Hydrogeologic Modeling to Improve Pit Slope Stability

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Abstract
An open-pit porphyry copper mine that has experienced periodic pit slope failures. In this pit and many others, slope stability is largely dependent on the management of mine water. Tetra Tech created an integrated groundwater model and slope stability analysis model that developed the best mine water control practices and proposed innovative management of an existing drainage gallery. Using these practices, slopes could be safely steepened from 26.5 degrees to 40 degrees in a large portion of the pit. Changing the slope angles would save the removal and disposal of millions of tonnes of waste rock.

Introduction
An open-pit porphyry copper mine located in Eastern Europe has experienced periodic pit slope failures. In this pit and many others, slope stability is largely dependent on the management of mine water due to the relationship between pore water pressure and their strength. Saturated, undrained materials have significantly lower effective strength due to water pressure within soil pores and water lubrication between soil particles. As a result, the client contracted Tetra Tech to evaluate the mine water management system and site hydrogeology to determine if improvements in water management could result in more stable slopes and steeper pit slope angles.

The investigation covered the following tasks:

- Site hydrogeologic characterization;
- Construction of a site wide predictive groundwater model;
- Predictions on various dewatering techniques in and around the pit;
- Recommendations on groundwater management options;
- Evaluating the factor of safety of different pit slope angles in different sectors of the mine pit; and
- Recommending new pit slope angles based on the results of the modeling.

Evaluation of Geologic Conditions
The mine is located in a hard-rock groundwater system with groundwater carried in the fractures and the matrix of three main rock types: propylite, argillite, and quartzite. All of these rock types represent different degrees of hydrothermal alteration to porphyry rocks and are described in detail below.
Propylite is a hydrothermally altered igneous rock associated with the porphyry copper deposit. It is typically associated with developments of chlorite, albite, epidote, and calcite. This is the rock type that is dominant in the area of the mine. Argillite is a metasomatically altered granitoid with the predominant mineral assemblage having been altered to clay minerals. This rock is moderately to strongly altered and is typically fairly strong, but when it is saturated, it loses a great deal of strength. The local Quartzite is a quartz-sericite altered granitoid which is moderately altered and forms a relatively strong rock unit.
Numerous faults and fractures exist in the model area. Major faults north and south of the mining pit strike roughly east-west. These faults separate the ore-bearing material from the surrounding rock. Field observations revealed that all site fractures contain low-conductivity clay gouge and act as barriers to groundwater flow.

Near the pit, faults have two functions:

- They can reduce the inflow to the pit from lateral groundwater flow (as they do on the north side of the pit); and
- They build water pressure on the upgradient side (as they do in the west and south side of the pit).

The further impacts of faults on slope stability are addressed below. No open, conductive fractures were observed in the pit. As a result, all faults are assumed to be barriers to groundwater flow rather than conduits for groundwater flow.

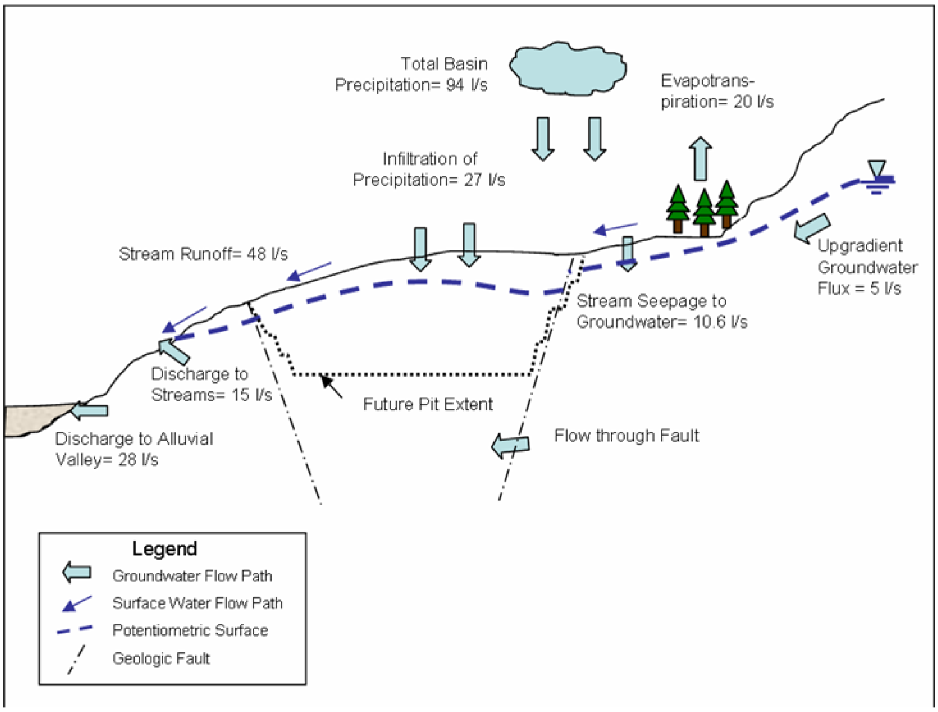
Problem Definition

The characterization of the geologic and hydrogeologic conditions revealed that the pit slope failures were due to excessive moisture in the pit walls with a high argillic alteration. The project therefore focused on how to better manage the pit dewatering system to minimize the moisture content of the pit walls. Computer modeling predicted the impacts of mine water management techniques, and pit slope stability modeling determined the new safe pit slope angles considering the reduced phreatic surface location predicted in the groundwater model.

Groundwater System Characterization

Figure 1 shows the groundwater system prior to mining.

***Figure 1** Groundwater System Schematic Prior to Mining*

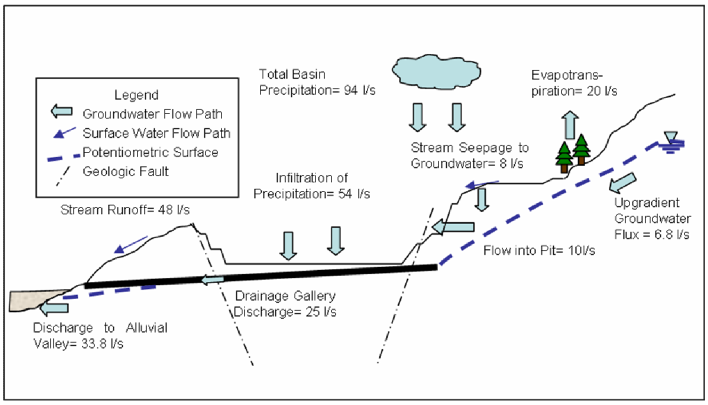


Groundwater originates as precipitation that seeps into rock fractures and the rock matrix, travels downgradient to eventually discharge into surface water or into valley fill porous media aquifers. Streams in the upper portions of the basin are ephemeral and contribute seepage water to the groundwater system, whereas, lower in the basin, the water table intersects the stream channels and groundwater discharges to streams. Trees and other vegetation consume groundwater, and 50 percent of the total basin precipitation runs off as surface water. Faults act as aquitards, but have a limited impact on the groundwater system prior to mining other than to hold a higher potentiometric surface on the upstream side of the fault.

Figure 2 shows the groundwater system during mining. A drainage gallery dominates the mine water conditions and is the only functioning dewatering mechanism for the mine.

As mining proceeds, the depth of the pit will cut into the drainage gallery, rendering it largely useless in removing water from the deepest portions of the pit. Tetra Tech observed that during the site visit, the in-pit mine water control system of sumps and trenches was not properly maintained. As a result, the pit had abundant pooled water that complicated operations and increase the moisture content of the pit slope materials.

Figure 2 Groundwater System Schematic During Mining



Groundwater Modeling

Tetra Tech created a three-dimensional groundwater model using MODFLOW-SURFACT to predict the impact of better mine water management on the potentiometeric surface and the moisture content of the pit walls. The model accounted for the site geology, the mine plan, and the drainage gallery. During the site visit, Tetra Tech observed that the drainage water collection pipes that were drilled horizontally out from the drainage gallery under the pit footprint were clogged with ferric oxide precipitates that substantially reduced flow. Therefore, modeling focused on the following water control techniques:

- Cleaning drainage gallery drainage pipes to improve inflow;
- Expanding the length and number of horizontal borings in the drainage gallery;
- Draining pit slopes using horizontal and/or vertical wells; and
- Improving the in-pit water capture system.

Modeling proved the effectiveness of the combination of all of the above except vertical wells, which were ineffectual due to the low conductivity of the geologic formations. The best method resulted in at least a 50 meter drawdown above the "no action" alternative. This changed the phreatic surface and the associated moisture content values for the pit slope materials which was used as the input for pit stability modeling.

Slope Stability Modeling

In general, the main pit has been excavated through a large, fault-bound body of propylitic alteration. The main structural bounding faults trend generally east-west exposing the propylitically altered zone in the south pit wall and scattered bodies throughout the remainder of the pit. Locally, there are small bodies of argillite which, when saturated, behaves more like a weak clayey-soil than a rock material. Based on the bench geology sections, there is also some unaltered country rock exposed in the northern pit wall. Recently, a slope failure occurred in the southeast section of the pit incorporating a zone of the weaker argillite and likely a shear zone.

The three distinct rock types, or structural domains, used to define the open pit mine sectors and the strength of the geologic units described above are as follows:

- Domain I or Strong rock consisting mainly of propylitically altered country rock;
- Domain II or Moderate Strength rock comprised of a higher degree of propylitic alteration with secondary quartz intrusions; and
- Domain III or Low Strength rock consisting of argillized country rock.

Each of these rock types or domains is present in the pit. The physical relationships of each rock type as well as major fault locations were extracted from bench geology maps provided by mine personnel.

Slope stability analyses were conducted along two cross-sections through the mine pit; one from north to south, and another from east to west. The purpose of these two sections was to effectively divide the pit into quadrants, or sectors, and isolate some of the assumed problem areas. Recommendations for pit slope angles are provided by quadrant.

Table 1 shows the material properties. Most of these values come from prior soil testing, but reduced cohesion in the Domain III material was set such that a back-calculated value for the material in the southern pit slope failure would fall within one standard deviation of the mean.

Table 1 *Slope Stability Material Properties*

Material	**Unit Weight (kN/m^3)**	**Mean Angle of Internal Friction (deg.)**	**Standard Deviation (deg.)**	**Mean Cohesion (kPa)**	**Standard Deviation (kPa)**
Domain I – Strong Rock	24.6	44.5	2.9	840	139
Domain II – Moderate Rock	24.6	32.4	4.7	470	127
Domain III – Weak Rock	22	30	5	50	20
Fault Zone	20	17	N/A	0	N/A

Slope stability evaluations were conducted using Slope/W, a limit equilibrium software package developed by GEO-SLOPE/W International, Ltd. This analysis tool generates thousands of probable failure surfaces based on user input and associated material properties to converge on a critical failure surface. These analyses were performed on two-dimensional cross-sections of the pit slopes adopting the Spencer method of slices which satisfies both force and moment limiting equilibrium. Additionally, the critical slip surface searches were evaluated using Monte-Carlo-type probabilistic analyses which varies user input parameters around the mean input values and adjusts the factor of safety of critical slip surfaces accordingly.

Modeling demonstrated that under baseline conditions, whereby no changes are made to the current ground water control techniques, slopes in the eastern quadrant of the pit developed through the year 2009 at 18-22 degree slopes will likely not remain stable. Modeling also showed that using best management practices for pit dewatering, the slopes could be significantly improved. Table 2 shows the new recommendations for slope angles based on improved water control techniques.

Table 2 *Pit Slope Recommendations*

Parameter	**Quadrant I (315° to 60°)**	**Quadrant II (60° to 135°)**	**Quadrant III (135° to 225°)**	**Quadrant IV (225° to 315°)**
Maximum Slope Height	305m	240m	270m	300m
Inter-ramp Angle (ratio)	45° (1h:1v)	40° (1.2h:1v)	40° (1.2h:1v)	45° (1h:1v)
Bench Height	15m	15m	15m	15m
Bench Face Angle	60°	60°	60°	60°
Berm Width	6.34m	9.22m	9.22m	6.34m

This significant increase in the slope angles would save the removal and disposal of millions of tonnes of waste rock. In addition, better mine water management would save operational costs by reducing pumping requirements, decrease maintenance requirements on haul roads, and improve mine safety.