Managing High Altitude Bog Deposits: An Investigation of the Hydrogeologic and Geotechnical Challenges associated with Andean Bofedal Sediments

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Abstract High altitude mine planning and development in the Andes Mountains must address the challenge of managing the low stability, low strength, high water content material found in bog deposits called bofedales. However, limited geotechnical and hydrogeologic information is available for bofedales. A testing program, geotechnical stability modeling, and groundwater modeling were used to investigate the material and develop strategies for dewatering, removing, and stockpiling of the material for reclamation.

Keywords High Altitude, Bofedal, Dewatering, Stability Analysis, Groundwater Modeling

Introduction

The Corani Project is a lead/zinc/silver mining project located in the central Andes Mountains operated by Bear Creek Mining. Throughout the site, the valleys and gently sloping terrain are often covered by deposits of glacial debris, aeolian sand deposits and post glacial lake deposits. Growing on these areas are dense mats of vegetation that over time, form deep peat-like organic soils called bofedal(es). Bofedales are characterized by dense bog-like vegetation and partial seasonal flooding which creates a hummocky terrain often punctuated with small bodies of standing water. The deposits have a high moisture retention capacity and store wet season precipitation, snowmelt, and glacial melt water eventually releasing the water as dry-season stream baseflow. Bofedales therefore sustain stream flow year-round and are an important component of the hydrologic system in the high Andes. Fig. 1 shows some of the key surface features of bofedal deposits: large spongy mats of vegetation that grow to create small pools of standing surface water.

Bofedal deposits are a significant geologic unit in the high Andes. Though potential challenges associated with bofedal arise at all stages of mine planning and development, and even though many projects in the Andes must contend with bofedal deposits, very little hydrologic or geotechnical data exists in the public domain.

There are several potential challenges associated with mine development in areas with large volumes of bofedal material. Natural bofedal material is saturated, low-strength, and compressible and consequently, is not suitable as a foundation for mining-related fa-

Fig. 1 *Picture of typical bofedal landscape at the Corani Site. Photo credit: Kevin Gunesch*

cilities. Standard Penetration Test (SPT) values are often below 5 blows per 6 in, and as a result, even drilling can be difficult due to the tendency of boreholes to collapse. Due to the high water content and low strength, stripping, stockpiling and management of this material are a unique challenge. Furthermore, the material's ecological value must be considered in closure planning.

At the Corani Project, bofedal is located beneath several proposed facilities including the pit, the waste rock dump, and the water supply pond. Specifically, the project must determine how to dewater bofedal so it can be excavated, stabilize bofedal in the pit excavation, and stabilize bofedal stockpiles until they are used for reclamation. In order to address these issues, a testing program, geotechnical stability modeling and groundwater modeling were performed. Based on these evaluations, the project developed a bofedal management plan to effectively manage this important material.

Methods

Field Testing and Lab Testing

Field testing was conducted to assess the *in situ* geotechnical and hydrogeologic properties of the bofedal and to determine the extent and depth of bofedal deposits. Six slug tests and a multiple well aquifer test were conducted on wells completed in the bofedal deposits. Resistivity surveys were run in the area of the pit and the main waste rock dump to determine an approximate thickness of the bofedal. In addition, Standard Penetration Tests were performed to assess the strength of the bofedal and underlying material.

Samples of the bofedal material were sent for laboratory testing to assess soil properties. Analyses included testing of moisture content, saturated hydraulic conductivity, effective porosity, and unsaturated conductivity. The same samples were tested at different densities to cover a range of potential construction uses.

Groundwater Modeling

Data from the field program and experience on this and other project sites indicated that it will be necessary to dewater the bofedal deposits prior to removal. MODFLOW-Surfact groundwater flow models were prepared to support the conceptual plan for the dewatering of the bofedal in the mine area. The purpose of the modeling was to determine the optimum approach for dewatering the bofedal deposits within the pit prior to excavating them, and also to predict the time needed for dewatering. Two methods were considered for dewatering the bofedal deposits: the excavation of shallow drainage trenches followed by staged soil removal; and alternately, a network of vertical dewatering wells. Trenches would be excavated using low-ground-pressure equipment (to ≈ 2 m depth) and dewatered by gravity flow. After dewatering, equipment would be used to remove soil to the level of the lowered water table, and new deeper trenches would be dug into the newly-exposed surface. The alternative method would install vertical wells through the full depth profile of the bofedal, and dewatering would precede excavation. Models were constructed to represent each method and dewatering rates were simulated under assumptions of various trench and pumping well patterns. The results were used to determine which method was most likely to efficiently and cost-effectively dewater the area of the bofedal.

Stability Modeling

Stability sections of bofedal excavation within the mine pit, and of stockpiled bofedal material, were modeled in SLOPE/W. Both static and pseudo-static conditions were analyzed. Seismic conditions were simulated with an anticipated 475 year seismic return event – peak ground acceleration (PGA) of 0.10 g. The potential for liquefaction of the bofedal material was anticipated due to field observations during drilling and SPT testing. Residual strength parameters were thus considered in the analysis. This was considered reasonable because the main interest of the stability analyses was overall stability and not detailed deformation.

Separate stability sections were analyzed for stockpile material to be placed on existing bofedal areas. In these areas, the objective was to determine a potential placement lift height (placement rate) that would maintain foundation pore-pressure within acceptable geotechnical limits. Because SLOPE/W is a simple limit equilibrium software for analyzing factor of safety of earth and rock slopes, it cannot intrinsically model pore-pressure increase and dissipation. Under dynamic loading the stability sections were instead analyzed with FLAC. FLAC is a more powerful, two-dimensional explicit finite difference program that permits plane-strain, plane-stress, fully dynamic analysis. The program simulates behavior of soil and rock structures that may undergo plastic flow when their yield limits are reached, suggesting a factor of safety less than 1.

Results

Material Properties

Drillings and resistivity surveys suggested the average thickness of the bofedal deposits to be around 15 – 20 m thick, with a maximum thickness of 35 – 40 m near the mine pit. Core samples retrieved from drilling showed the mat-like vegetation to be composed of nearly-saturated, dark, organic-rich sediments with dense root mass extending to around a meter in depth followed by alternating layers of sand deposits and organic sediment remains. The majority of the volume of the bofedal deposit is composed of uniform sand. "Bofedal deposit" as defined by the study, refers to the unconsolidated deposits of organic sediments and fine sand. Fig. 2 shows typical drill core photos of bofedal deposits at various depths.

First-hand observations of exposed bofedal areas and drilling samples provided reasonable assessments of typical soil material characteristics. Stand Penetration Test results (ASTM D1586 method) indicated a range of *in situ* strengths ranging from strength typical for sand to negligible strength typical for saturated silt and peat. It is believed that the SPT testing resulted in liquefaction of some materials as a consequence of the testing method. The SPT method is not applicable under these conditions. However, the SPT testing demonstrated the potential sensitivity of the unconsolidated soil materials to liquefaction under dynamic loading when saturated.

The results of the field testing indicated that the bofedal and associated sediments have an average hydraulic conductivity of 9.3×10^{-4} cm/s, or 8.0×10^{-1} m/d. Slug test data was analyzed using the Cooper-Bredehoeft-Papadopulos solution. Values ranged from 8.7×10^{-5} cm/s to 2.5×10^{-3} cm/s. This is consistent with silty and fine sands. The multiple well pumping test was analyzed using the Jacob Straight Line analytical method and showed a hydraulic conductivity on the order of 10^{-4} cm/s. Specific yield was calculated to be 0.004. However, the low pumping rate involved makes the applicability of the result uncertain. The results of the pumping test are shown in Fig. 3.

The laboratory testing revealed a hydraulic conductivity of 1.5×10^{-4} cm/s, consistent with the field testing. It also revealed a relatively high porosity of 51 %. These characteristics make bofedal ideal cover material for the planned evapotranspiration mine waste soil covers. High porosity and low spe-

Fig. 2 *Pictures of typical bofedal drill core.*

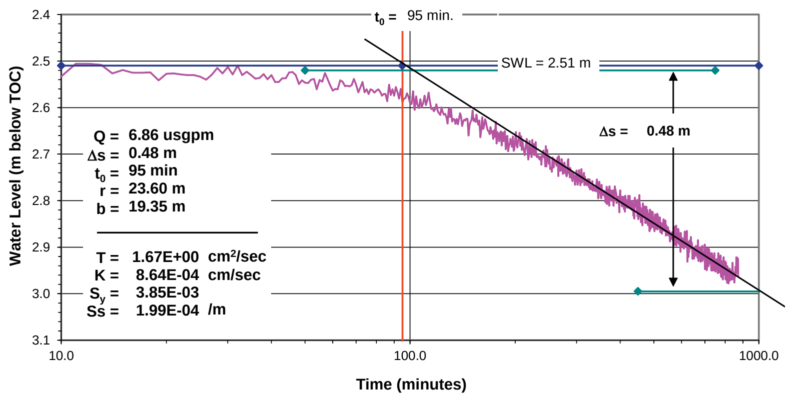

Fig. 3 *Pumping Test Observation Data Analysis-Jacob Straight Line Method*

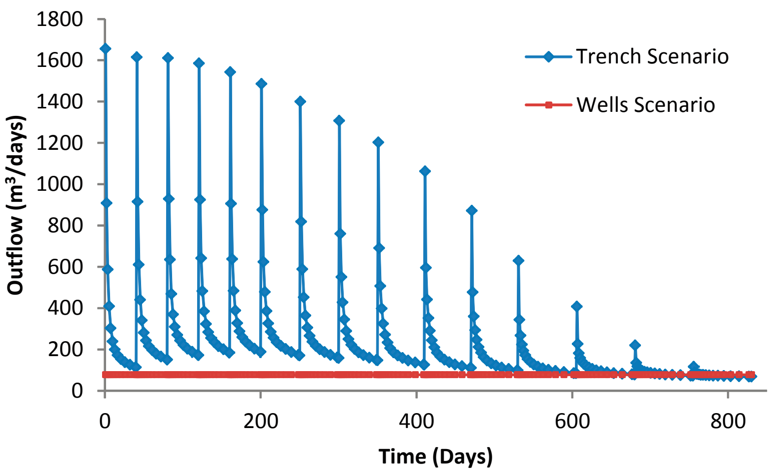

Fig. 4 *Estimated dewatering rates for two methods of dewatering: trenches and pumping wells*

cific yield suggest that the material retains water efficiently during the wet season (Fig. 4). Water is held in the pores as a result of low hydraulic conductivity and eventually evaporates, preventing water from passing through the cover to the underlying material.

Groundwater Model Results

The groundwater model results showed that trenching and passive draining is a more efficient dewatering method than the pumping well system. At the end of two years, pumping wells left a substantial volume of bofedal sediments saturated. The fundamental reason for this is that the low average hydraulic conductivity of the sediments results in formation of a steep cone of depression around each well. The low transmissibility of the formation means that the wells function as effective drains only for the sediments within a small radius of each well.

The trenching system proved to be a very effective dewatering method provided the trench density is high enough. The model predicts that under the trenching scenario, peak flow rates to the trenches could approach 1,600 m^3/d, but are expected to average 165 m^3/d over roughly two years. In contrast, the network of pumping wells, could only sustain a combined pumping rate of 77 m^3/d. Modeled flow rates over time are shown in Fig. 4.

The results predict that after the first round of trench excavation, dewatering of the uppermost sediment layer will be essentially complete after 30 days. However, excavation of the early-drained upper part of the material could begin sooner than that, with the limiting factor being that it may not be practical to excavate in some areas where the declining water table still remains too close to the active excavation surface. Based on the maximum bofedal thickness of about 45 m (near the center of the basin), it is expected that the dewatering project will require 15 rounds of trenching, dewatering, and excavation for a total bofedal excavation time of nearly two years.

Stability Model Results

A back analysis indicated that a typical bofedal soil stockpile will require the organic-sand mixture to have a minimum friction angle of 22°, where constructed with a 3H:1V slope and a 2 m high toe berm on a bedrock foundation, to be stable. Applying this result where soil stockpiles will be placed on existing bofedal soil foundations, the maximum theoretical lift thickness was determined to be 4 m in order to avoid potential bearing capacity failure due to excess foundation pore pressure. Actual lift thickness would be limited to around 2 m in order to provide an acceptable factor-of-safety during construction.

Slope stability modeling of the areas of the pit wall where bofedal will exist revealed that the remaining 5H:1V slope would be unstable under seismic loading, and would require a waste rock buttress for stability. Fig. 4 shows the buttress required to support a typical bofedal slope at the southern edge of the mine pit.

Conclusions

The results of the field and laboratory testing showed that bofedal must be dewatered and removed prior to the construction of project facilities. SPT tests and laboratory testing suggest that the *in situ* material has the potential to liquefy under dynamic loading. Other lab testing results indicate that bofedal would make an ideal mine waste cover material. The low hydraulic conductivity and high storage will prevent infiltration by facilitating surface evaporation and runoff, and ideally, will encourage the reestablishment of bofedal flora and fauna on reclaimed surfaces.

The results of the groundwater modeling suggest that a system of trenches is the most efficient method considered for dewatering bofedal sediments prior to excavation. It is important to note that the results of the groundwater model are a numerical exercise simulating dewatering times and volumes, which does not consider construction as well as geotechnical challenges. Such challenges could include instability of the trench walls, the time required to excavate dewatered material, and the ability of some areas of the bofedal to support earth-moving vehicles, along with others. This model is designed as a construction planning tool, and additional optimization will be required upon the final design based on the mine plan.

Excavating and stockpiling bofedal material will require extensive handling. In the pit

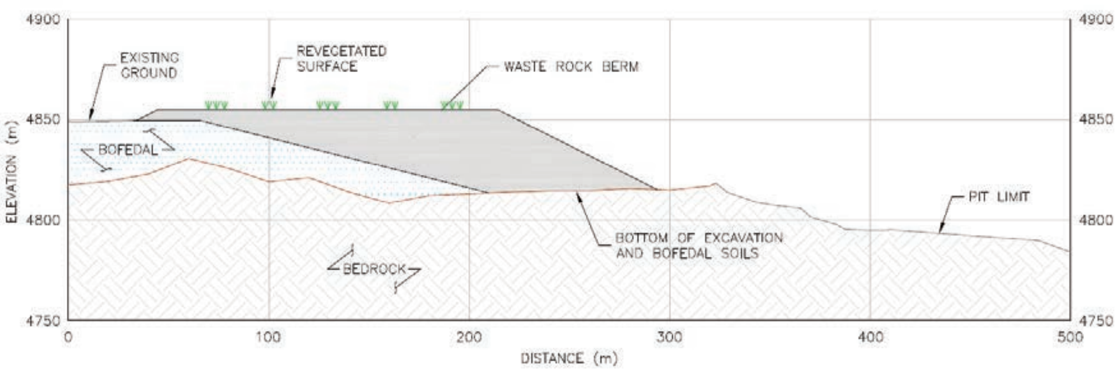

Fig. 5 Cross section of buttress required to support bofedal slope

where thick deposits will be excavated, large volumes of waste rock will buttress the 5H:1V excavated slope. Stable stockpiling of the bofedal material can be achieved by limiting construction lift height to around 2 m to allow for foundation excess pore pressure dissipation in areas where stockpiles are placed over existing bofedal soils.

The management of bofedal deposits is a major consideration of the Corani mine plan. Dewatering bofedal deposits will require two years of work with multiple stages of trenching, dewatering, and excavation. Bofedal stockpiles will cover 1.25 km^2 of surface area within the mine area, and bofedal pit slopes require specialized buttressing to be stable. The requirement for managing the bofedal soils is therefore a significant cost item in the mining capital and operations' costs. Therefore, a thorough understanding of bofedal deposits-their extent, impact, strength, and best management practices, is critical to accurate mine planning and cost estimation.

Disturbed bofedal deposits must be reclaimed upon closure, and their important hydrogeologic role must be duplicated or restored. The Corani closure planning is ongoing, but current plans include the restoration of bofedal deposits over the backfilled mine pit and on the surface of the tailings storage facility. After mine closure, the total area of restored bofedal will be greater than the current bofedal extent. The project has also committed to maintaining dry-season baseflow in mine-impacted watersheds during operations and post-closure.

Additional site investigation with sampling using thin-walled samplers and laboratory testing of undisturbed samples is recommended to improve and advance the present work.

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