Examples of open pit slope validation techniques to evaluate stability performance and design aspects

Edward Saunders, MEngSci

Senior Rock Mechanics Consultant, SRK Consulting, Vancouver, BC.

ABSTRACT The implementation of an open pit slope design is a function of the mine operational capabilities and the actual stability performance. Typically, the slope designs that are to be implemented are largely based on the results of drilling investigations and office-based stability assessment prior to significant pit wall exposure. Further, continual validation is required as the open pit may be significantly developed and the actual geotechnical conditions are far different to those expected during the design phase, resulting in potentially new stability risks.

From a geotechnical perspective, the implementation is closely related to the validation of the geology, structural geology, rock mass and hydrogeology components of the geotechnical model that form the basis for stability assessment and the open pit slope design procedures. This paper presents practical validation examples that are intended to demonstrate the evaluation of open pit stability performance and the slope design at operating mines.

Introduction

The intent of this paper is to present practical validation examples to evaluate open pit stability performance and the implemented pit slope designs at an operating mine. This paper is based on experience at open pit mines in Canada and internationally.

The techniques presented in this paper are industry established, however, the purpose is to demonstrate how a consulting or mining geotechnical engineer could develop work-flows to efficiently evaluate the stability performance and design aspects. Validation is an ongoing task and primary objectives of this work include the identification of new stability risks and suitability of a design based on operational capabilities and the geotechnical conditions. This type of work can allow geotechnical staff to make informed decisions with consideration to the suitability of the slope design, including:

- The implemented slope design is appropriate; or
- The implemented slope design is too aggressive as the expected stability performance is not adequately demonstrated; or
- The implemented slope design can be optimized as the stability performance is better than expected and the geotechnical conditions remain favourable.

Additionally, from a consultancy perspective, site visits can be infrequent or short in duration. Therefore, the design has to be validated efficiently as demonstrated in the office and field based examples presented in this paper.

The Geotechnical Model

The geotechnical model is the basis for the analyses and design of an open pit slope. The geotechnical model used to develop the slope design model needs to be continually validated by geologists, hydrogeologists and geotechnical engineers as new information becomes available to the project or the mine. The geotechnical conditions governing the stability performance, such as continuous fault systems, should be continuously reviewed and updated.

The geotechnical model comprises the expected geology, structural geology, rock mass and hydrogeology components (Read & Stacey, 2009). Typically, geology and structural geology is first investigated during the exploration phase of a study to define mineralization. Thereafter, the geotechnical model is constructed with the data collected from pre-feasibility and feasibility studies, and it continues to evolve with exposure of the slopes during open pit excavation.

The model can be further divided into sub-components as shown in Fig. 1.

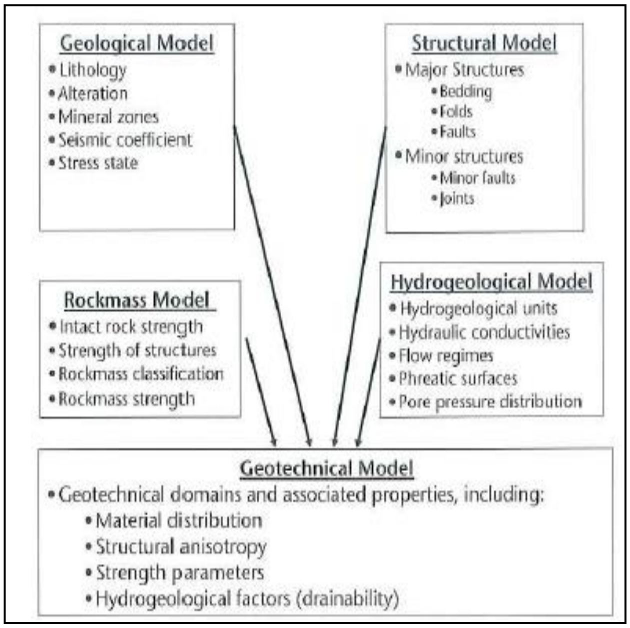

Fig. 1. Component and sub-components of the geotechnical model for open pit studies (Read and Stacey 2009).

It is industry practice to utilize three dimensional (3D) modelling software packages such as Maptek Vulcan™ and ARANZ Geo Leapfrog™ to generate a working geotechnical model. The visualization capabilities of these packages allows the user to easily identify uncertainties in existing data (i.e. continuity of a fault structures, lithology contacts) and data gaps (i.e. lack of unconfined compressive strength testing, limited drillhole coverage). An example of a 3D structural geological and geotechnical model is presented in Fig. 2.

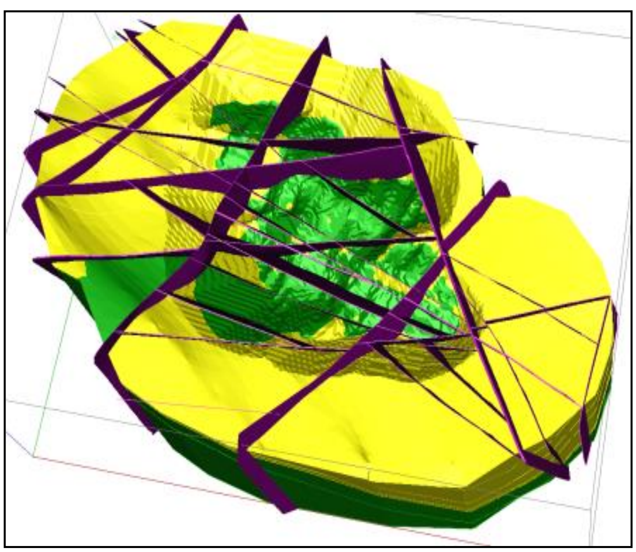

Fig. 2. Example of 3D Structural Geology and Lithology model. (SRK 2017)

The model should be continually updated with the gathering of new data as new bench slopes are exposed within the open pit. The model shown in Fig. 2 is clipped to the design shell in order to review how the expected structures and geotechnical conditions will be exposed in the ultimate pit walls.

Rock Slope Design Procedures

Rock slope design procedures are intended to establish pit slope design criteria based on the anticipated failure modes, as determined by the expected geological and geotechnical conditions. The intent of this paper is not to detail particular design methodologies, however, it should be noted that the expected performance of a slope is evaluated during the design phase of an open pit slope. A geotechnical flowchart outlining the steps required to develop an open pit slope design is presented in Fig. 3.

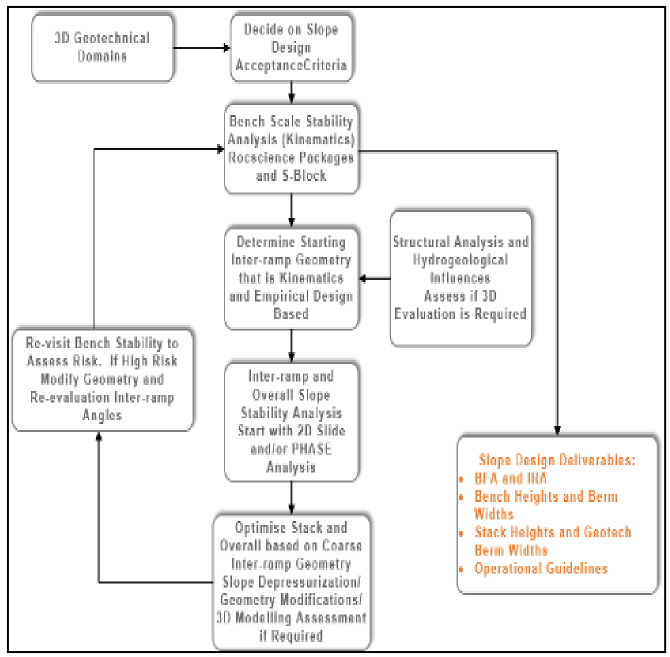

Fig. 3. Geotechnical flow chart showing key steps to develop an open pit slope design (SRK 2017)

Practical Validation Techniques

The following subsections summarise validation techniques than can be used by geotechnical staff to evaluate pit slope stability performance and the implemented slope design aspects.

Pit Slope Inspections

Pit slope inspections are a primary validation technique. The exposed pit slopes should be inspected on a regular basis to review stability performance aspects. The structural geology and rock mass stability controls identified at the slope design phase can be evaluated with respect to the observed performance. Operational capabilities such as drill and blasting practices can be assessed with consideration to the performance aspects.

The following geotechnical aspects may be inspected to review stability performance:

- The expected geology, structural geology, rock mass conditions and hydrogeology.
- Instabilities within the exposed pit slopes, including the identification of the kinematic failure mechanisms (Fig. 4).
- Major fault exposures and the impact on bench and inter ramp stability.
- Bench back-break and rock fall catchment.
- Seepage and surface water.

The operational capabilities can be inspected to review the wall control techniques. From a geotechnical perspective, these capabilities are predominantly related to the drill and blasting practices (Fig. 5). The following may be inspected:

- Bench crest back-break and/or toe flair.
- Blast induced fracturing of the rock mass exposed in the bench faces.
- Cleaning of the catch benches and scaling of the bench faces.
- The pit floor surface profile.
- Surface water ditches and sumps.

Fig. 4. Longitudinal tension cracks related to toppling failure mechanisms along sub-vertical joint structures exposed in the underlying bench.

Fig. 5. Back-break of benches due high fragmentation from poor blasting as well as unfavourably orientated joint structures.

Photography

A record of photography is essential to review the geotechnical components that govern stability performance through time, and in particular the major geological structures. For example, the geological structures that were exposed prior a push-back or pit flooding may still govern future potential instability. The photographic record can be used to review these structures with consideration to the previous, current and future slope performance.

As-built Surveys

Regular as-built surveys of the open pit provide a basis to compare the achieved slope profile against the design. Techniques including terrestrial surveying, laser scanning, drone scans and LiDAR can be used to generate as-built surveys. The comparison of surveys in two dimensional section provides a simple approach to review the achieved configuration against the design.

Bench face (BFA) and inter-ramp (IRA) angles, bench heights and widths, and stack heights should be measured off the as-built survey sections and regularly compared against the design parameters, as shown in Fig. 6. These comparisons allow the geotechnical staff to review and form a feedback loop into the design adopted by the mine planners. At the bench scale, the survey can provide valuable information pertinent to blasting such as bench break-back or toe flair. At the inter-ramp scale, the slope angles may be governed by the overall rock mass stability, and it is critical that these are at or below the recommended angles.

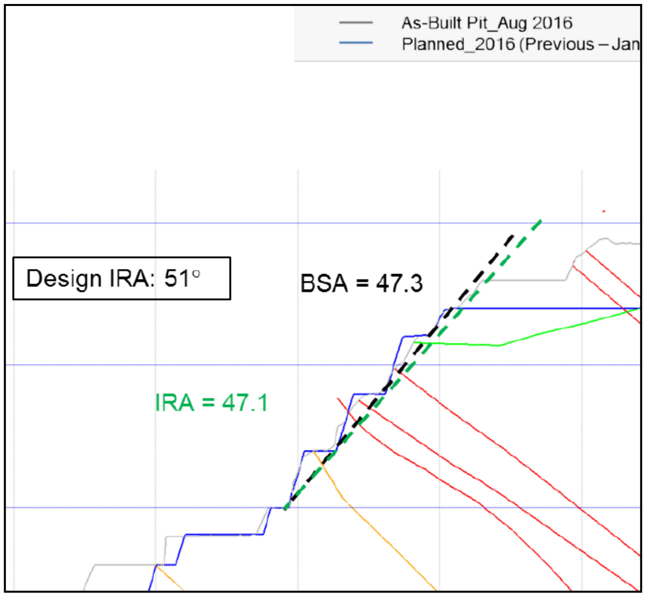

Fig. 6. Comparison of as-built pit survey (grey) and design pit shell (blue). Achieved IRA of 47 degrees is shallower than the design IRA of 51 degrees.

Bench widths can be measured off the as-built survey and the distributions graphed to compare against the design, as shown in Fig. 7. Where bench widths are regulated, such as the minimum 8 m design bench width in British Columbia, this validation approach can be used to demonstrate both the performance and design aspects. Where rock fall is significant, this approach may direct the geotechnical engineer to revise the allowable catch bench design for future excavations.

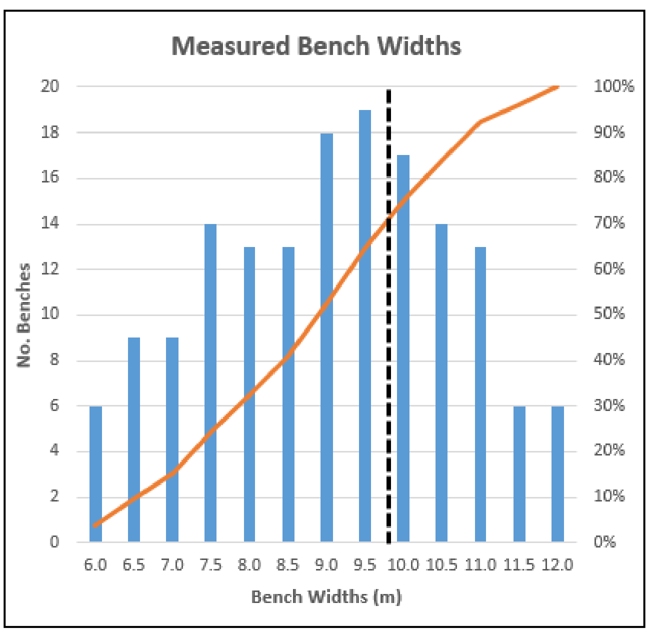

Fig. 7. Distribution of bench widths measured off an as-built survey. The design bench width of 9.8 m is shown with dashed line.

3D Structural Model

For structurally controlled pit slopes, the 3D geological model is critical to assessing current and future stability. The model should be reconciled regularly with mapping of the major and intermediate structures as new benches are exposed (Fig. 8). The location, orientation, character, and continuity of these structures should be documented in a structural matrix. The character information can be compared against the fault shear strength parameters in the computation stability analyses. Fig. 8 presents an example of orientation disks that represent pit mapping of major and intermediate fault structures. The mapping is compared against the existing 3D structural model. Where required, the structures should be revised to fit the location and orientation of the mapped structures within the pit.

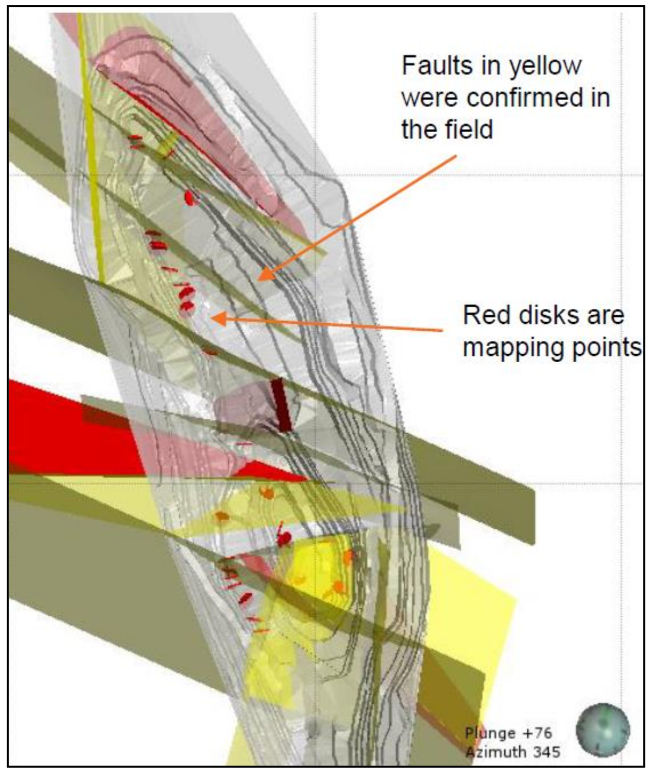

Fig. 8. Example of mapping orientation disks in red and the comparison against the existing 3D structural geological model.

Bench Face Mapping

Geotechnical mapping of newly exposed bench faces should be performed in order to collect rock mass and discontinuity data. This data can be used to validate the following:

- The fault and discontinuity sets that were used to evaluate the kinematic controls on bench and inter-ramp stability; and

- Rock mass classification and strengths that were used as input into the inter-ramp and overall stability analyses.

Slope Instability Records

Slope instabilities should be documented and plotted in plan to understand the performance of the respective geotechnical units within the pit. The documentation should include details such as date and time, instability mechanism, geotechnical unit(s), and estimated failure volume. These records can be used for the following:

- Prediction of future slope performance and instability based on similar kinematic and rock mass conditions;
- Provide empirical design guidance for future slope design, including slope height vs stability graphs (Fig. 9); and
- Perform back-analyses to determine shear strength parameters at failure for the respective geotechnical units. These back-analysed parameters can be evaluated against those used in design.

A stack height and inter-ramp slope angle chart for failed and stable slopes is presented in Fig. 9. This graph was used to empirically design inter-ramp slopes and maximum allowable stack heights for volcanic saprolite materials that were to be excavated in a nearby pit slope.

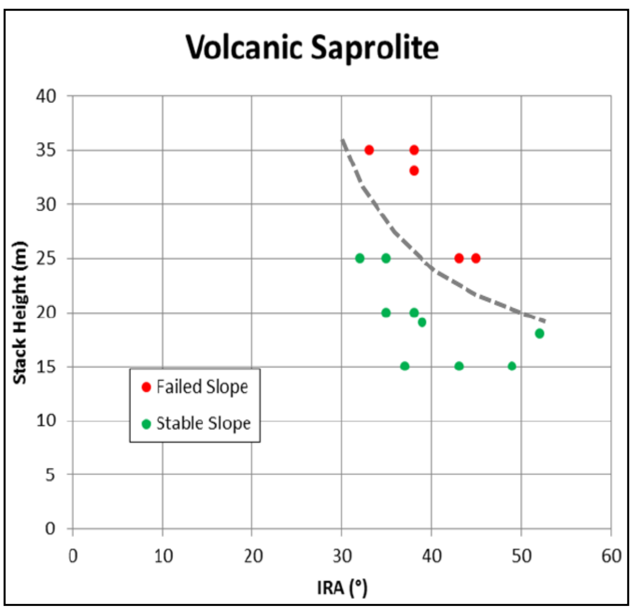

Fig. 9. Empirically derived chart for stable and failed slopes in volcanic saprolite materials. The chart was used as guidance for slope design in volcanic saprolite materials.

Slope Monitoring

Open pit slopes should be monitored both visually and with instrumentation, such as prisms and radar. Slope monitoring data collected from prism installations can provide a record of local and overall stability. Seasonal and baseline conditions can be established to identify potential instability trends. For example, increases in horizontal and vertical displacement in bench slopes can be observed during the spring freshet in British Colombia. This slope monitoring data can be additionally used to evaluate a direction of instability out of a slope and allow inverse velocity calculations to predict timing of a failure.

Hydrogeology Monitoring

Groundwater data collected from vibrating wire piezometers installed around the open pit should be reviewed on a regular basis to evaluate the dewatering and depressurization of the pit slopes with the lowering of the pit floor. The data can be used to identify seasonal trends and surface water responses that may adversely affect pit slopes, such as those excavated in weaker saprolite or weathered rock materials.

An example of a hydrograph showing groundwater elevations reducing with the excavation of a pit is shown in Fig. 10. The shallow sensors located in transition rock units indicate a direct surface water response to rainfall, and both the shallow and deeper sensors show continual dewatering trends with the lowering of the pit floor. The groundwater conditions can be evaluated against the predicated models developed during the initial slope design phase. Should the monitoring data indicate less favourable groundwater conditions, the data can be used to guide decision making toward passive measures such as horizontal drain holes or active depressurization using vertical pumping wells.

Summary

The validation examples presented in this paper have been used to evaluate the performance of open pit slopes and the suitability of the design that is being implemented by mine operations. There are a number of other techniques to those presented in this paper that can be applied, however, this summary paper is intended to present techniques that have been applied by the author to systematically evaluate performance and design aspects at mines in Canada and internationally.

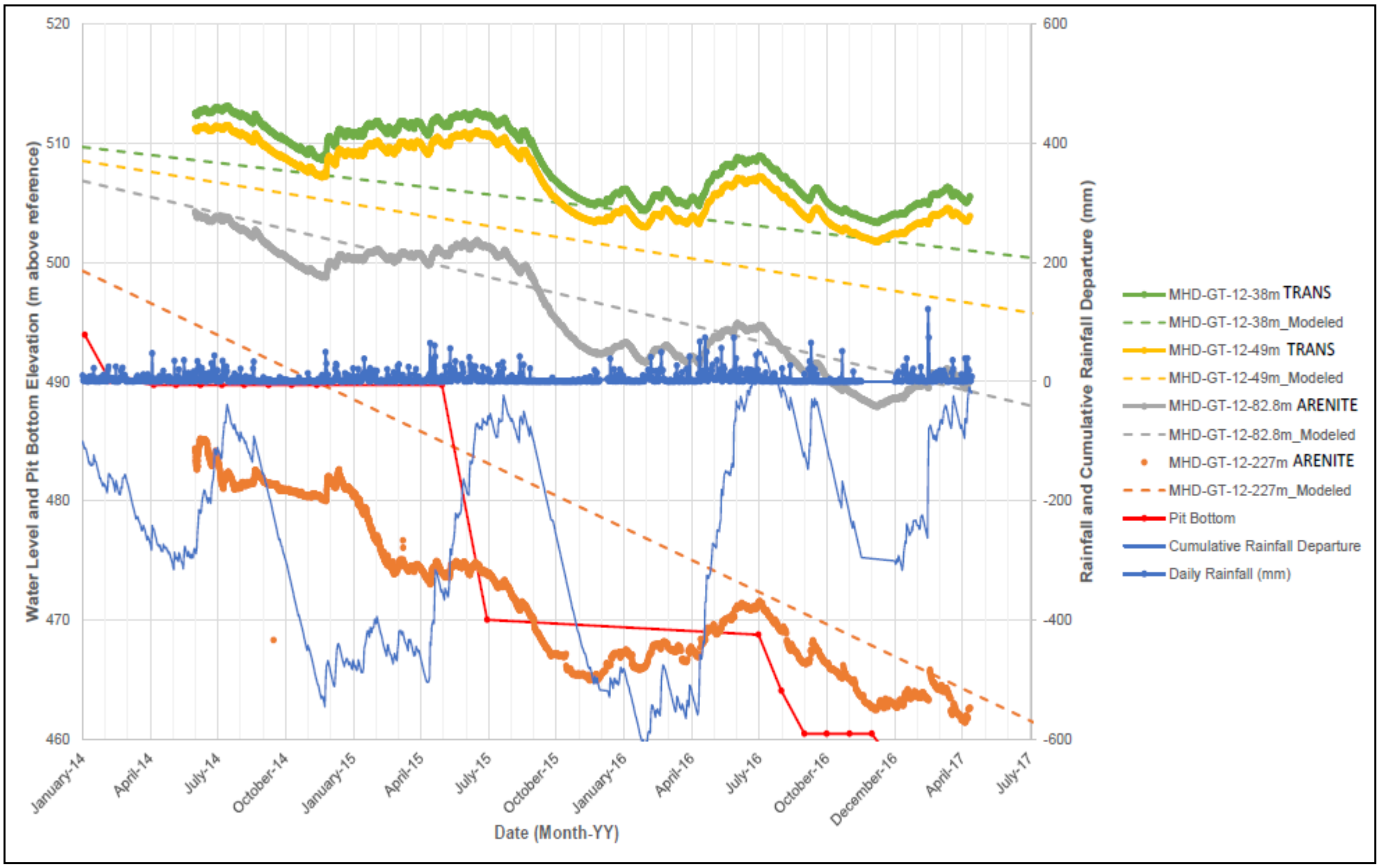

Fig.10. Hydrograph showing groundwater elevation data from a vibration wire piezometer installation. Hydrograph shows surface water responses in the shallow sensors and a general dewatering trend with lowering of the pit floor (red line).

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