Importance of pore pressure monitoring in high walls

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Synopsis

Groundwater and associated pore pressure represent elements that can have a negative impact on surface mining and slope stability. Groundwater flow and deformation within a slope influence each other. An increase in pore pressure will result in a decrease of effective stress; and conversely, if the pore pressure decreases, the effective stress increases. Slope analysis and slope design calculations require good information on pore pressure distribution around an open pit excavation. Until recently very little pore pressure data were available and assumptions had to be used.

Location and design of measuring points depend on geological and structural setting, geotechnical domains and practicality. Good planning and the use of sensitive point piezometers to measure *in situ* pore pressures means that real-time data can be collected and used for the construction of flow nets, the determination of pore pressure distribution around an open pit mine, the validation of the dewatering/depressurization requirements, the calculation of the efficiency of the dewatering system and finally the use of pore pressure data in slope stability analysis. The recommended layout for a monitoring system, types and design of piezometers, data collection and use of the pore pressure data are presented.

Introduction

It is commonly accepted that groundwater has a detrimental effect upon mining. The presence of groundwater in and around an open pit excavation affects mining by reducing the stability of the slopes—due to the modification of shear stress on potential failure surfaces, accelerated weathering, blockage and wedging of fractures due to freezing, increase in transport costs due to increased weight of wet materials, high maintenance costs for transport equipment, increased pumping costs, increased blasting costs and the aggravation of working in wet conditions. This paper concentrates on the slope stability issues related to groundwater and gives a recommended methodology for the measurement and control of pore pressures in high-wall formations.

Pore pressures and effective stress

Volume deformation in a homogenous high wall, will present (under various pressures and stresses) as three possible scenarios:

(1) compression of water in the formation pores,
(2) compression of individual particles, and
(3) rearrangement of particles, usually to a more compact configuration.

The stress state in a slope at any point is governed by the principal stresses and the acting water pressure. Figure 1 shows a hypothetical plane drawn through a saturated medium.

The primary effect of groundwater pressures is through effective stress. Rearrangement of particles (aka failure) is caused by changes in the effective stress, and not by changes in the total stress. The stress state at any given point is governed by the principal stresses and acting pore pressure.

The Mohr-Coulomb equation derived from the Coulomb-Terzaghi Equation states:

$$\tau = (\sigma - p)\tan\phi = c \qquad [1]$$

where:

τ = shear strength,
σ = total normal stress
p = pore water pressure
ϕ = internal angle of friction.
c = cohesion

Strength comes from the cohesion and the weight of the formations and weakness comes from the pore water pressures and internal angle of friction. A reduction in the effective stress ($\sigma' = \sigma - p$) will reduce the shear strength of the rock mass. Therefore in stability analysis it is essential to know the distribution of pore pressures in the pit slopes.

Hydrogeological terms explained phreatic surface, hydraulic head and hydraulic conductivity

Figure 2 is a simplified diagram of ground-

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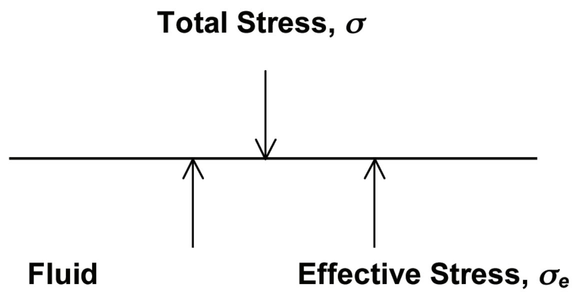

Figure 1—Directions of stress acting on a hypothetical plane

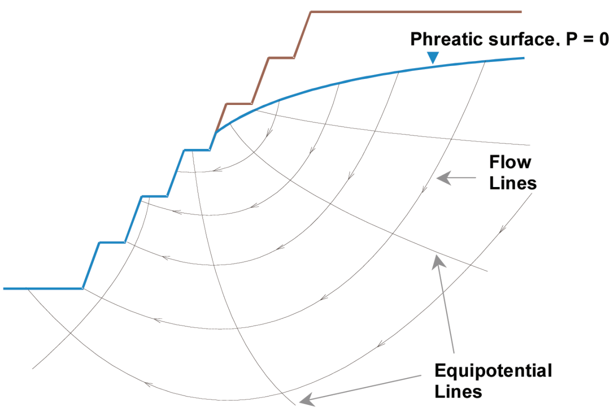

Figure 2—Groundwater flow in a slope (Atkinson, 2000)

water flow in a homogenous pit slope. The water flows from high to low hydraulic head.

The water table, or phreatic surface, is represented by the boundary line between the saturated and unsaturated formation, where pressure (p) is equal to zero, i.e. $P = 0$, for atmospheric pressure. The hydraulic head, h, measured at any given point, is the elevation head and the pressure head at that particular point.

$$h = h_p + h_z = \frac{F}{pg} + z \qquad [2]$$

where:

h = hydraulic head
P = pressure
ρ = density of water
g = gravitational constant
z = elevation above sea level (datum = 0)
h_p = pressure head
h_z = elevation head

The equipotential lines represent where the hydraulic head is the same as the flow field. The flow is from high to low hydraulic head. Generally, during simple monitoring programmes, what is measured as water level (in elevation terms) in a point piezometer, is the hydraulic head at the intake point. The pressure, as metres of water, is the hydraulic head minus the elevation of intake point. The piezometric surface is a plot of the water levels or pressures measured in piezometers.

In understanding groundwater flow, the most significant property of a rock is the hydraulic conductivity. Hydraulic conductivity (K) is derived from the Darcy's Law,

$$Q = K\,t\,A \qquad [3]$$

where,

Q = flow rate
K = an empirical constant of proportionality
i = hydraulic gradient which causes flow to occur;

$$t = \frac{\Delta h}{\Delta L}$$: change in head, h, over distance, L.

A = known cross-sectional area

Hydraulic conductivity is defined as the flow rate per unit area of material under a hydraulic gradient of 1:

$$K = \frac{Q}{A} \qquad [4]$$

Geological materials have hydraulic conductivity values ranging over 13 to 14 orders of magnitude (Freeze and Cherry, 1979). In a pit slope, hydraulic conductivity is highly heterogenic and anisotropic with values varying over 3–4 orders of magnitude within the same lithology. Groundwater flow is controlled primarily by hydraulic conductivity; therefore flow lines and pore pressures have a non-uniform distribution in pit slope formations. This is illustrated in Figure 3, where drawdown created in an aquifer after 100 days of pumping, has propagated differently in formations of different hydraulic conductivity.

Piezometers and monitoring networks

Hydraulic heads can be measured by measuring the water

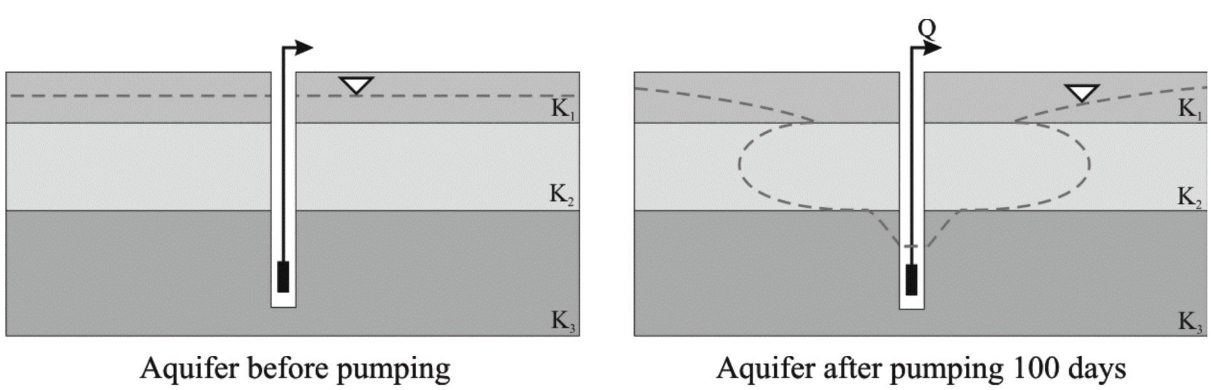

Figure 3—Drawdown in an aquifer after 100 days of pumping

level or pressure head in boreholes, core holes, tubes or pipes. These are all called piezometers. The construction of a piezometer can be simple or complex. The choice of piezometer type depends on what needs to be measured, i.e. an open hole water level or the pressure at a specific point under a slope. An open hole piezometer measures the sum of all pressures along the open section of the borehole. A piezometer must be open to water flow at the bottom and open to atmospheric pressure at the top,

- ➤ The intake (point of measurement) can be slotted casing or a porous piezometer tip
- ➤ Measurement can be by hand dipping of a water level or by electronic measurement using a vibrating wire or diaphragm type device
- ➤ It is important to understand what is being measured in each piezometer and its relevance to the high wall under investigation
- ➤ Results from open hole water levels should be considered separately from heads measured in point piezometers.

A sealed piezometer measures the pressure at the point where the piezometer tip is in contact with the formation. The measured hydraulic head refers to the intake point (Figure 4).

A monitoring network is made up of multiple piezometers. Ideally the following should be measured:

- ➤ Water table around the mine, beyond its zone of influence
- ➤ Water table close to the pit shoulder
- ➤ Pressure heads within each formation in the pit slopes.

Alignment with the geotechnical design sections is preferred so that the water levels and pressures can be incorporated in the slope monitoring and modelling.

The choice and type of piezometers depend on the location, and the distance between each piezometer, and on the complexity of the geology, the structural elements and the geotechnical domains. Two to three piezometers should be installed in each quadrant of the pit along the geotechnical design sections, to allow the accurate definition of hydraulic heads and piezometric surface on the respective design section.

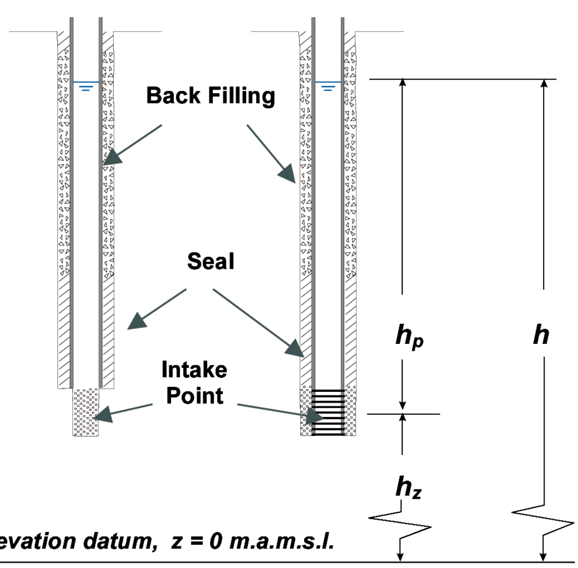

Figure 4—Simple piezometers

Figure 5 illustrates the use of point piezometers in measuring hydraulic head in different fractures in a formation in space and over time.

Piezometer design considerations

The depth of the targeted formation will determine the depth/length of the piezometer. The intake point of a good piezometer will be at the bottom of the strata to be monitored. If only one formation needs to be monitored, then a simple piezometer construction, as shown in Figure 4, is sufficient. However, if more than one formation must be monitored, a nested piezometer should be constructed. Figure 6 shows two designs for a nested piezometer. It is also possible to install a string of piezometers along a commercially available factory constructed tool (Westbay).

The piezometers can be constructed open hole, using stand pipes or conduits (Figures 4 and 6) or can be sealed into the formation as grouted-in point piezometers (Figure 7). They can be vertical, horizontal or any angle in between.

The borehole diameter depends on the type of piezometers being constructed. The drilled diameter needs to be large enough to accommodate the stand-pipe, the gravel pack and the seal. When the piezometer is sealed, the diameter must also be able to accommodate the tremmie pipe for feeding in the sealant.

The conduit used for measurement can be PVC tubing for shallower piezometers, or steel tubing for greater depths (>250 m). The diameter should be at least 2½ inches. The conduit has to be perforated at the intake point, also 2½ inches in diameter, to allow for the measurement device to be fitted.

The measuring device can be a dip-meter—used for manual measurements, or automated transducers or divers.

Depending on access, target position and whether installed in an open pit or underground mine, piezometers

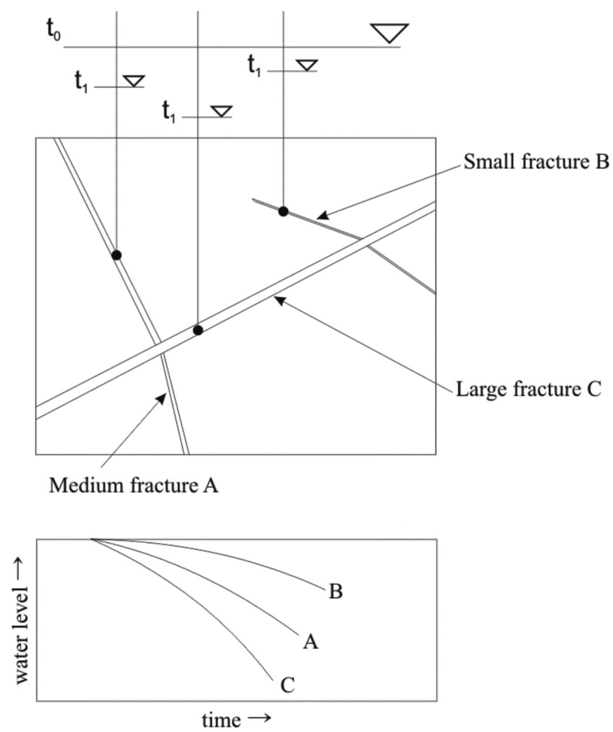

Figure 5—What a piezometer actually measures

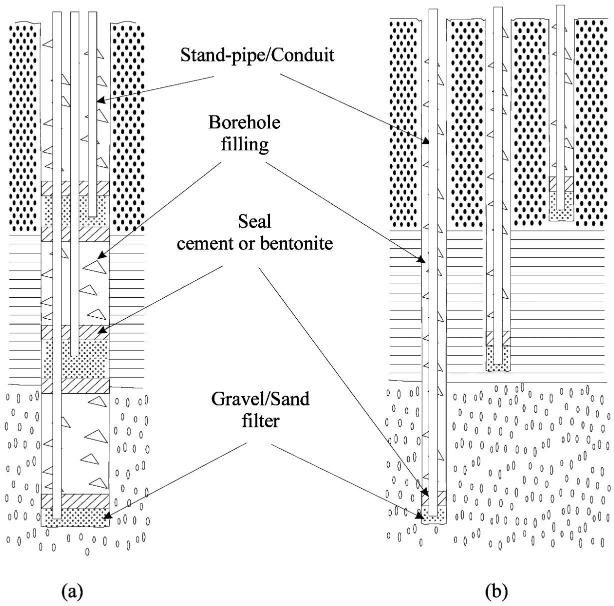

Figure 6—Nested piezometers: (a) in one borehole, (b) in a cluster of boreholes

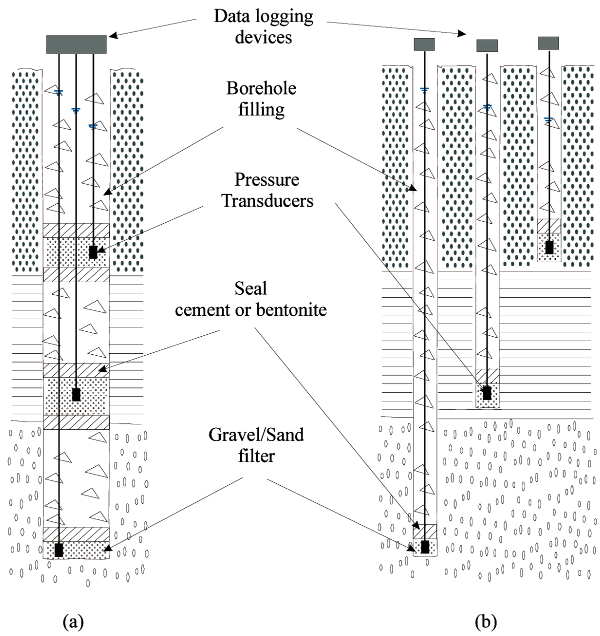

Figure 7—Nested grouted-in pressure transducers: (a) in one borehole, (b) in a cluster of boreholes

can be installed in angled holes that are either horizontal or are sub-horizontal. In a horizontal or angled hole the head measured represents the vertical hydraulic head at the measuring point (Figure 8).

Plotting of pore pressure distribution

The data collected from piezometers can be used for plotting hydraulic heads and piezometric surfaces around the open pit in space and over time. Piezometric data are usually represented as hydrographs, which are graphic representations of piezometric head vs. time in one observation point, or piezometric heads for a group of observation points at different times (Figure 9).

The plots show the position of the water table or pressure head and illustrate the effectiveness of a dewatering system, as well as pore pressure distribution in the high walls. Long-term data collection can also be used in the calibration of numeric hydrogeological models, as well as an input to slope design and coupled analysis.

Figure 11 shows a design section of a pit, simulated in a groundwater flow model, in which pore pressures have been predicted for different years.

Case study from Orapa mine, Botswana

Orapa Mine is an open pit situated in the Central Kalahari of Botswana. It is operated by the Debswana Mining Company (Figure 12).

The geology around Orapa Mine is a layered sequence (from surface down) of calcrete, Stormberg basalt, Ntane sandstone, Mosolotsane sandstone and siltstone, Tlhabala and Tlapana mudstones, coal seams, Mea arkose and granite basement. A generalized stratigraphy is shown next to the plan of the open pit (Figure 13).

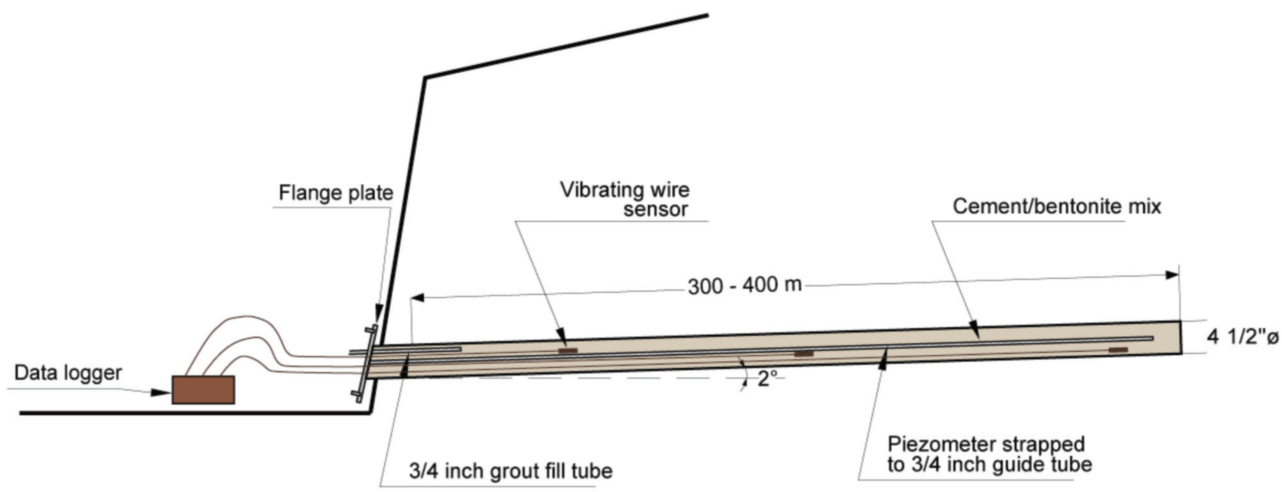

Figure 8—Nested grouted-in pressure transducers in sub-horizontal piezometers (LOP 2008)

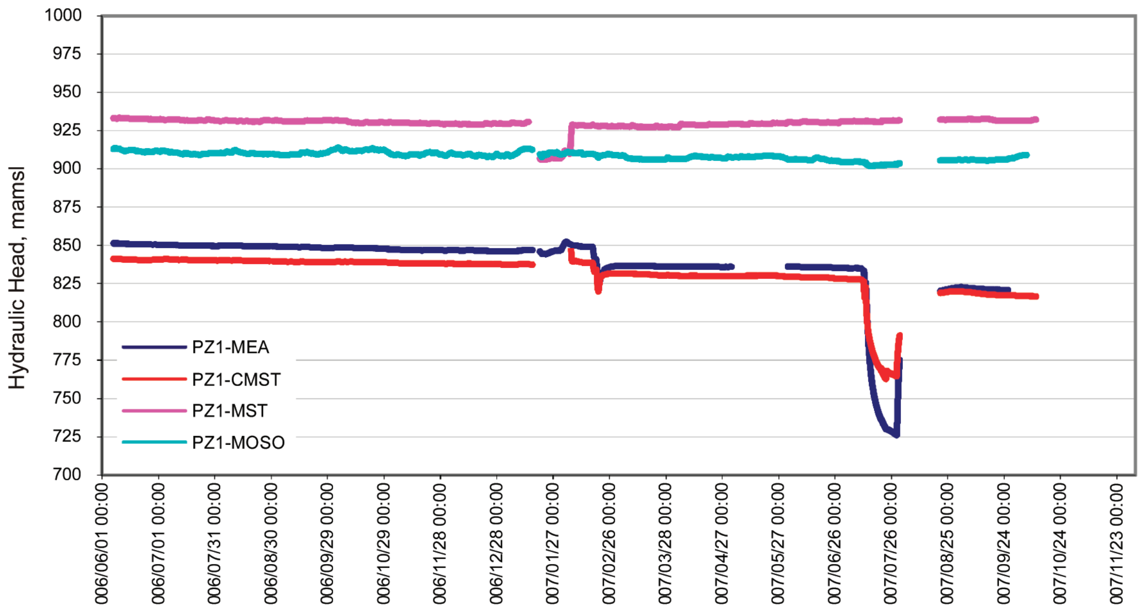

Figure 9—Hydrograph showing hydraulic head vs. time for four sealed piezometers

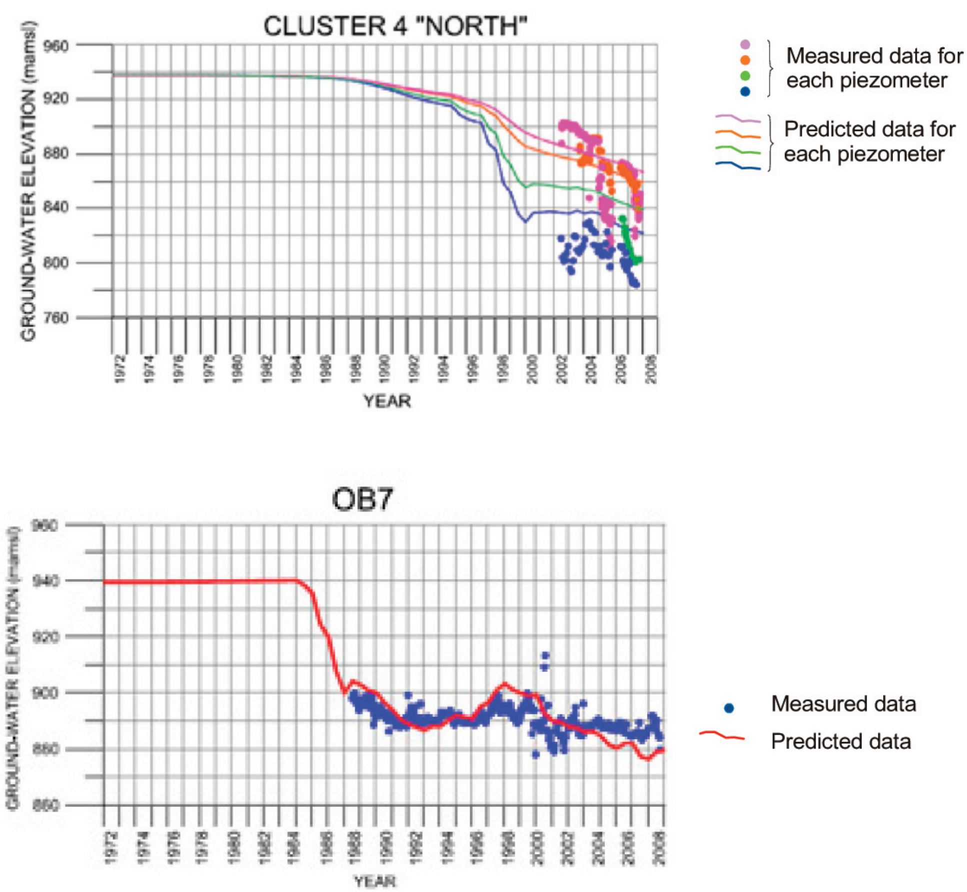

Figure 10—Calibration plots from a hydrogeological model using monitoring data from four point piezometers

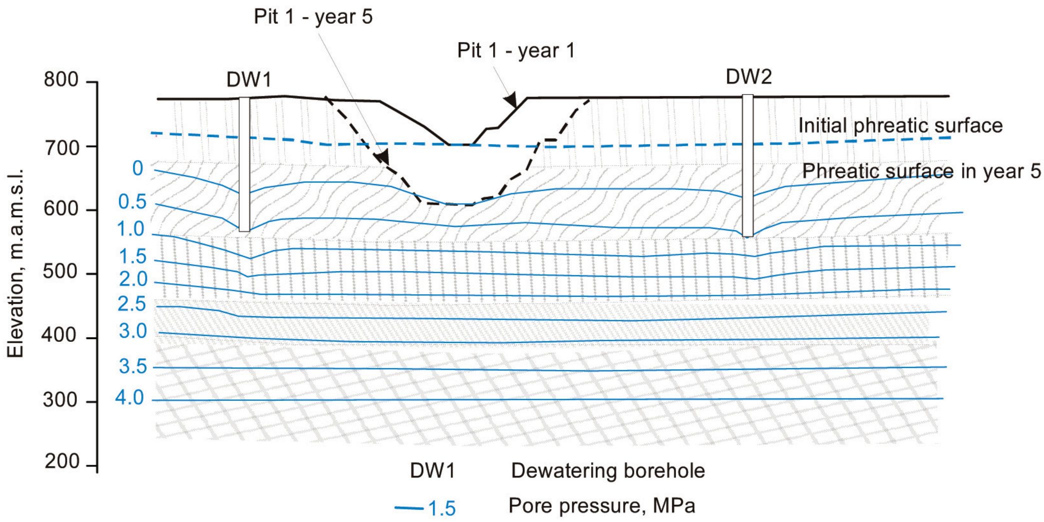

Figure 11—Modelled pore pressure distribution (after HCI, 2007)

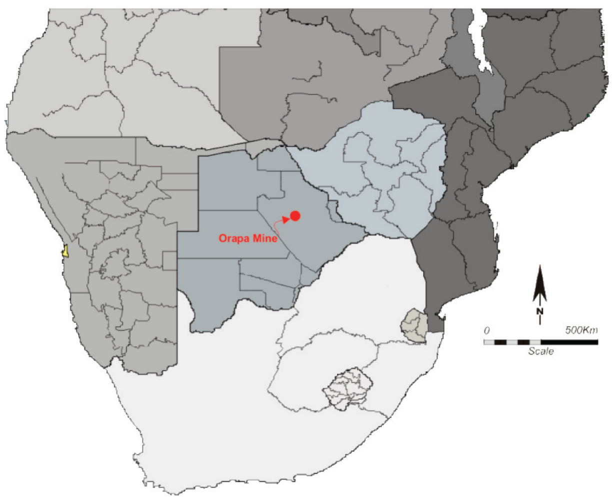

Figure 12—The location of Orapa Mine in Southern Africa

The main pit (AK1) is about 2 km long (N-S) by 1.25 km wide (E-W). Current depth is 200 m

The upper aquifers are made up of the Ntane sandstone and Mosolotsane sandstone. The lower, deep seated aquifers, are the sandstone layers between the coals seams found in the lower part of the Tlapana mudstones. Water is also found on the granite contact. The AK1 pit is planned to reach a depth of 500 m.

The upper Ntane aquifer has been dewatered but high water pressures from the Mosolotsane and lower aquifers can still be measured in the pit slopes.

The pit is dewatered using 42 pit perimeter pumping boreholes and sump pumping. The Geotechnical department monitors the effectiveness of the dewatering through the Groundwater Control Project. Specially designed piezometers have been installed around the pit in between pumping boreholes, on design sections and at distance from the pit. Where possible three points per slope have been installed and are monitored. There are 5 open hole piezometers and 16 sealed piezometers

The piezometers were installed to meet two objectives: first, the testing and monitoring of formations below the Mosolotsane sandstone and secondly the monitoring of the upper sandstone aquifer (Mosolotsane).

Two types of piezometers were constructed:

- nested piezometers for testing and monitoring
- simple piezometers for monitoring of upper sandstones.

The pressure profiles for each slope have been plotted. Figure 14 shows a cross-section of the pit with the planned depths for cuts 2, 3 and 4. The piezometric surface as of October 2003 and the simulated piezometric surface, predicted for October 2008, have been superimposed.

Figure 9 showed the individual hydrographs for four sealed piezometers sited in one area of the pit perimeter at Orapa. The piezometers are sealed in the Mea arkose (PZ1-MEA), the carbonaceous mudstone (PZ1-CMST), the upper mudstone (PZ1-MST) and the upper sandstone (PZ1-MOSO). In slope stability analysis the mudstones are of the most interest and it can be seen that they respond differently to pumping stresses. This data will be used in the slope design for the mudstone section.

Conclusions

Groundwater flow and deformation within a slope influence each other. An increase in pore pressure will result in a decrease of effective stress; and conversely if the pore pressure decreases, the effective stress increases. Slope analysis and slope design calculations require good information on pore pressure distribution around an open pit excavation.

Until recently very little pore pressure data were available and assumptions had to be used. Monitoring of pore pressures and groundwater gradient can be done using either open hole or sealed point piezometers or a combination of both. It is important that the piezometers are sited to obtain representative pore pressure values for at least three points in a slope.

Orapa mine has instigated a detailed monitoring network and has been able to plot and predict the water table and pressures so as to understand the current piezometric

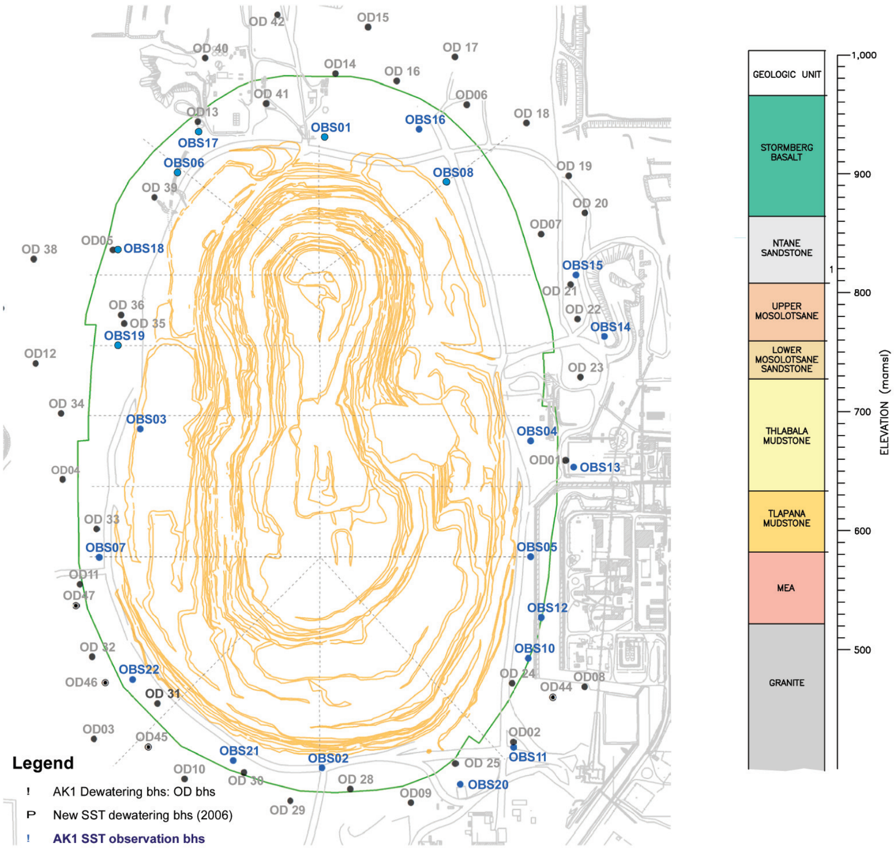

Figure 13—Plan Orapa open pit showing the piezometer and a generalized stratigraphic column

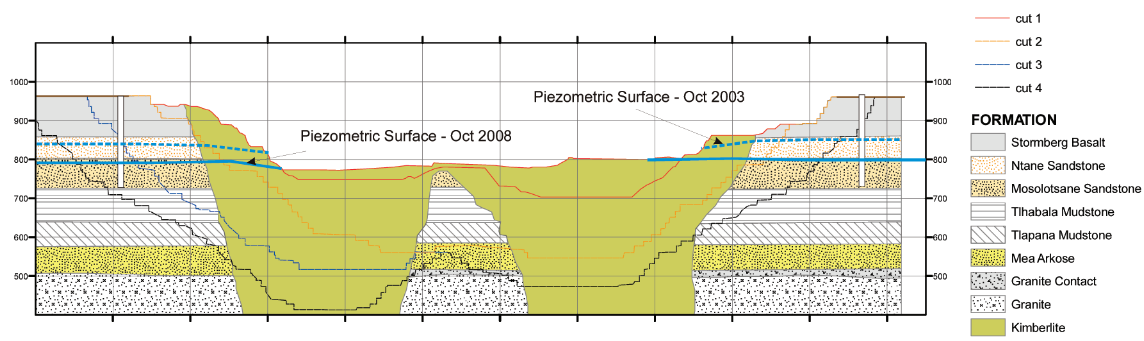

Figure 14—Cross section of Orapa pit

distribution and to ensure information is available for use in the slope design.

Location and design of measuring points depend on the geological and structural settings as well as the geotechnical domains and practicality. Good planning and the use of sensitive point piezometers to measure *in situ* pore pressures means that real-time data can be collected and used for the construction of flow nets, the determination of pore pressure distribution around an open pit mine, the validation of the dewatering/depressurization requirements, the calculation of the efficiency of the dewatering system and finally the use of pore pressure data in slope stability analysis. This data is then be used to predict dewatering effectiveness and becomes part of the slope stability analysis.

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