Utilizing pore pressure simulations with an unstructured mesh for closure design optimization of the Wanagon Stockpile at the Grasberg Mine

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Abstract

Estimating pore pressures distributions within stockpiles poses a significant challenge in industry as the distribution of hydraulic properties is linked to construction methodology, materials, and sequence. This paper presents a case study demonstrating how a FEFLOW 3D unstructured meshing approach can be used to simulate a complex hydrogeologic system. Advanced tools were developed and used to build numerical models supporting design and material optimization, locating monitoring targets, and developing Trigger Action Response Plans. Utilizing identical meshes for hydrogeologic and geotechnical models allows for direct transfer of pore pressure distributions and eliminates the need for interpolation between the models.

Keywords: Grasberg, heterogeneity, pore pressure modelling, design optimization, closure monitoring

Introduction

The Grasberg surface mine, operated by PT Freeport Indonesia and located in Papua Province, Indonesia, began ore production in 1990 until open pit mining operations ceased in 2020. The topography surrounding the Grasberg Mine is rugged with steep slopes, sharp peaks, and deeply incised valleys with elevations in the area between 3200 and 4600 m. The climate is considered alpine/sub-alpine with little variation of temperatures throughout the year, and rainfall occurring nearly every day. The extreme environment left few options for storing overburden removed to access metal containing ore and required operational and engineering controls to safely operate in this unforgiving and challenging environment. The Wanagon Basin, located to the west of the Grasberg open pit, was one of the locations selected for long term material storage. This basin included lakes and natural drainage channels that would be filled by OBS materials. Fig. 1 presents topographic contours of the Wanagon area prior to OBS filling and identifies important features. As open pit mining began, stockpile plans were developed and engineering work commenced to identify operational (Irwandy 2004), environmental (Miller 2003, Prawawa 2018, Widjijanto 2015), and long-term closure options (Mahayasa 2021).

OBS was placed in the Wanagon Basin with run of mine (ROM) material delivered by haul trucks and from a crushing and conveying (C&C) stacker system. Filling was completed using top-down construction forming continuous stockpile slopes with heights up to 400 m. Three primary placement elevations were used and include the upper area (4200 m), the middle area (3845 m) and the lower area (3685 m), with the toe of OBS material reaching the 3200 m elevation.

Using advanced tools developed by CNI, a 3D unstructured mesh was created for geotechnical and hydrogeological numerical analysis where material properties were uniquely defined based on the location, method, type, and sequence of material placement. A FEFLOW model was calibrated to match observed data then forward analyses and sensitivity studies were conducted to support Wanagon closure.

Wanagon Closure Goals

There have been numerous challenges because of site-specific conditions which include steep terrain, foundations containing lakes, vegetation, and alluvial deposits, and a high precipitation environment. These challenges during the operational and closure periods were mitigated through operational practices and engineering designs.

Closure design of the OBS had to include feature to prevent surface erosion and a basal drain zone to accommodate subsurface flows through the OBS. These surface and subsurface water conveyance systems must have the capacity to accommodate maximum precipitation events to manage safety risks during construction and for long-term facility stability.

Primary considerations for stability include:

1. Reclaiming the stockpile slopes to a geometry to accommodate erosional design elements to capture, direct, and discharge surface water flows in a controlled manner.
2. Resloping the overall stockpile to an appropriate slope angle considering stockpile geometry, foundation, and water pressures within the stockpile due to precipitation infiltration and flows through the basal drain system.
3. Engineering and constructing a stockpile underdrain exit structure at the toe of the stockpile to allow water discharge under maximum event flow conditions without erosion of the exit structure.

To achieve these goals, critical areas of the OBS were identified, TARPS and monitoring systems were developed for risk management, and locations for long-term monitoring systems were identified. Finally, the closure design, material requirements, and construction techniques were optimized to minimize construction time and costs.

Hydrogeological Setting

The final OBS facility has a volume of ≈465 Mm^3 equivalent to ≈837 M tonnes of fill, with an infiltration surface area of 3.1 Mm2. Ground water flow through the system is generally from the northern end at an elevation of 3960 m, to the south-southwestern end at 3,200 m. Using an approximate path length of 4,080 m, the overall topographic gradient is 0.18 %. Fig. 2 shows topography of the final Wanagon OBS Design along with adjacent excavations of the WWSS and the South Knob.

C-SUM Mesh Generation

Analyses in geotechnical engineering often involves complex three-dimensional geometries representing geologic structures and material properties coupled with a defined sequence of excavation or filling steps to assess stability during and after construction. Stability is assessed using numerical geomechanical stress models and plasticity criterion to determine yielding. When groundwater is present, pore pressures need to be incorporated in the stress analysis, as pore pressures can have a destabilizing effect. FEFLOW is a groundwater modelling software used to simulate pore pressure distributions needed for stress analysis.

Conditions that necessitate both stress-based geotechnical and hydrogeologic modelling can be expensive and time consuming, requiring the construction of multiple models for each analysis type. Unstructured meshing is available in FEFLOW, but it cannot generate a mixed element mesh. To simplify the modelling, CNI has developed proprietary tools and processes to create three-dimensional mixed element unstructured meshes for numerical analyses.

CNI Synchronized Unstructured Mesh (C-SUM) incorporates complex 3D model geometries and material property assignments which can vary both temporally and spatially. The mesh developed using C-SUM can be used in different numerical analysis packages allowing elemental and nodal values to be directly synchronized between analysis types, eliminating the need for interpolation between dissimilar model meshes. While not presented in this case study, a structured mesh was used for the same model volume. General observations between these two approaches indicates the C-SUM approach requires fewer elements and nodes, has more consistent element sizes, faster solve times, improved mass balance, and better numerical stability.

Model Definition

C-SUM was used to define a 3D FEFLOW model, for the end of year 2022 (EOY2022) and final (YRFinal) design surfaces, to simulate groundwater flows and pore pressure distributions throughout the OBS facility.

The OBS construction sequence and placement method were used to define three-dimensional material domains in twelve steps. Every element was assigned properties representative of the placement sequence, relative position, and material type. The YRFinal model contains ≈313 k nodes defining ≈317 k active elements.

Material types were categorized as: 1) ROM, 2) C&C, 3) screened coarse, or 4) rehandled. ROM and C&C materials were placed using a top-down method which resulted in gravity segregation with the coarsest particles at the base of the stockpile, and the finest particles retained near the crest. Particle sizes also vary with C&C being crushed to a maximum particle size of 8 inches. The screened coarse material was processed to provide a well sorted material for constructing the outflow exit structure. Lastly, rehandle material consists of material placed without segregation resulting in lower conductivity.

Boundary conditions representing the OBS system, as described above in hydrogeologic setting, were defined. Conventional groundwater flow boundary conditions were used to represent fluxes and forms the basis of the water balance of the system.

Model Methods and Results

The YR2022 model was used to generate a steady state solution to define initial conditions prior to transient flow analysis. Transient boundary conditions were defined along with modulation functions to represent fluctuating conditions that affect infiltration and groundwater flows. Simulations were conducted to adjust hydraulic conductivities to match the system response as observed by groundwater flows, and vibrating piezometer measurements collected during 2022. A calibrated model was achieved matching piezometer measurements in both magnitude and behaviour, as shown in Fig. 3, and to estimated flows into and out of the system.

The YRFinal model, which has two primary objectives, added additional material downstream of YR2022 geometry and incorporated the engineered toe exit structure. The first objective was to guide the material requirements and placement methodology to ensure the system has the capability of discharging high flows through an erosionally stable toe exit structure. The second objective was to verify flows can be transferred through the system without increased pore pressures that may impact stability.

Using the calibrated YR2022 model properties transferred into the YRFinal model, a steady state solution was generated for initial conditions for predictive transient simulations. Predictive simulations evaluated the capability of the system to transfer flows with and without a functioning WDD dewatering system.

Fig. 4 shows geometry, hydrogeologic units (HGU), head, and pressure contours along a section (Fig. 1), assuming the WDD is functional. Results indicate that the system including the engineered exit structure is sufficient to convey all flows through the system. No pressure increases were noted. With the WDD dewatering turned off, increased pressures were noted; however, the increases were insufficient to be detrimental for stability.

Using the model results, areas were identified 1) where pressure increases originate, and 2) where elevated pressures may result in stability concerns. TARPS were defined for critical areas and piezometers installed to trigger actions to manage operational risks. Once closure activities are completed and for long term facility management, additional piezometers are planned to monitor drain zone performance and to provide data needed for future calibrations and predictive analysis.

Conclusion

This case study demonstrates that an unstructured FEFLOW 3D mesh can be used to model a complex hydrogeologic system such as the Wanagon OBS. The model was successfully calibrated using as-placed materials, measured water flows, and pressures. TARPS were defined by using model results to identify critical areas.

With this new approach, the resolution of the pore pressure model was enhanced. Compared to a traditional structured (layered) mesh, improvements were observed. Numerical stability had a reduced error field, run times decreased, convergence improved due to element size consistency, and mass balance is easier to achieve.

For the toe exit structure, material and geometry requirements were determined. While results are not specifically presented in this paper, using an unstructured mesh approach allows results from the hydrogeologic model to be imported directly into geotechnical stability models without the need for interpolating values.

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References

Irwandy A, Sengara W, Adisoma G, Wawa JS, Stawski M, Nasution Y (2004) Post failure stability analysis and management of Wanagon Overburden Dump. In: Hardygora M, Paszkowska G, Sikora M (Eds), Proceedings of the Thirteenth Symposium on Mine Planning and Equipment Selection. p. 91–96.

Mahayasa M, Simanjuntak M, Johnson M (2021) Wanagon overburden stability; Grasberg surface mine closure. In: Fourie AB, Tibbett M, Sharkuu A (Eds), Mine Closure 2021: Proceedings of the 14th International Conference on Mine Closure, QMC Group, Ulaanbaatar, https://doi.org/10.36487/ACG_repo/2152_04.

Miller S, Andriana J, Richards D (2003) Overburden Geochemistry and Acid Rock Drainage Scale-Up Investigations at the Grasberg Mine, Papua Province, Indonesia. In: Proceedings Sixth International Conference on Acid Rock Drainage (ICARD), Cairns, QLD, July 12-18, 2003. p. 111–121.

Prabawa Y, Bugaleng L, Gautama R, Widiajanto E (2018) Blasting, fragmentation and wall quality result at West Wanagon slope stability project on Grasberg Mine. In: IOP Conf. Ser.: Earth Environ. Sci. 212 012066.

Widijanto E, Setiawan I, Prasetyo G (2015) Dedicated Underground Drainage Drift for Dewatering Wanagon Overburden Stockpile, Grasberg Mine – PT. Freeport Indonesia. *Prosiding TPT XXIV dan Kongres Perhapi.*

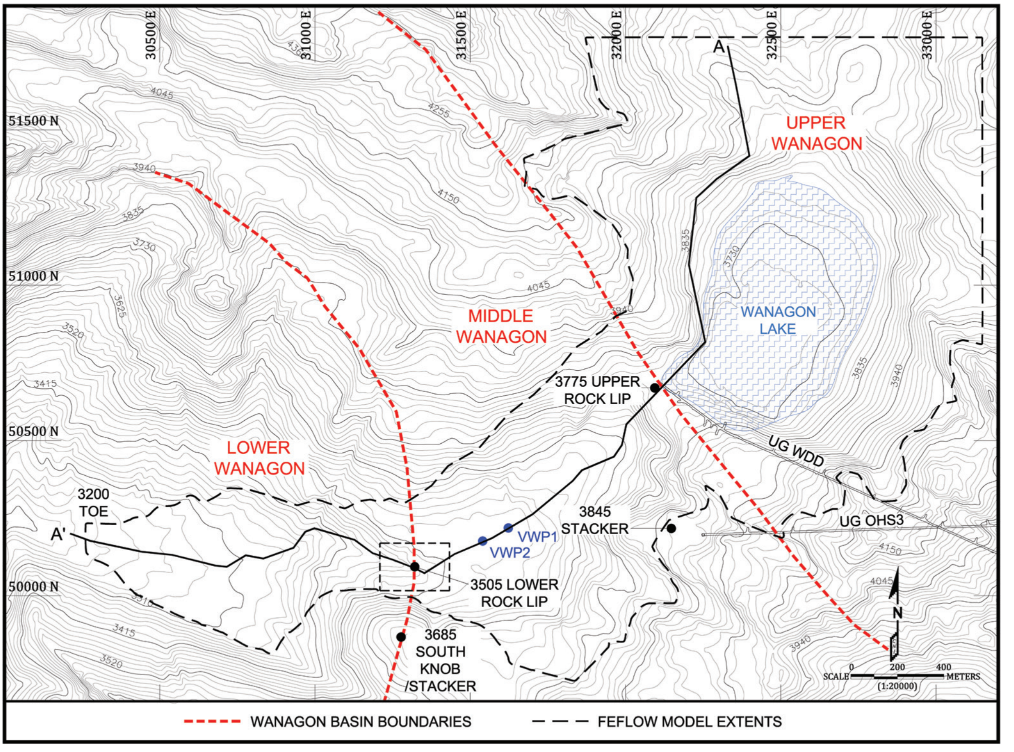

Figure 1 *Topography, features, and locations in the Wanagon Basin before stockpile placement.*

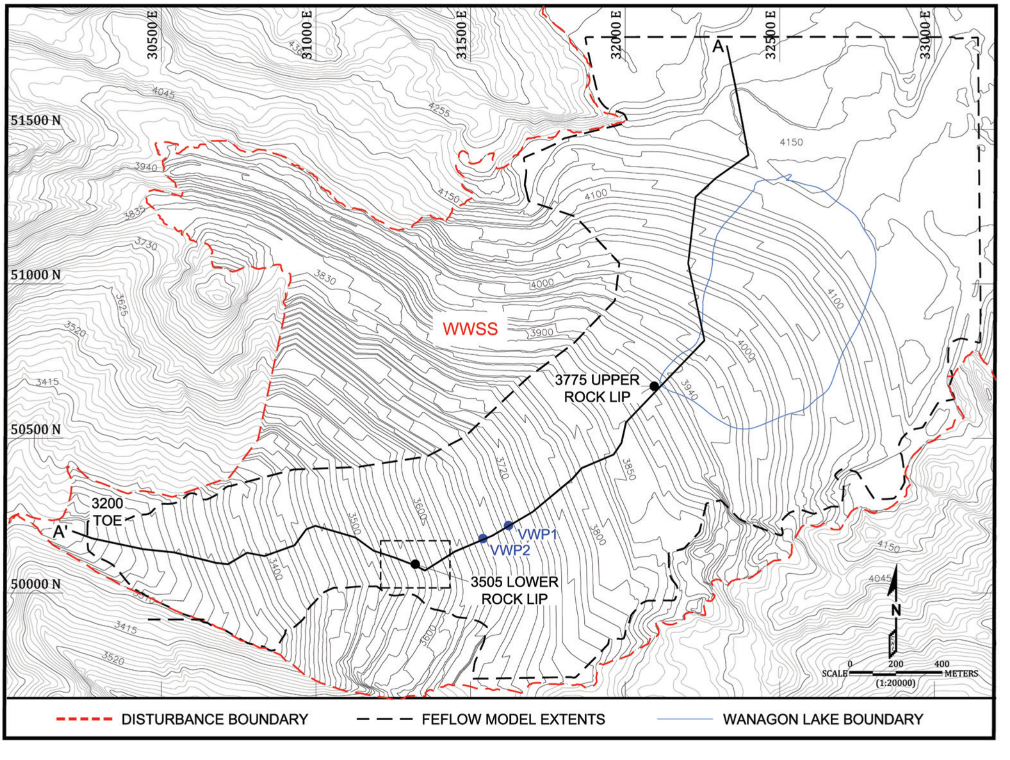

Figure 2 *Topography, features, and locations for the final Wanagon OBS Design.*

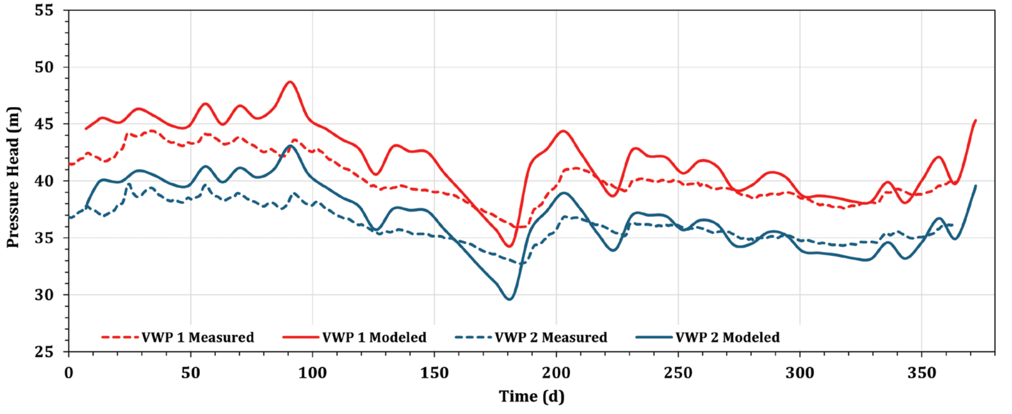

Figure 3 Calibration results for the YR2022 model.

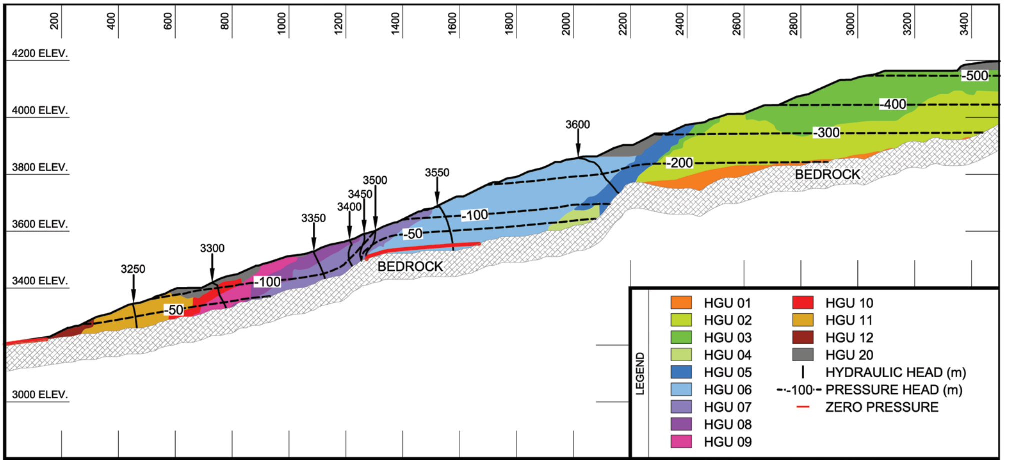

Figure 4 Results for the YRFinal model including the WDD dewatering along section A-A'.