrographs of observed and calculated head distribution for 176 days discharge and 175 days

5.1.3 Predictive simulations

Upon completion of the calibration and model verification, the groundwater model was used to predict the potentiometric head distribution and drawdown effect of the Basement formation, especially under C1pit, for different pumping schedules for 7 years from 2010 to 2017. Predictive simulations were conducted up to the year 2017, because according to the slope stability analysis results, potential instabilities can be occurred in the year 2017 in C1 pit and hence it is essential to predict the groundwater head distribution in 2017. Predictive simulations were completed in order to determine the drawdown capability of the conceptual dewatering schemes mainly concerning the depressurization response of Argillite formation under C1 pit.

5.1.3.1 Predictive simulation 1

Potentiometric head distribution at the end of the year 2009 was predicted from this simulation. According to the groundwater discharge schedule of 1998 to 2009, predicted potentiometric head distribution in the Basement formation at the end of the year 2009 was achieved. The main purpose of predictive simulation 1 was to generate head distributions at the end of the year 2009, which can be aided for forecasting the groundwater flow behavior from 2010 to 2017.

5.1.3.2 Predictive simulation 2

Predictive simulation 2A was performed assuming no excavation has been preceded within the mine, since 1994. In this simulation, groundwater was discharged from three pumping wells; PA12B, OA64B and PA13B which have been screened into the limestone layer under NE pit. The objective of this predictive simulation was to determine the drawdown response of Argillite within the Basement formation under C1 pit, when groundwater was discharged from the limestone under NE pit and also to determine the effect of mining on potentiometric head distribution.

Figure 5.6 illustrate the predicted potentiometric head distribution and drawdown in the basement formation in different time steps during 2010 to 2017. It shows Argillite takes more time to respond pumping groundwater from Limestone aquifer. Both, head distribution and drawdown contour maps illustrate that, when pumping begins, water levels within the pumping wells were lowered. As the pumping proceeds, water is pulled or withdrawn from the aquifer and a cone of depression is created. With time more water must be drawn from the storage at greater distance, because the limestone layer within the Basement formation is limited to a small area under NE pit. Hence, a cone of depression expands and drawdown increase to provide the required head to ease the flowing of more water from the greater distance.

The shape of the cone developed mainly depend on the pumping rate, pumping duration, aquifer characteristics, slope of the water table and recharge within the cone of depression of the well (Health 1983). In isotropic condition this drawdown induced a same gradient or slope all around the well bore (Figure 5.7). Due to the anisotropic condition within the Mea Moh aquifer system cone of depression vary accordingly. It tends to draw more water from the limestone layer than surrounding low permeable layers. According to Driscoll (1986), the cone of depression will continue to enlarge until one or more of the following condition is met.

- It intercepts enough of flow in the aquifer to equal the pumping rate.
- It intercepts a body of surface water from which enough additional water will enter the aquifer to equal the pumping rate when combine with all the flow toward the well.
- Enough vertical recharge from precipitation occurs within the radius of influence to equal the pumping rate.
- Sufficient leakage occurs through overlying or underline formation to equal the pumping rate.

5.1.3.3 Predictive simulation 3

Figure 5.8 illustrates the predicted potentiometric head distribution in the basement formation for steady state simulation under two configurations. Figure 5.8(a) was resulted from the steady state simulation for 2010 mine configuration with groundwater discharging from limestone layer under NE pit. Figure 5.8(b) was resulted from the steady state simulation for 2017 mine configuration with same groundwater pumping rates. As shown in the figures there is no any distinguishable variation in the potentiometric head variation in two occasions. Although potentiometric head distributions were not varying, the water table was lowered in 2017.

4.1.3.4 Predictive simulation 4

Predictive simulation 4 was completed with integrating the results of slope stability analysis. From the results of slope stability analysis, potentially unstable slopes were identified within N24 to N26 (Figure 1.2 and Figure 1.3), in the west low wall of C1 pit. Hence 2 pumping wells were used to observe the efficiency of pumping from the Argillite formation within the critical slope region.

The predicted potentiometric head distributions and draw down response (Figure 5.9) showed that the cone of depression is limited to small area due to the low permeability of the formation and the maximum amount which can be discharged from the Argillite formation is 60 m^3/day.

The results of predictive simulations 2, 3 and 4 of the groundwater flow model show that the drawdown response of the low permeability Argillite for the dewatering from more permeable limestone within NE pit is small and specially from predictive simulation 3 shows that deepening of the C1 pit does not make a considerable change in the lowering of the potentiometric head within the Argillite formation.

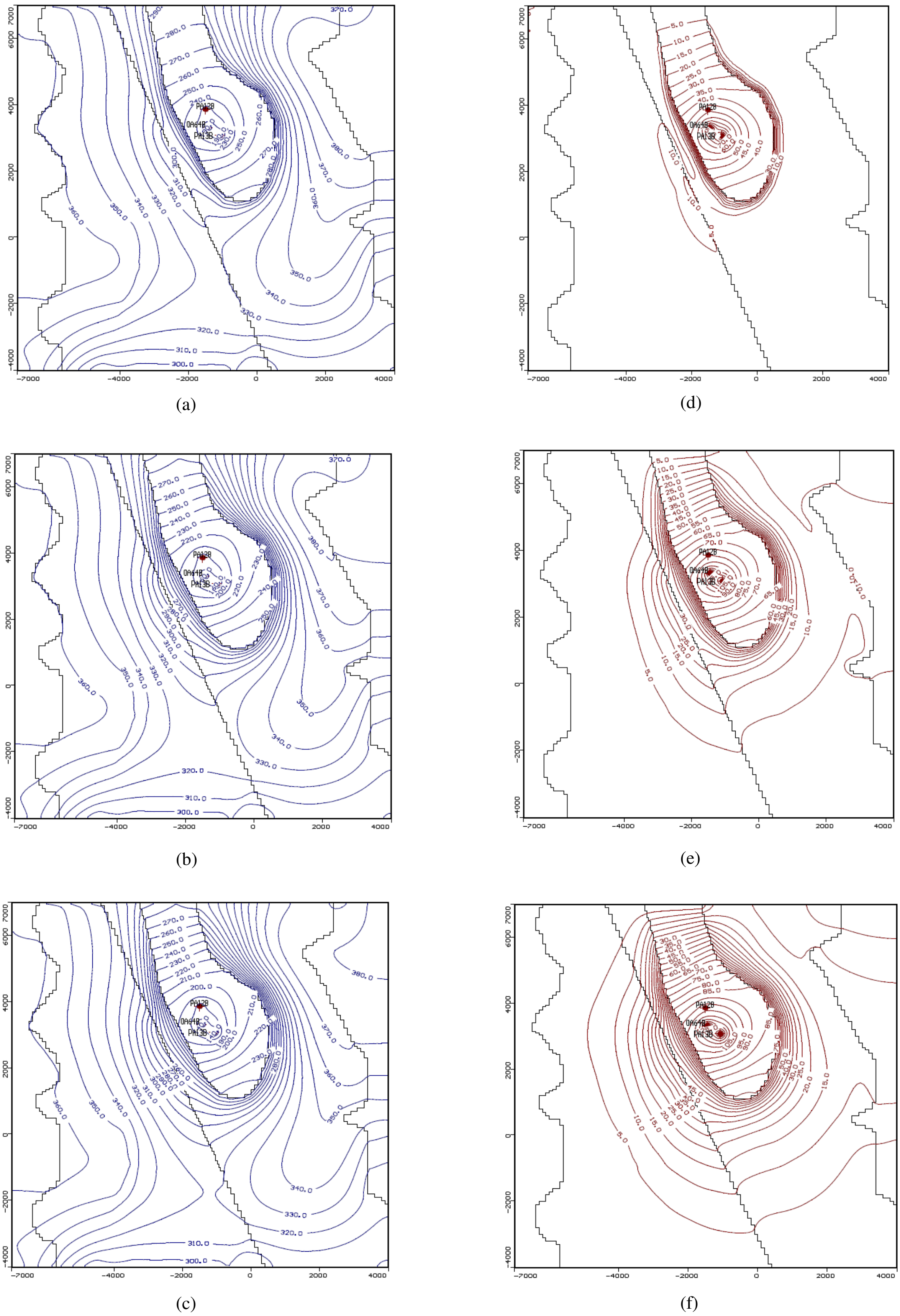


Figure 5.6 Predictive simulation 2A - Predicted potentiometric head distribution in Basement Formation (a) after 216 days (b) after 1271 days (c) 2555 days and Predicted drawdown distribution in Basement Formation (d) after 216 days (e) after 1271 days f) 2555 days

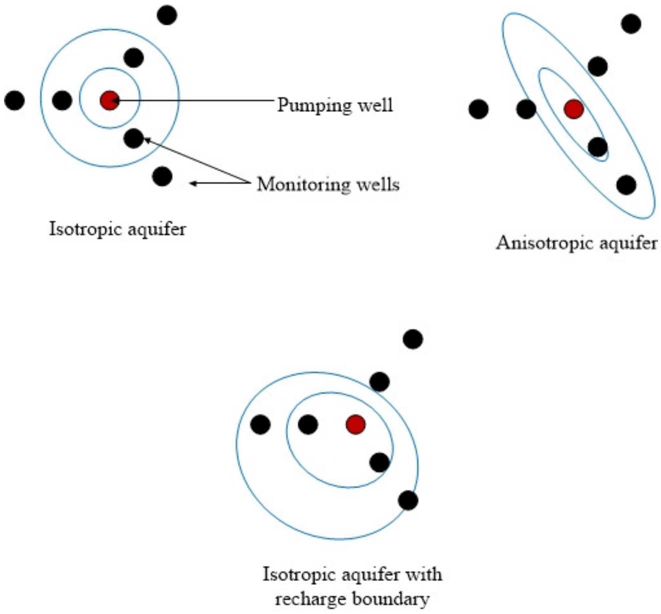


Figure 5.7 Cross section of variation of cone of depression

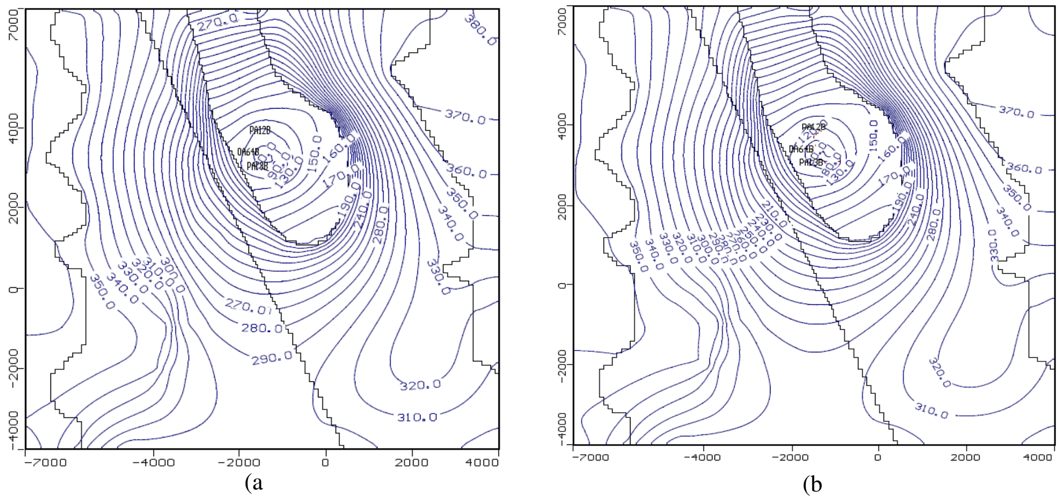


Figure 5.8 Head distribution resulted from the steady state simulation for (a) 2010 mine configuration (b) 2017 mine configuration

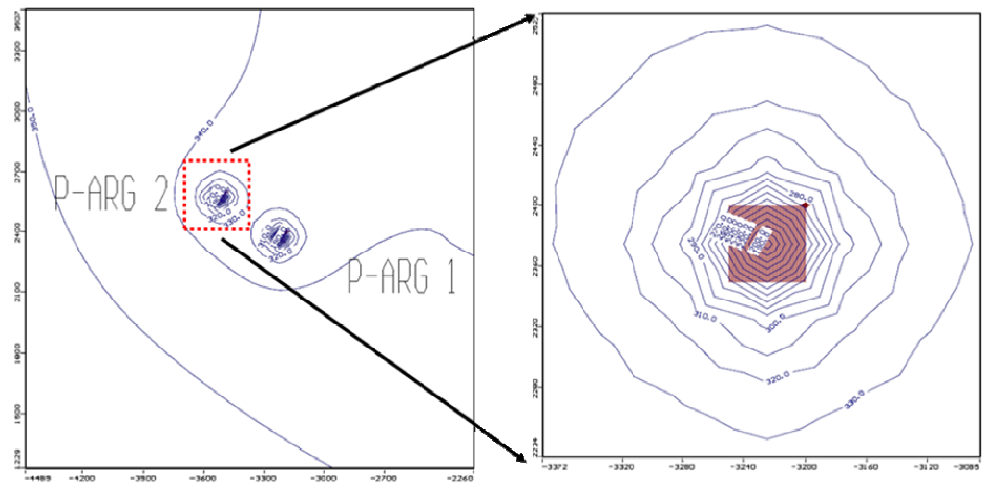


Figure 5.9 Predictive simulation 4-Pumping from argillite formation Potentiometric head variation near well point

As discussed under the predictive simulation 4 pumping from Argillite formation is not feasible because the area of influence from one pumping well in Argillite formation is only up to 25 m and cannot pump more than 60 m^3/day due to low hydraulic conductivity in the formation. Installation of several pumping wells within the area is uneconomical although it could reduce the potentimetric head up to a certain level

5.2 Slope stability analysis

5.2.1 Physical properties

During the phase 2 geo-hydrological study of Mae Moh mine, a large number of core samples from the drilling program were tested to determine the basic physical and engineering properties of material within Mae Moh mine. These samples were tested by the Mae Moh mine Geotechnical division and Asian Institute of Technology. Most of the core samples were tested to determine the physical properties; dry density, water content and porosity under ASTM standard test procedures. According to the test results the dry density of all material ranges from 1.6 and 2.6 t/m^3. It appears that the mean value of dry density increases with the depth and Huai King and Basement formations shows significantly higher dry densities; range from 2 to 2.7 t/m^3, than other rock formations. Water contents of the material types were highly variable and mean value range between 10 to 20%. The interburden and overburden show the highest values. This may due to the high porosity of associated with these materials.

5.2.2 Strength parameters

When comparing the residual shear strength of previous investigations, there is not much difference between the parameters except SW pit. Previous records show that the green clay in the SW pit is stronger than the green clay in the C1 and NE pit.

SW pit	$C_r = 15$ KPa	$\phi_r = 18.5°$ (Buncha, 1996).
NE and C1 pit	$C_r = 0$	$\phi_r = 12°$

From recent studies a huge shell bed was discovered in the SW pit. Since this fossil in the SW pit have been discovered, EGAT decided to preserve this fossil by suspending further excavation in this area. Due to these fossils the clay matrix of the SW pit includes some shell fragments which may increase the shear strength along the sheared surface passing through those fragments (EGAT 1995).

5.2.3 Stability Analysis of West Wall of C1 Pit

Within N20 to N 23 there are no identifiable potential problems. It is because, the proposed final pit slope in year 2017 within the area of concern is well above the weak green clay layers and hence green clay will not expose at the slope face within that region. According to the slope geometry and structural geology, 4 locations have been identified as potential to slide along the plane of weak green clay layer G6 associating the effect of easterly dipping faults (Figure 5.10). Stability of the identified slopes was analyzed analytically by limit equilibrium analysis. The output of the limit equilibrium analysis is the factor of safety determined from analyzing resisting and disturbing forces.

The results of the stability analysis show that all the slopes are stable for dry condition. Factor of safety of these slopes ranges from 4 to 12, when considering dry slope condition. Considering the economical feasibility, only up to Q lignite seam will be extracted within this area. Hence, after Q lignite seam will be extracted from this area, underlying claystone will be exposed into the surface. At this situation slope may cause stability problems due to the existence of weak green clay layers associated with faults. When groundwater is encountered in the analysis, the stability of the slopes reduced as shown in the graphs of factor of safety versus water level (Z_w) (Figure 5.11).

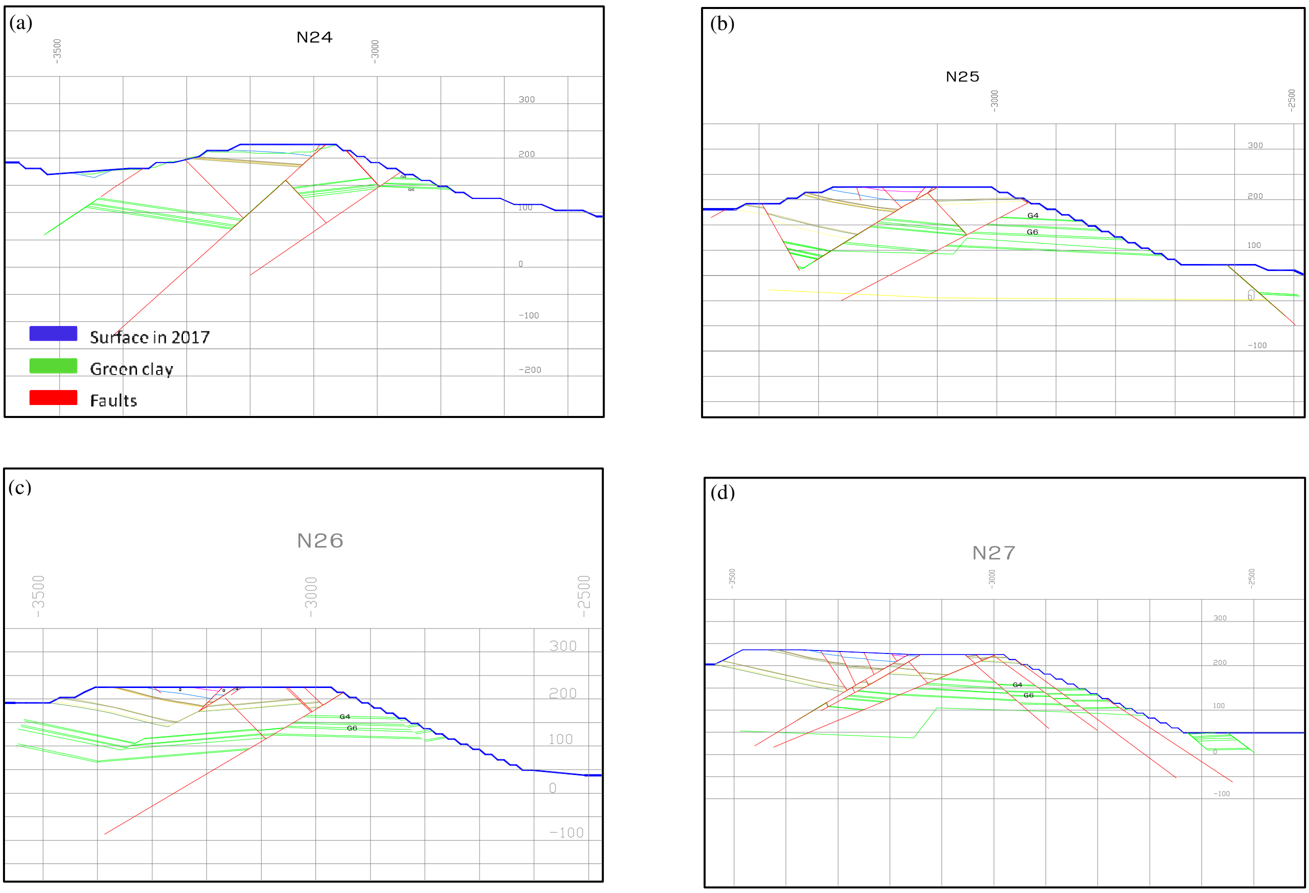


Figure 5.10 Critical locations along (a) section N24 (b) section N25 (c) section N26 (d) section N27

From the results of the slope stability analysis of the section N24 (Figures 5.11 and 5.12) (only state about section 24 in this paper as it shows the lowest or critical condition among all), to maintain a safe slope condition in west low wall of the C1 pit, potentiometric head should be maintained below 170 m, MSL in this region. According to the results of predictive simulations 2 of groundwater flow modeling of Mae Moh basin, the head distribution within Basement formation under C1 pit in Year 2017 will be 250-320 m, MSL if only discharge from the limestone layer under NE pit. Predictive simulation 2 shows it is not possible to lower the groundwater head within a low permeable Argillite formation up to a favorable level by discharging water from the more permeable limestone layer under NE pit.

According to predictive simulation 3, potentiometric head of the basement formation will not vary as the overburden removal.

As discussed under predictive simulation 4 pumping from Argillite formation is not feasible because the area of influence from one pumping well in Argillite formation is only up to 25 m and cannot pump more than 60 m^3/day due to low hydraulic conductivity in the formation. Installation of several pumping wells within the area is uneconomical although it could reduce the potentimetric head up to a certain level.

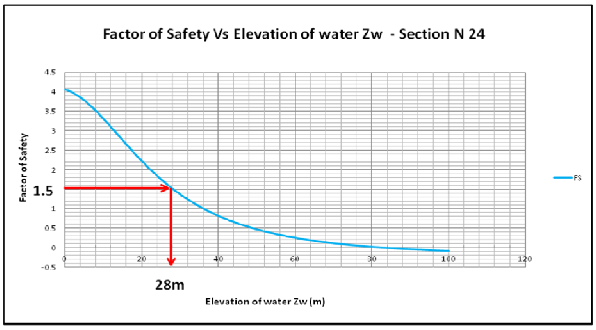


Figure 5.11 Factor of safety with the variation of water level (cross section N 24)

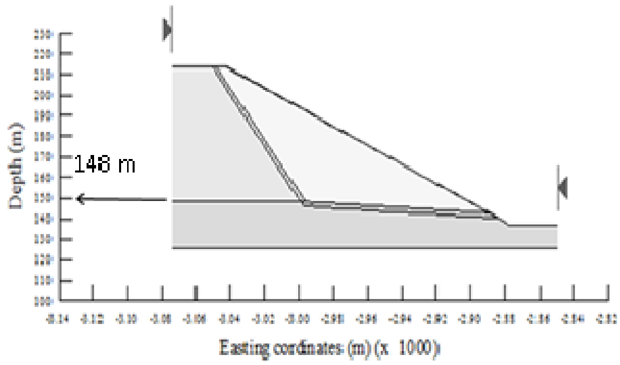


Figure 5.12 Geometry of the critical slope in cross section N24

6. CONCLUSIONS AND RECOMMENDATIONS

Based on the results of groundwater flow modeling of Mae Moh mine, the pertinent conclusion which can be reached are outlined below.

- Low permeable Argillite underlying the west wall of C1 pit is problematic as low drawdowns were obtained for short term pumping from Argillite formation.
- Long term pumping schedules must be initiated to lower the potentiometric head within Argillite formation by pumping from limestone under Northeast (NE) pit.
- Stability of the west wall of the C1 pit for 2017 pit slope was evaluated in terms of the safety factor by the limit equilibrium method. Results obtained in this study indicated that the west wall is susceptible to failure due to water pressure associated with it. To maintain a safe slope, potentiometric head within west wall of C1 pit should be maintained below 170m, MSL.

Long term pumping schedule should be initiated focusing the drawdown response of Argillite formation within C1 pit.

In order to determine the presence of an aquifer zone under the mining area, it is essential to have a clear understanding about the structural geology and lithological distribution of the basement formation. Hence, investigation should be continued by using existing and new bore holes to clarify the structural geology and lithology in order to determine the precise hydrologeological condition within the basement formation.

Presence of temperature gradient can cause groundwater flow (as well as heat flow), even when the hydraulic gradient does not exist. Hence it is essential to refine the groundwater temperature in order to determine the potential effect on aquifer depressurization and groundwater movement in the basin using new temperature measurements.

By installing and testing water table piezometers at various locations in the basin specially in the geological and hydrological risky(critical) zones, to determine the effects of depressurization on the water table and recharge discharge mechanism to aid an uninterrupted operational sequence within the mine.

7. REFERENCES

ADAB., (1985). Mea Moh geotechnical Report, EGAT, Vol.1

Anderson, M.P., Woessner, W.W. (1992): Applied Groundwater Modeling, Simulation of flow and advective transport. – Academic Press, London..

ASTM (American Society for Testing and Materials) (1996). ASTM Standards on Analysis of Hydrologic Parameters and Ground Water Modeling

Buncha, C.(1996). Re-Evaluation of the Stability of South West Pit Mae Moh Mine, Lampang, Thesis No. GE 96-25, M.Sc, Asian Institute of Technology, Bangkok, Thailand.

Bunopas, S., and P. Vella (1983). Tectonic and geologic evolution of Thailand, In: P. Nutalaya (ed.), Proceedings of the Workshop on Stratigraphic Correlation of Thailand and Malaysia, Had Yai, Thailand. Tech., 1, 307-323..

Corsiri R., and Crouch A., 1985, Mae Moh coal deposit: Geologic report, Volume 1: Thailand/Australia Lignite Mines Development Project, Electricity Generating Authority of Thailand, 448 p.

Dames & Moore, (1995). Mae Moh Mine Geohydrology Programme- Geohydrology studies Phase 2, EGAT, Thailand

Dames & Moore, (1998). Mae Moh Mine Geohydrology Programme- Additional Groundwater studies 1994-1996, EGAT, Thailand

Driscoll, F.G. (1986). Groundwater and Wells UOP Johnson Division

Evans, P.R and Jitapunluk, S (1989). Geology of the Mae Moh Basin, Nothern Thailand, EGAT Technical report, 1989

Franke, O.L. and Reilly, T.E. (1987) The Effects of Boundary Conditions on the Steady-state Response of Three Hypothetical Ground- Water Systems Results and Implications of Numerical Experiments: U.S.Geological Survey Water-Supply Paper 2315, 19 p.

Freeze R. A , and Cherry J.A. (1979). Groundwater, 2nd edition. (Prentice Hall). pp 10-20

Heath, R. C. (1983). *Basic ground-water hydrology.* U.S Geological Survey, Water Supply Paper 2220 prepared in cooperation with theNorth Carolina Department of Natural Resources and Community Development.

McDonald, M.G., and Harbaugh, A.W. (1988). A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model. U.S. Geological Survey Techniques of Water-Resources Investigations, Book 6.

Punyawadee, V., Phothisuwan, R. Winichaikule, N. and Satienperakul, K. (2006) Costs And Benefits Of Flue Gas

Desulfurization For Pollution Control at the Mae Moh Power Plant, Thailand. Research report; no. 2006-RR4

Reilly, T.E. (2001). System and Boundary Conceptualization in Ground-water Flow Simulation: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 3, Chapter B8, 26 p.

Tandicul, W. (1991). Criteria for the design of Mae Moh Drainage system. EGAT Technical report 1991

Thirapong, P., Mohammad, H. Khosravi, P. and Doncommul, N. M. (2009). Excavation Problems in the Mae Moh Lignite Open-Pit Mine of Thailand, pp 459-46

Thōranī, P. D. S. (2001). Geology and mineral resources of Thailand. 2p.