UNDERGROUND WATER IN OPEN PIT MINING AT MAE MOH MINE OF THAILAND

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Abstract

The groundwater problem at Mae Moh mine has drawn attention as the mining excavation goes deeper, thus resulting in detailed investigation of hydrogeological condition. One of the problems facing the mining is floor heave influenced by groundwater. The control of groundwater pressure in deep-seated aquifers with high elevation becomes important in the mining. In addition, the underground water at Mae Moh mine is naturally contaminated by arsenic. Therefore, the developments of 3D groundwater model of deep pit mine using Modflow simulation and the studies of underground water treatment are needed for the future planning. The predictive simulations were carried out for eight years (2007 to 2015). Because stability of the Mae Moh mine shows how can be closely linked to the water environment, this paper aims to report the field visits to the water related facilities of the mine, which were conducted during 2010-2013. The result reveals that the potentiometric head level is strongly increased, which might be a potential risk for the floor heave; thus, depressurization is required. Field measurements reveal pH level at 8 and a range of total dissolved solid (TDS) at 870-2020 ppm. Treatment efficiency shows that more than 95% of the arsenic can be successfully removed using ferric chloride.

Keywords: Arsenic, Field measurement, Floor heave, Ground water, Modflow, Open pit

Introduction

The Mae Moh mine (Figure 1), one of the largest open-pit mines in the region where deposits cover an area of more than 38 km^2, has been planned and operated by the Electricity Generating Authority of Thailand (EGAT) since 1955. Mae Moh mine supplies up to 50,000 tons of lignite to daily feed the power plants located in the mining area. The current deepest level of pit is about 300 meters in the northeast mine area, while the final depth will be 490 meters at the end of production. Due to a huge volume of overburden excavation of about 60-80 million cubic meters per year, many engineering problems caused by the deep open-cut have been reported and handled [1-3].

One of the problems facing the mining operation is floor heave influenced by groundwater; therefore, the control of groundwater pressure in deep-seated aquifers with high elevation becomes important in the mining. Therefore several numbers of groundwater deep wells have been equipped since 1989 in the critical areas of floor heave to release high water pressure of local sand aquifers and major aquifer zones of limestone. Problems concerning the underground water have been studied in the past [4-7].

In an attempt to determine the critical area against the floor heave and depressurization requirement, a 3D groundwater model for a particular pit with three aquifers and one aquitard was studied by Pongpanlarp [8] using the finite difference method. Based on his study, groundwater piezometric head required in the year 2007 was + 200 m MSL, which will be the same in the year 2012. Minimum groundwater discharge rate was required for securing the safety factor greater than 1. Three existing wells in the critical area should be operated at the pumping rate of 4,000 m^3/day to reduce deep groundwater pressure to +200 m. The dewatering plan to pump out the underground of 12,000 m^3/day by 3 production wells has been arranged during 2007-2012 as a minimum requirement.

Table 1. Summary of Field Visits the Water Related Mining Fasciitis of the Mae Moh Mine Conducted during 2010-2013

Period of the Field Visit	Field Observation
September 20-23, 2010	sump, production well, settling pond and wetland
September 13-14, 2011	water treatment plant (before full operation)
March 28-29, 2012	ash/gypsum and sludge disposal site
October 30, 2012	sump
March 12, 2013	water treatment plant (after full operation)

The current total discharge of the production wells is estimated at 9,000-15,000 m^3/day. The underground water is naturally contaminated; therefore the groundwater pumped is transferred to the water treatment plant with operating capacity of 12,000 m^3/day in order to reduce or eliminate the arsenic before heading to the settling pond and wetland. Because the stability of Mae Moh mine can be closely linked to the water environment, this paper aims to report the field visits on the water related mining facilities including the underground water treatment facilities conducted during 2010-2013 as summarized in Table 1 [9].

3D groundwater flow model of Mae Moh mine has been developed by considering the geological stratigraphy of the area and hydrology in order to determine the groundwater flow behavior in the basement formation beneath the C1 pit as shown in Figure 2.

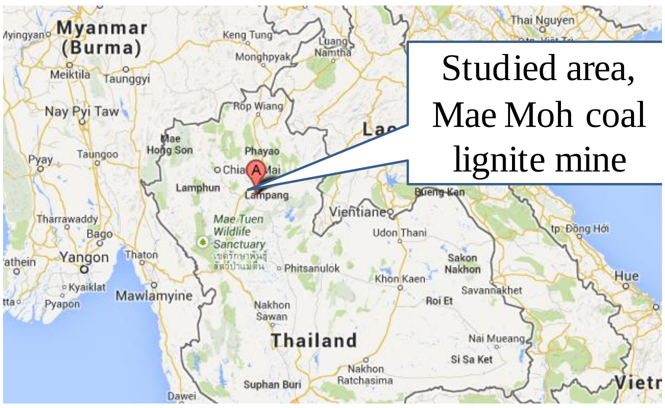

Figure 1. Map of Thailand where studied area is situated in the northern part (Source: Google map)

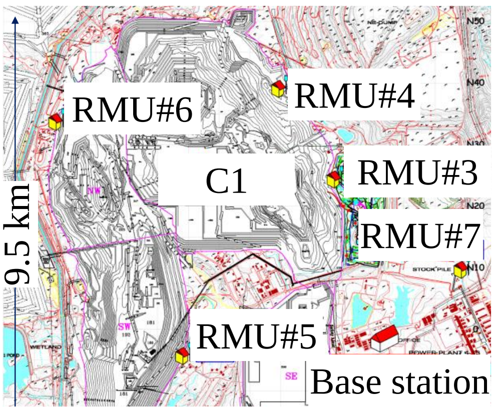

Figure 2. Rain gauge stations installed at different locations in Mae Moh coal lignite mine

Geologic Setting of Mae Moh Mine

Mae Moh mine is situated in the Mae Moh tertiary basin, which has more than 1,000 m of maximum thickness. The original ground surface of the Mae Moh Basin was flat to gently rolling, consisting of easily eroded tertiary rocks and the overlying younger sediments. The natural landforms within the basin have largely been changed by the mining activities (open pit lignite mine and heaped dumps), the infrastructure construction activities (housing resettlement areas, power plant construction), and the dam construction for water supply and storage associated with the power plants.

According to the recent studies on sedimentary rocks [10-13], five main geological formations, namely, Quaternary, Huai Luang, Na Khaem, Huai King, and basement, are found in the Mae Moh basin as summarized in Table 3. Huai Luang formation is the youngest tertiary formation with thickness varying from 5 to 350 meters. It consists of red to brownish-red semi-consolidated and unconsolidated claystone, siltstone, and sandstone. Na Khaem formation is the most significant lignite-bearing formation with thickness of 250-400 meters. Five lignite seams (J, K, Q, R, and S) are also found in this formation. It is composed of lignite seams and gray to greenish-gray claystone and mudstone. The Huai King formation is a fluvial sequence consisting of semi-consolidated fine to coarse sandstone, claystone, mudstone, and conglomerate with green, yellow, blue, and purple color with thickness varying from 15 to 150 meters. This geological formation occurs within both the Western and Eastern sub-basins, being widespread to the south, and extends beneath the basaltic lavas of the southern Mae Moh Basin [6].

The groundwater problem at Mae Moh mine has drawn attention as the mining excavation goes deeper, thus resulting in detailed investigation of hydrogeological condition. The Huai Luang formation contains sands that are minor local aquifer zones. The clays swell when wetting and can cause severe drilling problems in the upper portion of drill holes. The Na Khaem formation is the main confining layer for the underlying Huai King and basement formations and is thought to form an effective low-permeability confining aquitard. The Huai King formation was thought to be a major aquifer at the base of the tertiary succession. The basement rock layer below the Huai King formation is complex, thus making it difficult to differentiate the formation. The detailed structure of the basement formations has not been not well understood. The rocks are extensively folded and faulted, and there are not enough data to fully define the structure and detailed lithology under the central basin area. Aquifers are only present in the basement formations because of secondary structures, fault after Triassic formation and cavity in limestone formation [14]. The Basement formation was group of Triassic rock compose of Tr1 - Tr5. The main aquifer was limestone layer (Tr4) in karst topography and argillite and sandstone layers (Tr3) in which the water seeps in the fractures and weather zone.

Rainfall

There are five gauging stations installed at different locations to gather the amount of precipitation in Mae Moh mine as presented in Figure 2. The precipitation data at the gauging station were used to examine the hydrological condition for the open pit area. The rain gauge, which is also known as precipitation gauge or pluviometer, can measure the amount of rainfall, and these data were transmitted to the base station through the radio telemetry system. The ID of the gauging stations shown in Figure 2 is the overview of the gauging station around study area. This representative data are calculated from the average of five gauging stations named RUM#6, RUM#3, RUM#5, RUM#7, and RUM#2. Histograms of annual rainfall data recorded from 2005 until 2012 in Mae Moh mine are presented in Figure 3. The maximum amount of rain precipitated in the late rainy season of

September and the minimum in the early year of February. Records of the 8-year period point out that the Mae Moh basin received the majority surface runoff with the highest rainfall of 2,155 mm in 2011 and the lowest rainfall was 825 mm in 2012. The average annual rainfall was about 1,316 mm.

Observation Wells

Groundwater is one of the most critical factors in slope stability problem. This groundwater primarily originates from rainfalls. Some water infiltrates into the ground and percolates downwards to the phreatic zone, while some flows over the surface as surface runoff. Some amount of groundwater in the saturated zone might move toward the pond. Figure 4 illustrates the observation wells installed at different locations in Mae Moh coal lignite mine. Numerous borehole logs associated with the groundwater drilling investigations have been recorded over Mae Moh lignite mine and in the open pit area. The hydraulic parameter testing methods used for this study are pumping test, air lifting test, falling head test, and flow recession test. The field monitoring program for groundwater bores started from the first completed groundwater bore in the Mae Moh basin. This program continued through the drilling and testing program and is still continuing. It consists of a regular monitoring routine such as groundwater level measurements, discharge rate measurements for artesian bores, groundwater sampling, and groundwater temperature.

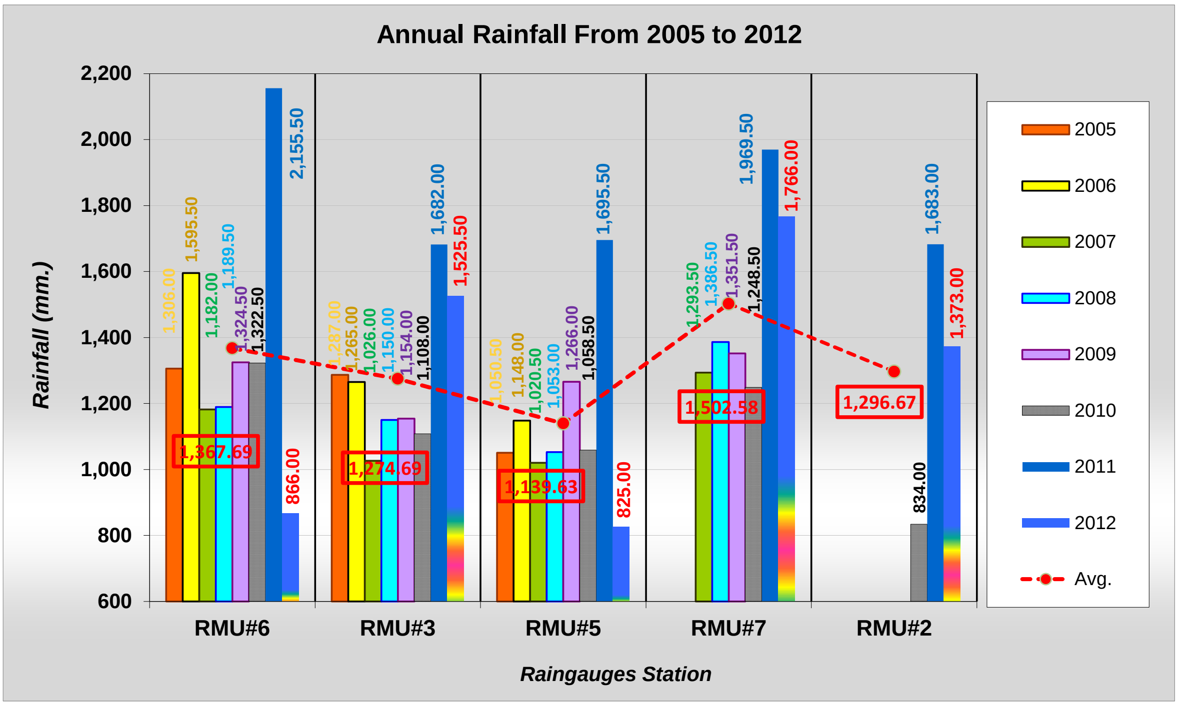

Figure 3. Average of annual rainfall data (Courtesy of EGAT)

Surface Water

Figure 5 shows the discharge of surface water, e.g., through drainage pipes to stabilize slopes, which will be later collected into the sump as shown in Figure 6. The pH, electrical conductivity (EC), total dissolved solid (TDS), and salinity of water taken from the Sump 1C1 using PCTestr 35 (Eutech Instruments) are reported in Table 2 (as of 2010 and 2012). Field measurements reveal pH level at 8 and a range of TDS at 870-2020 ppm (parts per million or mg/L) due to sulfate. The surface water is pumped to the settling pond and wetland for treatment.

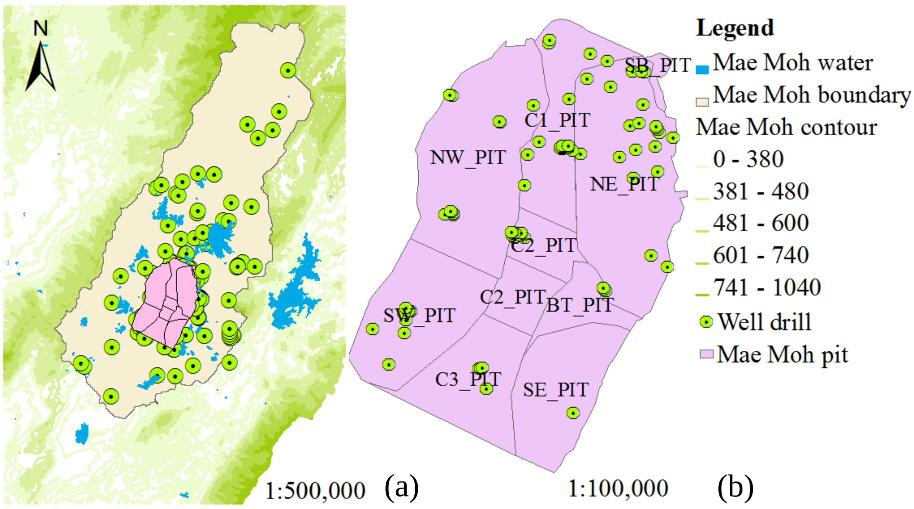

Figure 4. Observation wells (a) outside open pit area (b) inside open pit area (Reproduced from EGAT)

Underground Water

The underground water influences the magnitude and extent of strata depressurization, which have a potential impact on the Mae Moh area. Figure 7 shows a pumping well with a pipe feeding underground water to the collecting sump (20,000 m^3) as shown in Figure 8 before pumping to the holding pond (lined by plastic-sheet) of the water treatment plant. According to Pongpanlarp (2007) [8], the hydrologic stratigraphy from top to bottom of the Mae Moh basin is summarized in Table 3.

Table 2. Field Measurement Conducted on September 23, 2010 and October 31, 2012

Year	pH	Conductivity dS/m	Total Dissolved Solid ppm	Salinity ppm	Temperature °C
2010	8.0	1.24	873	576	35.0
2012	7.8	2.31	1660	1190	32.1
2012	7.8	2.85	1990	1420	31.6
2012	7.8	2.90	2020	1450	32.7

Figure 5. Discharge of surface water through drainage pipes

Figure 6. Sump and pumping platform at Sump 1 C1

Figure 7. Pumping well with pipe

Figure 8. Collecting sump (20,000 m^3)

Groundwater Model

Conceptual Model

This research essentially concentrates on the modeling of groundwater pressure effect against floor heaving. The input data from groundwater model were required to be reviewed and identified from site investigating. Based on 40 year old power plan of Mae Moh mine, the critical area in the year 2007 was situated in N30-N50, W35-W0 in mine grid. Therefore, the modeling was focus on this critical area. The conceptual model was designed as a fundamental graphical illustration of multiple layers of the natural aquifer system within the model boundary. The components of the conceptual model involved with the determination of model boundary and properties of the aquifer system. Generally, the conceptual model is considered as the overall purpose of the groundwater modeling. A 3D geological stratigraphy of groundwater model is presented in Figure 9. In order to simplify the model, quaternary, Huai Luang, and Na Kham formation were grouped as one layer and followed by the Huai King Formation. The basement was divided into three layers. The model comprises of three aquifers and one aquitard as illustrated in Table 4. Because material and hydraulic properties of Quaternary, Huai Luang and Na Kham are quite similar; therefore these formations were grouped together for the sake of simplification of groundwater modeling.

Table 3. Characteristics of Hydrologic Stratigraphy of the Mae Moh Basin [8]

Layers	Characteristics
Quaternary deposit	This unsaturated layer of 20 m is mostly deposited in the Mae Moh basin with water table nearly parallel to its topography. Alluvium sand and gravel partly appear.
Huai Luang formation	This semi-consolidated red-brown clay with thickness of 170 m is generally considered as aquitard despite the existence of minor local aquifer zone due to sand.
Na Khaem formation	This saturated layer with thickness of about 5-300 m is considered as local minor aquifer. Some faults/joints passing the Na Khaem formation to basement formation might cause floor heave and stress release due to high underground water pressure.
Huai King formation	This semi-confining layer above the basement formation is considered as major aquifer with thickness of about 40-230 m. The water head in sand layer is 20 m above the ground level; therefore, dewatering is required.
Basement formation	This major aquifer has thickness of about 10-1,000 m. Limestone layer is an important aquifer.

Model Domain and Grid Design

The groundwater modeling of the C1 pit was established using the Modflow package (GMS 9.1, Aquaveo). The model boundary was defined as 3.5 km × 2 km, which were split into 9 material types and grid cell of 100 rows, 190 columns, and 15 layers. The model configuration was formed based on the conceptual model, which was principally reviewed from the past investigations [6, 8].

Material Properties

Many field investigations especially pumping tests were conducted in Mae Moh mine by EGAT. Therefore, the initial hydraulic properties of groundwater modeling were based on their results of field investigations. These parameters were modified accordingly within acceptable range for model calibrations. In order to define the hydraulic properties of the Huai King and basement formation, numerous field tests were investigated during Phase 2 groundwater studies program of Mae Moh mine. An additional underground field investigation was also conducted from 1994 to 1996. The hydraulic conductivity and specific storage values after the model calibration were assigned as shown in Table 5. The hydraulic conductivity and the storage properties were adjusted during the steady state calibration and transient state calibration. The parameters adjusted for all nodes. First, the aquifer properties were correlated with the standard aquifer properties of each rock according to Freeze and Cherry [15] and adjusted with result of aquifer properties from the monitor wells. The computed potentiometric heads were compared with the observed heads in order to get acceptable results. The variation of aquifer parameters during model calibration was adopted in the range of standard values from Freeze and Cherry [15]. The final values were in the acceptable range.

Table 4. Geological Units in Conceptual Groundwater Model

Formation		Hydrostratigraphy
Quaternary Huai Luang Na Kham	UB Claystone	Aquitard
Huai King	Semi-consolidated	Aquifer
Basement	Limestone	Aquifer
	Sandstone Argillite	Aquifer

General Head Boundary (GHB)

The GHB is head-dependent recharge or discharge across an aquifer boundary. Proper boundary conditions were defined for mathematical computation according to the potentiometric head distribution along the boundary of the model. The general head values of the hydrographs from observation borehole logs along the model domain boundary were selected for GHB. Specifically, the GHB conditions were defined only to the Huai King Formation, basement formation, and free flow in the pumping well PA12B (Figure 10). The increase in heads is not due to increasing recharge rates from the regional recharge zones during the observation period. There is no significant influence of regional groundwater on the head of the study area because the model was focus on the basement formation underneath a very thick layer of the claystone which consider as aquitard zone. The hydrology of the model (study) area is not related to the regional flow patterns because below the basement formation is bedrock with consider as aquitard. There is no flow due to recharge but there is flow due to discharge caused by wells.

Initial Piezometric Heads

The starting piezometric heads of all layers were specified as +300 meters above mean sea level. The values of starting head were assigned according to the starting head from the past research in 1994 as illustrated in Figure 11 [7]. This procedure is conducted for steady state calibration simulation. The computed results of piezometric heads from steady state calibration were applied as starting piezometric heads for the transient calibration for both modeled calibration and prediction. Figure 11 shows that groundwater from the northeast and western sides of the model area seem to be recharging the mine site. These groundwater zones with high potentiometric surfaces provide the upward movement underneath the mine pit.

Table 5. Modeled Hydraulic Parameters (After Calibration)

Description	k_h	k_v	k_h/k_v	S_s	S_y	Porosity
	m/s	m/s	-	1/m	-	-
Claystone1	$1.00{\times}10^{-07}$	$1.00{\times}10^{-08}$	10	0.0093	0.001	0.1
Claystone2	$1.00{\times}10^{-07}$	$1.00{\times}10^{-08}$	10	$2.4{\times}10^{-05}$	0.01	0.1
Huai King1	$1.16{\times}10^{-06}$	$1.16{\times}10^{-07}$	10	$2.4{\times}10^{-05}$	0.01	0.1
Argillite1	$5.78{\times}10^{-06}$	$5.78{\times}10^{-07}$	10	$5.30{\times}10^{-08}$	0.001	0.1
Argillite2	$1.57{\times}10^{-06}$	$1.57{\times}10^{-07}$	10	$7.00{\times}10^{-06}$	0.001	0.1
Limestone	$5.787{\times}10^{-05}$	$5.79{\times}10^{-06}$	10	$5.60{\times}10^{-07}$	0.001	0.1
Fault1	$1.00{\times}10^{-09}$	$1.00{\times}10^{-10}$	10	0.0001	0.001	0.1
Huai King2	$1.70{\times}10^{-08}$	$1.70{\times}10^{-09}$	10	0.0001	0.02	0.1
Fault2	$1.00{\times}10^{-04}$	$1.00{\times}10^{-04}$	1	0.0001	0.02	0.1

Notes: k_h is horizontal hydraulic conductivity, k_v is vertical hydraulic conductivity, S_s is specific storage, and S_y is specific yield.

Model Simulation

Model simulation were operated using the Modflow package in order to examine the groundwater flow behavior of the layer comprised of limestone in the basement formation in the C1 pit. The simulations divided into two steps such as calibration and prediction. Specifically, steady state and transient simulation were adopted for groundwater modeling based on the available input data from the conceptual model.

Observation Well of Groundwater Model

Observation wells were used for calibrating the model both steady state and transient conditions. This calibration was carried out by using the potentiometric head distribution of 12 observation wells within the model domain as illustrated in Figure 10 and Table 6. The average value of potentiometric heads from the observation wells was utilized for the steady state calibration. On the other hand, the transient calibration was operated by using the variations of potentiometric heads over time. The role of theses observation wells were to match between the observed head and the computed head around the model boundary. Deep observation wells have been established since 1989 in the critical areas of floor heaving effect to draw down high water pressure of local sand aquifers and major aquifer zones in limestone. The observation wells outside the mine area are referred to indicate the regional flow.

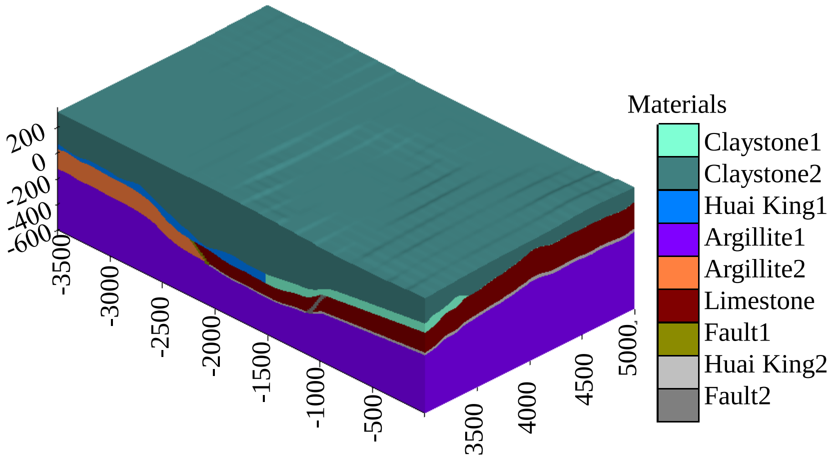

Figure 9. 3D Geological stratigraphy of groundwater model

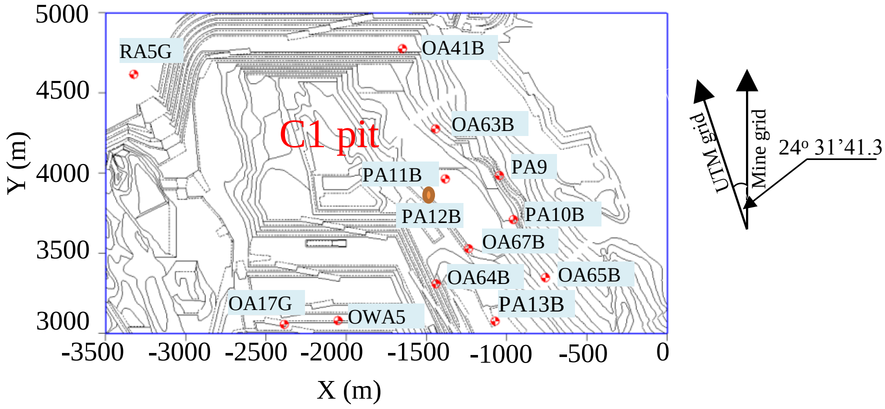

Figure 10. Observation wells used in the model calibration for steady-state and transient condition, pumping well (PA12B), and mining plan in 1998 used as background

Table 6. The Formation Lithology of Observation Wells

ID	Formation lithology		
PA9	Limestone	OA17/2G	Sandstone
PA10B	Limestone	OA64B	Limestone
PA11B	Limestone	OA41B	Limestone
PA13B	Limestone	OA63B	Limestone
OWA5	Limestone	OA65B	Limestone
RA5G	Argillite	OA67B	Limestone

Model Calibration

In order to assign the hydraulic properties from the initial model parameters, the calibration is adopted to process the initial model parameters. Those parameters for the calibration were hydraulic properties, and boundary conditions to obtain a suitable agreement between the computed and observed results of the groundwater flow system [16].

The model calibration was achieved both for the steady state simulation and transient simulation. Specifically, the calibration is the process of modifying or improving the input data to reach the acceptable agreement between the model simulation and the observed data in groundwater flow system [17]. Hence, the aim of calibration is very important for the model simulation to reach the suitable approximation of real and computed head distribution of the C1 pit. The trial and error were operated until the acceptable results were met for all calibrations.

The model calibration was assessed using the specified statistical criteria such as (i) high magnitude of R^2 values, (ii) low value of root mean square error, and (iii) low percentage value of relative root mean square error.

The formula of root mean square error (RMSE) and relative root mean square error (RRMSE) [18] are shown below:

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Y_i - X_i)^2} \quad (1)$$

$$\mathrm{RRMSE} = \frac{100}{\overline{X}_i}\sqrt{\frac{1}{n}\sum_{i=1}^{n}(Y_i - X_i)^2} \quad (2)$$

where Y_i and X_i are the predicted and observed values, respectively; X_i is the observed mean value; and n is the number of samples.

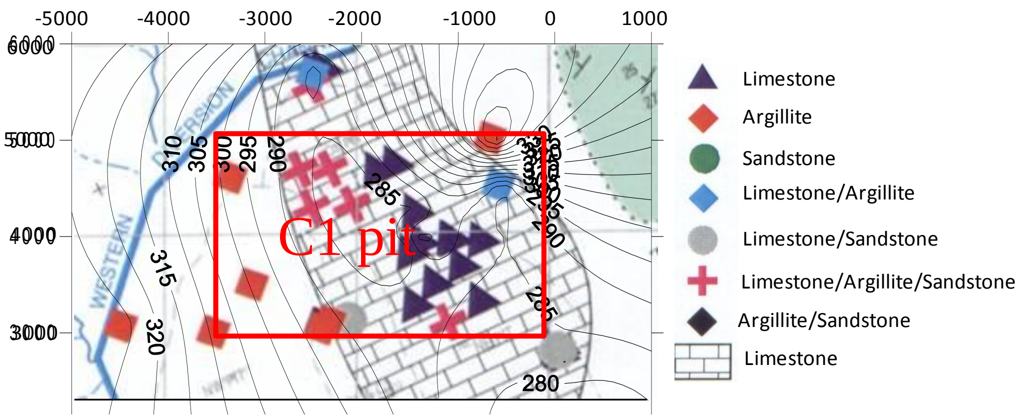

Figure 11. Initial head condition of Mae Moh mine in 1995 (Courtesy of Electricity Generating Authority of Thailand, EGAT)

Steady-State Calibration

The steady state calibration was performed to balance the observed potentiometric head distribution by presuming that there is no pumping condition. The potentiometer heads of each observation were averaged for steady state calibration. Steady state model calibration was conducted to obtain starting head for transient model calibration. Steady state calibration was successfully accomplished by adjusting the input aquifer parameters and boundary conditions using several trial and error methods.

Figure 12 demonstrates the scatter plots between the computed and observed head values. The observed heads were on the x axis, while the computed ones were on the y axis. Each of the scatter points on the x axis depicts the potentiometric heads from the observation well data. The points which represent the best calibration should be in a minimum level of scattering. This implies that the point should be neighbored to the diagonal line of perfect fit through the origin. The result reveals that the computed heads are in an acceptable agreement with the observed heads as the data points were almost located on the diagonal line, having RMSE=2.74 m and RRMSE= 1.20%.

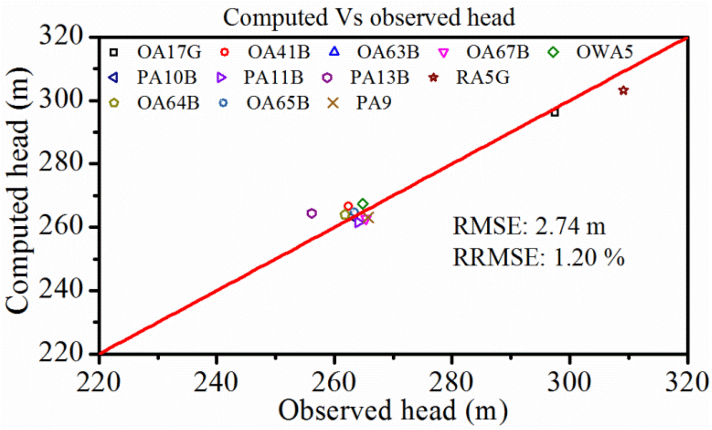

Figure 12. Ground water flow modeling: Steady-state calibration

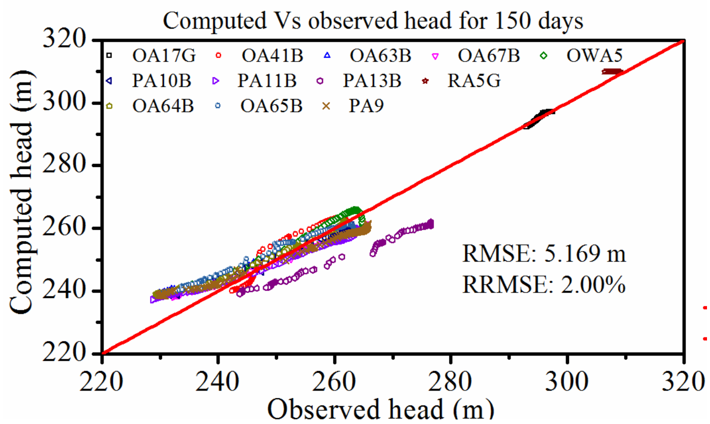

Figure 13. Ground water flow modeling: Transient calibration

Transient Calibration

Even though the steady state calibration could be used in modeling practice, a transient calibration should be conducted because groundwater flow behavior is varied by nature and frequently by human activities. Thus, the transient calibration must be operated after the steady state calibration to obtain practical model simulation. The computed heads were compared with the observed heads during transient calibration for 150 days. Also, the trial and error method were operated to achieve the model in order to minimize the difference between the computed and observed heads. At this process, the aquifer parameters were adjusted within an acceptable range. Some input parameters were not adjusted at the same time for the model simulation as they may affect the model simulation. The prediction might not able to identify to reach the final result. As mentioned, the resulted head distributions from steady state calibration were used as the starting potentiometric heads for transient calibration. As shown in Figure 13, the transient calibration was successfully met the requirement of statistical criteria with RMSE=5.169 m and RRMSE=2.00%. Hydrographs of the observations wells display an acceptable agreement between the observed and computed potentiometric head distribution during the simulation period of 150 days. The computed and observed heads were slightly different because the input aquifer properties were slightly different from the actual properties which are very difficult to determinate precisely.

Model Prediction

After the model calibration was completed, the ground-water simulation was conducted to predict the potentiometric the head distribution in the groundwater modeling. The simulation was applied particularly at time interval for eight years. Because this model prediction was conducted according to past study of Pongpanlarp [8], the GHB conditions and observation wells were up to year 2007. Therefore, the model simulation was done for eight years (2007-2015). Several assumptions were used for model simulation such as no change in soil stratigraphy, hydraulic parameters, and GHB condition.

Table 7. Performance of Water Treatment Plant of Mae Moh Lignite Mine (as of 2013) (Sourced from the Data of Mine Environmental Management Department, EGAT)

Maximum capacity	12,000 m^3/day
Amount of ferric chloride	1,000 kg/day ($FeCl_3$ 40% w/w 1.8 m^3/day)
Dry weight of sludge	800 kg/day
Treatment efficiency	greater than 95%
Cost of treatment	3 Baht/m^3 (about 9 JPY/m^3 or 0.10 US$/$m^3$)
Inflow of arsenic	200-500 μg/L
Outflow of arsenic	less than 10 μg/L

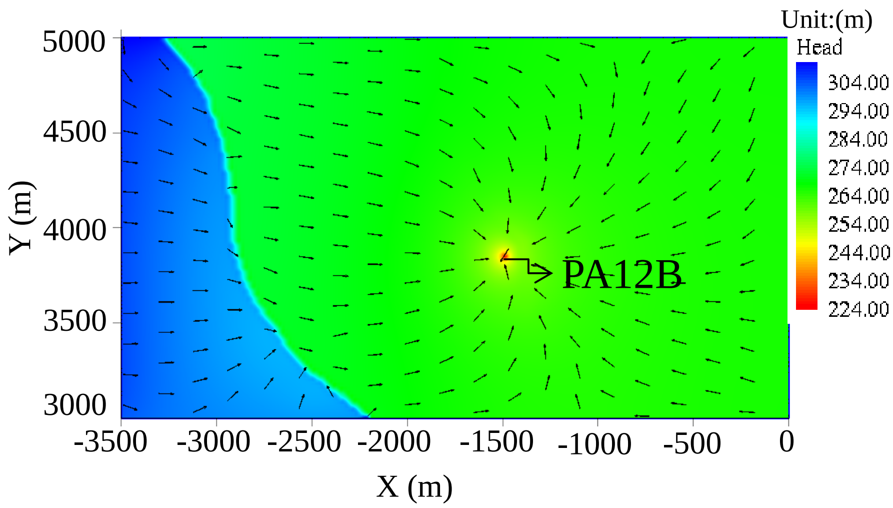

Figure 14. Steady-state simulation of head distribution on top limestone layer

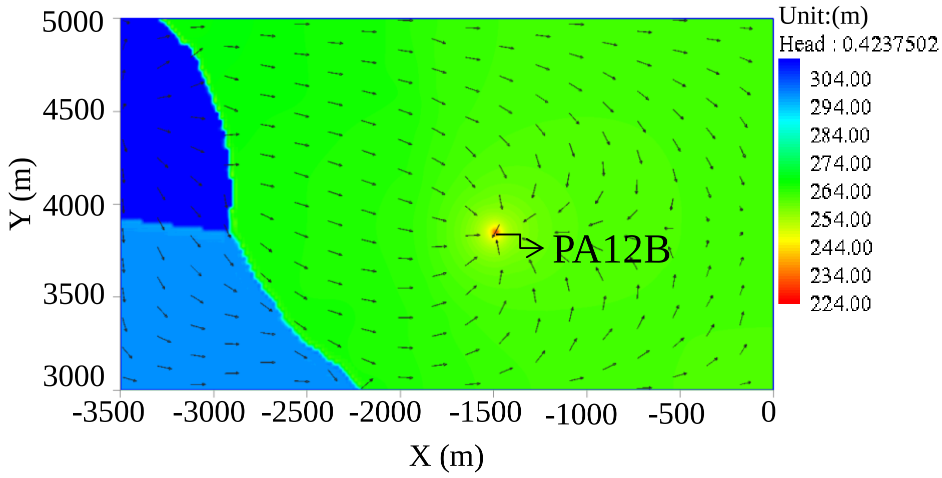

Figure 15. Transient simulation of head distribution in 2007 on top limestone layer

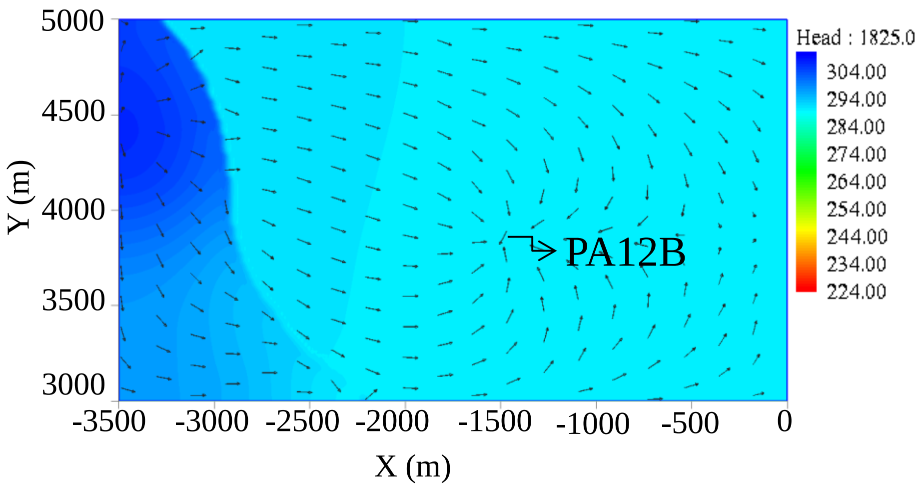

Figure 16. Transient simulation of head distribution in 2012 on top limestone layer

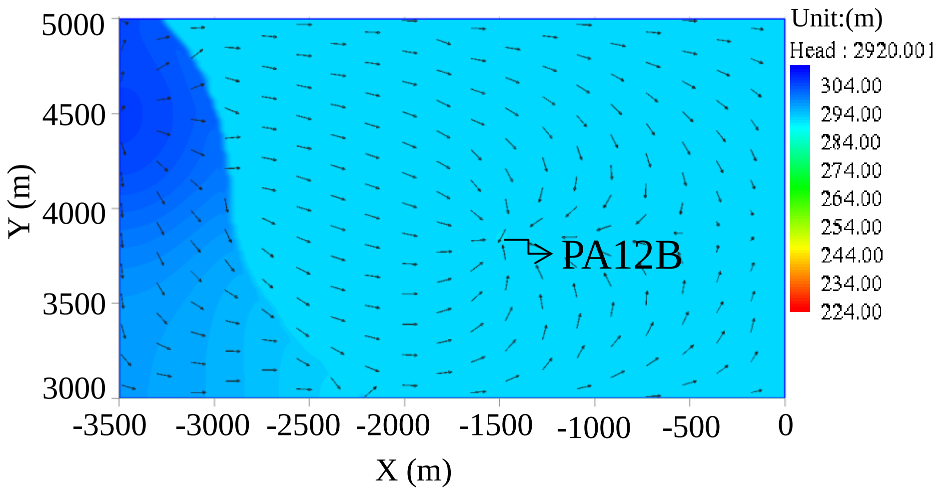

Figure 17. Transient simulation of head distribution in 2015 on top limestone layer

The result of potentiometric head distribution on the top limestone layer obtained from the steady-state calibration is presented in Figure 14. The potentiometric head varies from 224 m to 310 m. The simulated groundwater flow direction is from northwest toward the center of the basin. The potentiometric head is very low around the pumping well (PA12B).

Figure15–Figure17 illustrates the predicted potentiometric head distributions in the basement formation (top of limestone) in different time steps during 2007 to 2015. The results revealed that the potentiometric head level strongly increased during 2007-2012 (Figure 15 and Figure 16), which might be a potential for floor heave; thus, depressurization is required. In addition, the potentiometric head is gradually increased until 2015 (Figure 17). The dewatering plan was operated to pump out the underground water to decrease the deep ground water pressure head to +200m MSL. This operation was established using three wells × 4,000 m^3/day = 12,000 m^3/day in total during 2007–2012 as the minimum specification according to the studies of Pongpanlarp [8]. Therefore, studies of groundwater flow against floor heaving are needed because of deeper excavation. The dewatering plan is needed to establish after current plan (2007-2012) because the potentiometric head was gradually increased until 2015.

Water Treatment Plant

Arsenic (As) is a toxic metal that naturally appears in groundwater as oxyanion compounds. The arsenic removal mechanism is explained based on the report/data of the Mine Environmental Management Department, EGAT [9]. The water treatment plant utilizes the chemical process to remove the existing arsenic in the underground water. The process starts from the pumping of underground water from the collecting sump to the holding pond and then pumping water to rapid mixing tanks for the pH adjustment process using sodium hydroxide, followed by the reaction tank where the ferric chloride ($FeCl_3$) is reacted by the following equations. Note that the pH of Mae Moh underground water is usually around 7.5-8.5; therefore, NaOH is practically unused in the water treatment process of Mae Moh mine.

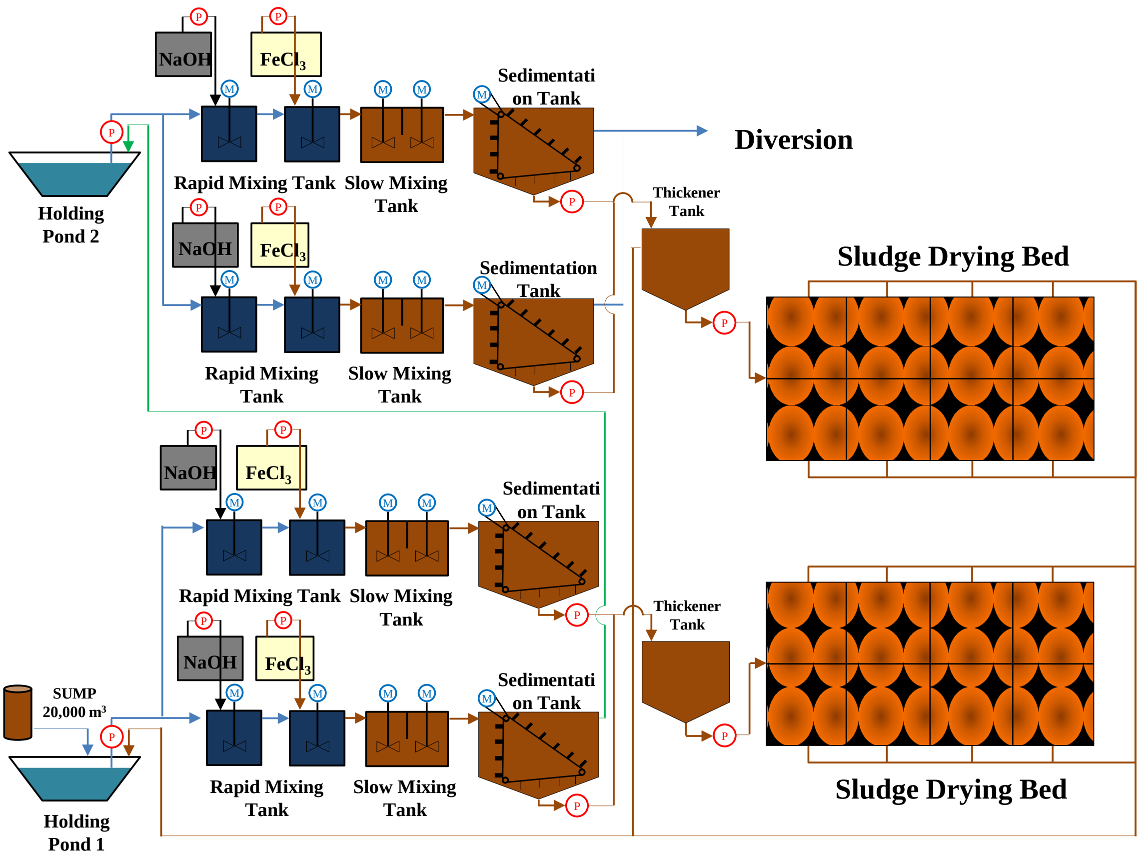

Figure 18. Flow diagram of water treatment plant of Mae Moh lignite mine (as of 2013) (Reproduced from the chart of Mine Environmental Management Department, EGAT)

$$FeCl_3 + 3(H_2O) \rightarrow Fe(OH)_3 + 3H^+ + 3Cl^- \quad (3)$$

$$Fe(OH)_3 + HAsO_4^{2-} + 2H^+ \rightarrow FeAsO_4{\cdot}2H_2O + H_2O \quad (4)$$

After the process, the water will be flowed out to the slow mixing tanks to collect the precipitated arsenic compounds before flowing to the sedimentation tanks to collect the sediments deposited at the bottom of the tanks. The water will be pumped to sludge thickening tanks and then pumped to sludge drying beds. The clear water on the upper portion will be spilled over the system for diversion to the outsides. Details are described in Table 7 and Figure 18. Though amount of surface water seasonally changes, there is no influence of seasons to the running condition of the water treatment facility as the water is pumped from the sump and keeps in the holding pond before feeding water to the water treatment plant. The water treatment plant is fully operated. Therefore the amounts of ferric chloride (0.01% by volume of water treatment), arsenic concentration or treatment efficiency are almost constant all year round.

Conclusions

The study of underground mining resulting from field investigation was reported. The study reveals that the underground water influences the magnitude and extent of strata depressurization, which have potential impact on the Mae Moh area. The monitoring program of underground water is necessary to preserve long-term usage of the lignite mine. The potential of floor heaving in the C1 pit has been examined using a 3D groundwater model with three aquifers and one aquitard. The analysis of floor heaving was carried out before, but in the paper we aimed to report not only the groundwater modeling but also the groundwater treatment plant. Further publication reporting the evaluation of floor heaving will refer to the groundwater modeling reported in this paper.

The treatment efficiency study showed that more than 95% of the arsenic can be successfully removed using ferric chloride. To make some water quality parameters conformable to the Thai stream standard, the arsenic concentration remains below 10 μg/L after treatment. The arsenic removal process and the performance of water treatment plant at Mae Moh mine could provide assurance to the community that this potential risk has been minimized. In geotechnical engineering viewpoint, the site perfectly shows how stability can be linked to the water environment.

For general viewpoint, this site shows a good example of how the geotechnical engineering problem can be linked to the environmental engineering problem. Therefore, we can realize that a solution to one problem might cause another problem and engineers/experts in different fields are required to work together, share data and exchange opinions. The scope of this paper is to develop the 3D groundwater modeling for future planning as well as the field report of water treatment plant. The water balance analysis to show the relationship of rainfall to the other major processes (runoff, infiltration, evaporation) in the basin and hence possible recharge to the groundwater should be considered for further study. In addition, the effect on the piezometric head upon removal of the overburden through mining through the years could also be considered for future research.

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