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IMWA INSIGHTS

Pit Wall Depressurization Using Horizontal Drains: MODFLOW-Based Analysis Techniques

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Abstract
Horizontal drains (HDs) are commonly deployed at open pit mines to depressurize the pit walls and thereby improve pit wall stability. If successful, depressurization maintains current pit wall angles and improves stripping ratios, which directly influences mine economics. HDs are commonly designed using empirical approaches that have been developed based on experience at other mines and are often aided by 2D and 3D analysis using groundwater models at sites with complex geological and structural settings. Specialized techniques for simulating HDs in these models became available nearly 20 years ago with the introduction of discrete feature elements in FEFLOW, a proprietary groundwater modelling package. More recently, introduction of unstructured grids allowed direct representation of HDs and their sequencing in MODFLOW, a publicly available modelling package that is widely used at mine sites. This paper provides an example of how HD design can be aided by 3D numerical analysis that utilizes these new MODFLOW simulation capabilities.

Keywords Horizontal drains · Pit wall stability · Depressurization · MODFLOW

Introduction

Depressurization of the rock mass behind the walls of an open pit is often required to mitigate pore pressures that adversely affect slope stability in poor quality rock. Elevated pore pressures may occur at open pits constructed near water bodies, in areas of high groundwater recharge, or high topographic relief, as well as at sites where geological and structural settings promote such pressure as mining advances. Depressurization allows maintenance of appropriate factors of safety (FOS) for the pit walls without adjustments to the pit wall angles and modifications of the pit wall design. In the absence of depressurization, pit wall angles may have to be reduced, which can increase the stripping ratio and thus directly affect economic performance.

Read and Stacey (2009) and Beale and Read (2013) discuss various depressurization methods used at open pit mines including HDs, vertical wells, passive pressure-relief wells, drainage galleries, and their combination. The key advantages of HDs are their relatively low cost, ease of installation using equipment readily available at the mines, and ability to rapidly cover target sectors of the pit walls where excessive pore pressures are identified. Their main disadvantages are their inability to depressurize the pit wall at depth before the pit bottom is advanced and challenges with collection and conveyance of discharge from multiple HD collars to the open pit's dewatering system. Nevertheless, HDs often serve as the first line of defense before more costly depressurization methods are deployed.

Design of HDs for open pits ranges from empirical approaches with fixed HD spacing and length to complex 3D analyses that can be conducted using a variety of groundwater modelling codes. Beale and Read (2013) and a recent review of HD implementation at several sites (not published) show that initially they are typically installed at larger lateral and vertical spacing that is subsequently refined based on pressure monitoring in the piezometers installed behind the pit walls, and that their length ranges between 150 and 250 m. Cashman and Preene (2020) indicate that HDs employed for rock slope depressurization in other applications range in length between 10 and 100 m and have diameter of 75 to 125 mm. A common rule of thumb adopted in these empirical approaches is that the length of each HD should be approximately twice the thickness of the depressurization zone required to maintain adequate FOS and/or

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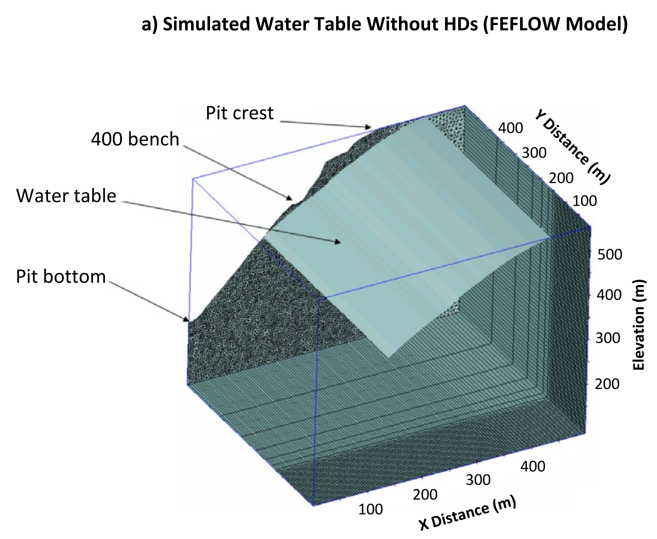

Fig. 1 A quasi-3D FEFLOW numerical model simulating: **a** water table and hydraulic heads prior to the implementation of the HDs and **b** water table and hydraulic heads following sequential activation of the HDs. The images were generated 20 years ago using a UNIX version of FEFLOW

that its length should be approximately half of the ultimate depth of the open pit.

Detailed three dimensional (3D) analysis of HD performance at the pit scale became possible nearly two decades ago with the introduction of discrete feature elements in FEFLOW (Diersch 2014), a proprietary finite-element modelling code currently distributed by DHI (DHI 2023). Due to the fine spatial discretization possible using a fine element mesh, this code allowed representation of individual HDs and groups of HDs across specific sectors of the pit walls that were sequentially activated as the pit wall advanced. In this modelling technique, each HD was simulated using a line of one dimensional (1D) discrete elements placed along the HD alignment and connected to a zero-pressure boundary at the pit wall face that only allowed outflow from these elements, with individual boundaries activated according to the HD implementation schedule. Flow within the 1D elements representing the HDs could be simulated using relationships that accounted for laminar or turbulent flow within each HD, as required for the problem under investigation. This modelling technique, in combination with fine spatial discretization necessary to represent the radial flow field in the vicinity of each HD, allowed assessment of the effects of HD spacing and length on required depressurization targets. An example of this early application at an open mine in folded and thrusted sedimentary rocks using a quasi-3D FEFLOW model is presented as Fig. 1a for the pit wall conditions prior to implementation of the HDs and Fig. 1b for the pit wall with HDs active. The quasi-3D model represented pit wall sector with complex hydrostratigraphy and challenging pore pressures; hence, the estimated HDs spacing and length were considered conservative when applied elsewhere along the pit walls.

In recent years, unstructured grids were adopted into several finite-difference/finite-volume modelling codes including MODFLOW-USG, a groundwater modelling package publicly available from the U.S. Geological Survey (Panday et al. 2013). Unstructured grids allow for a fine level of spatial discretization comparable to what was possible previously using finite elements, but that was difficult to implement in the earlier versions of MODFLOW that relied on rectangular grids (McDonald and Harbaugh 1988). This, in combination with the widespread application of MODFLOW at mine sites, makes its use for assessing HD depressurization a viable alternative. The objective of this paper is to present a methodology that we recently developed for the design of a pit wall depressurization system at a proposed mine in North America using the unstructured grid capabilities of MODFLOW-USG.

Methods

Rockmass depressurization at the proposed open pit mine, which is located in an alpine setting in highly faulted volcanic rocks, was assessed using two groundwater flow models developed using MODFLOW-USG: (1) a 3D regional-scale model that encompassed the entire project footprint and extended to appropriate watershed boundaries and sufficient depth to simulate overall hydrogeologic conditions over the life of mine near the pit and other mine facilities, and (2) a quasi-3D cross-sectional model of a pit wall that incorporated a width of the pit perpendicular to the pit

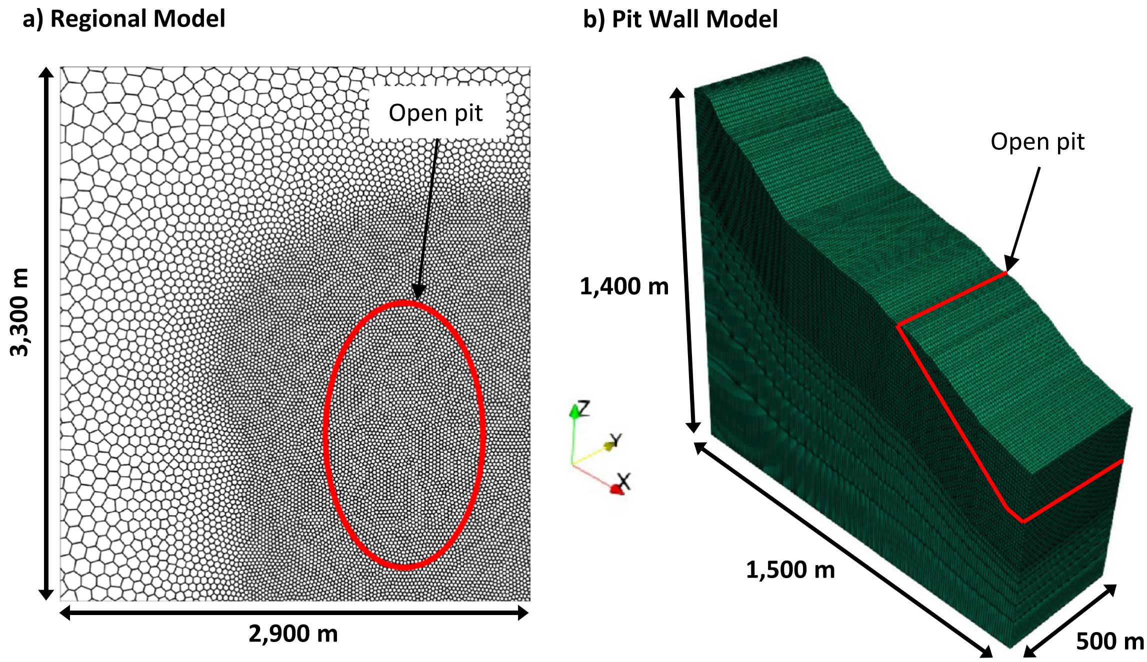

Fig. 2 Numerical grids used for: **a** the 3D regional-scale model and **b** quasi-3D cross-sectional. Note that less than 5% of the regional-scale model grid is shown in **a**; the full model extent covered an area of ≈ 200 km^2. Approximate open pit outlines are shown in red

wall. As in the FEFLOW example (Fig. 1), the quasi-3D model represented a section of the open pit with complex hydrostratigraphy and challenging pore pressures, making its predictions conservative for other areas of the open pit. The cross-sectional model was used to rapidly assess (simulation time on the order of minutes) optimal HD spacing (both lateral and vertical) and length to achieve adequate pit wall depressurization required to maintain appropriate FOS during pit development, with maximum hydraulic heads (minimum FOS) evaluated mid-way between simulated HDs. The optimized HD spacing was then implemented into the regional-scale model (simulation time of hours) to simulate hydrogeologic conditions (water table position and distribution of hydraulic heads, groundwater discharge to HDs and pit face) in a 3D framework during pit development and considering sequential implementation of the HDs throughout the mine plan. This methodology is also suitable for optimizing the configuration of other depressurization measures (e.g. pumping wells, vertical drains); however, for the purposes of this paper, simulated pit depressurization measures were limited to HDs.

The regional-scale model incorporated an unstructured Voronoi grid that was refined in the vicinity of the proposed mine with cell widths on the order of 25 m (Fig. 2a), which was considered sufficient for simulating pit-scale depressurization while maintaining the overall grid size to a practical level (i.e. ≈ 1.5 million grid blocks). The cross-sectional model used a standard rectangular grid with cell sizes of 10 m within the pit footprint (Fig. 2b), which allowed assessment of lateral and vertical HD spacing of 50 to 300 m and HD lengths of 50 to 300 m, the ranges considered in this study. Hydrogeologic parameters (e.g. hydraulic conductivity, groundwater recharge) for the models were derived by calibration of the regional-scale model to several datasets (e.g. average and seasonal hydraulic heads, baseflow observations, and results of several pumping tests) using manual and automated calibration techniques.

The MODFLOW drain package was used to simulate the HDs and open pit. For the HDs, the boundary conductance was calculated based on equations from Thiem (1906) and Peaceman (1983) that accounted for model cell dimensions, bedrock hydraulic conductivity, and HD dimensions. Other boundary conditions implemented in the models included groundwater recharge and evapotranspiration along with a combination of the general head boundary and drain packages to represent respective perennial and ephemeral drainages.

Results

Figure 3 presents the results of the numerical simulations at the end of mining for the ultimate open pit. Passive drainage during pit development is predicted to depressurize the upper portions of the pit wall; however, seepage or wet conditions along the lower half of the pit wall are predicted to persist to the end of mining (Fig. 3a). In these areas of the pit wall, elevated pore pressures and low FOS may

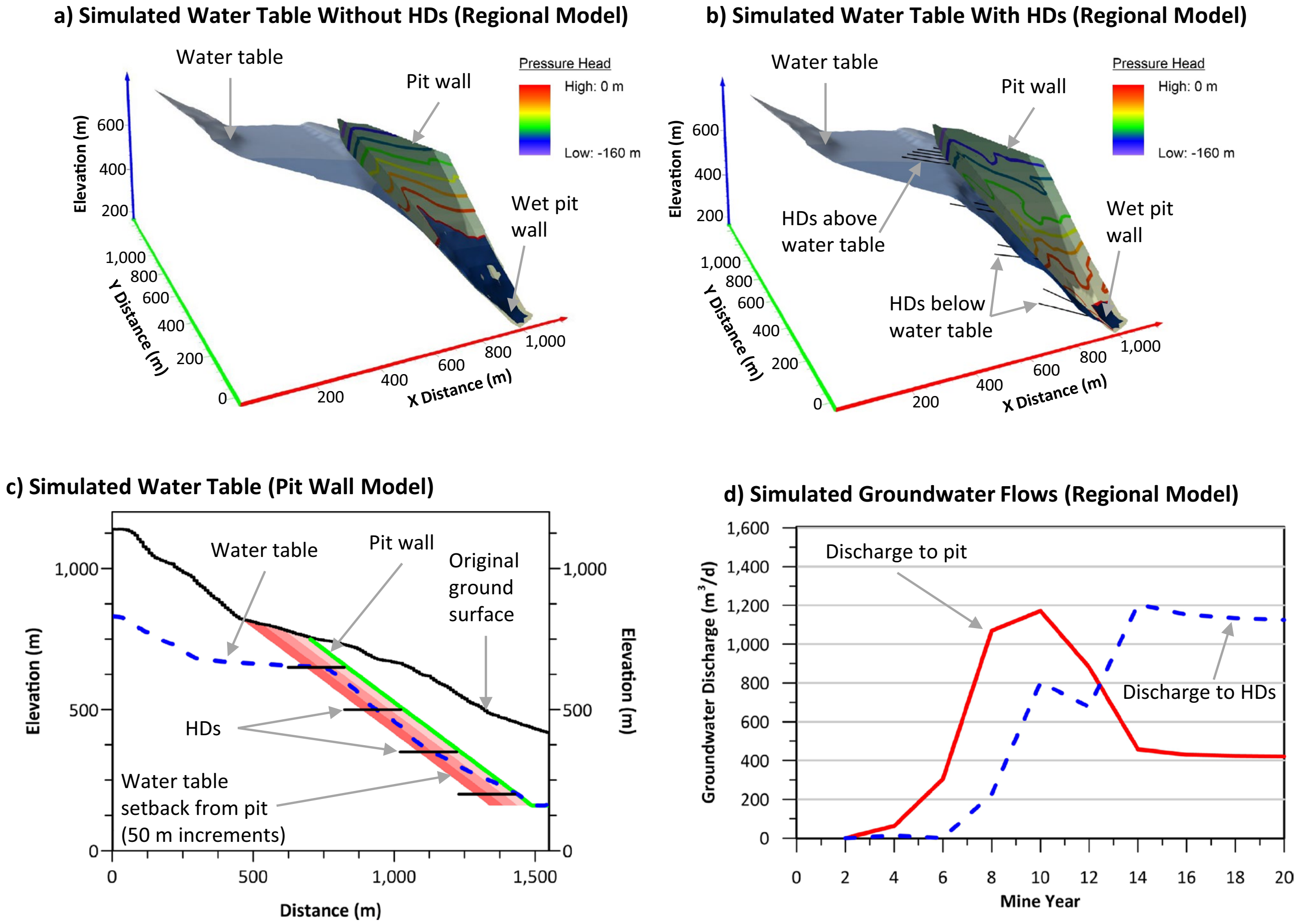

Fig. 3 Influence of horizontal drains (HDs) on the simulated water table (blue) relative to the pit wall (green): **a** regional model without HDs, **b** regional model with HDs, and **c** pit wall model with HDs (red shading indicates water table setback from pit wall in 50 m increments). Predicted groundwater discharge to the pit and HDs for the regional model are also provided in **d**

present unacceptable risk to mining operations. Implementation of HDs should depressurize most of the pit wall, with wet conditions limited to the base of the wall (Fig. 3b). A similar water table configuration is predicted by both the regional-scale model (Fig. 3b) and the cross-sectional model (Fig. 3c), with the water table being set back from the pit wall by generally more than 50 m. Elevated pit groundwater discharge is predicted in the initial years of mining prior to HD implementation (Fig. 3d); however, groundwater discharge to the pit is predicted to gradually decrease as the pit advances and HDs progressively become established, with discharges from the HDs ultimately comprising about 70% of the total groundwater to be managed at the pit.

Wet conditions predicted at the base of the pit wall (Fig. 3b, c) indicate that closer HD spacing or other depressurization measures would be required to achieve satisfactory FOS for the full pit wall. For this example, sufficient depressurization was predicted (results not shown) using a combination of advanced dewatering with vertical pumping wells along with a uniform HD configuration incorporating 200 m long HDs spaced ≈ 100 m (horizontal) and 150 m (vertical) apart, with a total length of implemented HDs on the order of 10 km. While a uniform HD configuration was used here, the outlined methodology is suitable for simulating the non-uniform HD configurations often required to target specific lithologies or discrete fault structures.

Conclusions

Overall, the methodology presented here provides a relatively rapid method of assessing a HD configuration for pit wall depressurization using a physically based approach and a publicly available modelling code like MODFLOW-USG (Panday et al. 2013). The methodology relies on combining a quasi-3D pit-wall scale and a 3D regional-scale groundwater models, with the former used to efficiently evaluate the HD spacing and length required to achieve depressurization targets at the pit-wall scale and the latter used to inform the pit-scale depressurization strategy (i.e. the number and location of HDs throughout the mine life). The approach is applicable to mining projects ranging from scoping studies with limited hydrogeologic data to existing open pits at advanced stages of development.

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