Application of GeoHazmap to the Pit Slope Design for the Detour Lake Project

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Abstract
The management of a large amount of geotechnical data is always challenging in any pit slope design. The development of GeoHazmap© has allowed the integration of the data, the evaluation of potential hazards to the pit design, and the estimation of an overall hazard index, which can be customized and/or calibrated to actual pit slope performance. In addition, by plotting individual hazards or overall hazard index on any phased pit shell, GeoHazmap can simplify and improve the understanding of the hazards for the pit slope design.

GeoHazmap, developed by Mira Geoscience in partnership with Golder Associates, is a system for geotechnical hazard analysis. It leverages GOCAD’s unique 3D-GIS capability to quantitatively integrate multiple inputs with different assigned ratings into a meaningful output that can be queried. For the Feasibility Study of the Detour Lake project, owned and operated by Detour Gold Corporation (“Detour Gold”), GeoHazmap was applied to create a general (or composite) hazard index by applying ratings (or weighting) for the following site specific hazards: i) proximity to weak talc chlorite zones, of concern for pit stability, ii) proximity to interpreted faults (which were also sub-classified by their importance from the rock mechanics viewpoint), iii) proximity to existing drifts and underground stopes and iv) orientation of the wall in relation to the main foliation sets. Once the hazards workflow was created, it was applied to the intermediate and final planned pit shells to generate the overall hazard index. This was then plotted on the planned pit walls, highlighting the critical design sectors and assisting Detour Gold in defining appropriate acceptance criteria for the pit slope design, i.e., defining the level of performance required for any slope segment against instability and determining the best location for the ramp.

As the project advances to design implementation during mine operation, the GeoHazmap program will be used for: a) the reconciliation of the planned and actual slope geometries, and ii) real-time integration of the monitoring of slope deformation to evaluate slope performance.

1 GeoHazmap as a geotechnical data management tool

Mine engineers and planners need to understand the hazards associated with the ground that they are, or will be, working in. Poor rock quality, dilution, excessive ground stresses, and water inflows, for example, can have significant impact on mine scheduling and revenues. Inadequate understanding or disregard for these hazards can cost a mining company money, equipment, and, in extreme cases, lives. Geotechnical hazards need to be considered and quantified through observation and measurement. Ideally, the geotechnical model (a.k.a. engineering geology model), would continue to grow and evolve as more of the mine is uncovered.

For a mine engineer or mine planner, technology can be both friend and foe. Over the past 10 years or more, the world has gone digital, mines being no exception. Computer screens and keyboards are replacing traditional pencil and paper at mine sites and at corporate offices. With this advance in technology, tens of thousands of
metres of drill core data can be analyzed and processed in a few days, and a virtual mine can be developed in a few weeks.

The downside of these advances might be summarized by the expression ‘too much of a good thing’. With the flood of digital data, the answers, and ideas which are required in the design process might lie hidden in a mine-site computer, rather than be on display for all to see and discuss. A simple drawing table with up-to-date mine plans and sections is becoming a rarity. In turn, communication of concepts and ideas has become more about exchanging emails and trading memory sticks. Our world is going digital, as are our mine offices. The difficulty is in keeping up and on top.

The challenge of keeping up-to-date on geotechnical data was a primary reason for the development of the software application GeoHazmap. GeoHazmap is a GOCAD plug-in developed by Mira Geoscience in partnership with Golder Associates. The goal of the software is to evaluate potential hazards related to open pit and underground mines both spatially and statistically, and to present the results of the hazard assessment in 3D graphical form. This 3D ‘hazard map’ provides a one-off tool for planners and decision makers, which allows quick and easy identification of potential hazard areas, and thereby helps to prioritize investigation and design targets, and plan pit schedules.

2 The GeoHazmap workflow

The main benefits of the GeoHazmap plug-in stem from its simplicity and ease of customization. The main steps of the hazard mapping process include:

1. Identification of geotechnical hazards;
2. Assignment of a hazard rating scale to each hazard, and;
3. Calculation of the overall hazard index by spatial location and time.

These main steps are discussed in more detail below:

2.1 Identification of geotechnical hazards

The identification of geotechnical hazards typically begins during the early stages of a mining project. A simple Scoping Level desktop study is often able to identify geotechnical hazards which might become an ongoing concern. Information on a site’s regional, local and structural geology can help identify locations of major faults, adverse rock structure, poor quality rock domains, etc.

As the project evolves through Pre-Feasibility and Feasibility planning stages, data collection, analyses, and numerical simulation help refine the understanding of these various geotechnical hazards, which may help understand the actual level of risk. For example, a fault that geologists have inferred through lithological offsets at the preliminary stages of a project, may prove to have inconsequential geotechnical risk once its properties are shown to be similar to those of the host rock.

Geotechnical data access increases exponentially once mining commences. Measurement of ground response (stresses, displacements, seismicity), and collection of geotechnical parameters (through mapping and drilling) can provide great insights into operational risks. This in situ data collection can then be carried forward into future planning stages. It can also result in large amounts of data which need to be effectively managed and communicated.

A summary of potential geotechnical hazards is not given in this document, since these hazards need to be identified and addressed on a case by case basis. Some hazards, such as the locations of faults, adverse dipping of foliation/bedding, poor quality rock units, existing underground workings, etc., can be obvious and easily explained. Others might be less obvious (e.g., occurrence of high water pressures or high induced stresses), and may require experience and careful study during operations.
In addition to geotechnical/hydrogeological hazards there could be other mine hazards associated with high risk impact potential, such as proximity to: old underground openings, mine infrastructure (e.g., shaft and waste dumps), environmentally protected areas (creeks, marshlands), or public roads. These types of hazards can also be tied into the GeoHazmap.

2.2 Assignment of the hazard rating scale

A hazard rating scale is required to quantify identified hazards at a mine site. Through a task driven workflow, hazard criteria are selected and scored according to their relative risks and consequences. They are then summed to produce an overall hazard index on the surfaces of the pit shell or on a vertical section through the pit.

In the GeoHazmap, the hazard risk criteria selected by the user are normalized to a common scale so that the hazards can be appropriately weighted relative to one another. If no weighting scheme is used, a simple binary (yes/no) rating system can be used. For example, if 5 hazards are identified for the mine, and each one has a value between 0 and 1, this would result in an overall hazard rating scale of 0 to 5. In this system, a rating index of 5 in an area represents the highest potential hazard.

In a weighted rating system, the perceived risk for any one particular hazard might be notably higher, and therefore a higher weighting is applied to this hazard. For example, it might be decided that the distance to the intersection of two faults may present more risk than simply the distance to a single fault, and therefore would be assigned a higher rating factor. A maximum rating index of 0 to 2 could be applied to the fault intersection; the single fault would have a maximum rating of 0 to 1, while the overall hazard index would increase up to 6, following the example from the previous paragraph.

The RMR values, obtained from rock mass classification, can be plotted as varying from 0 to 100, in 20 point intervals, or as hazard ratings ranging from 0 to 1, in 0.25 intervals. This makes it easier to visualize areas of poor rock mass quality.

In addition to measured rock mass and hydrogeological parameters, predictive data from numerical models, such as pore pressures, induced stresses, and displacements, can be applied to the hazard model.

It should also be appreciated that the hazard rating process in itself can provide valuable discussions and insights into the mine project. The hazards can be plotted individually to better understand the components of the overall rating system.

2.3 Calculation and plotting of the hazard index

In its simplest form a mine hazard can be represented as a function of location (X, Y, Z), time, and risk. The summation (or any other mathematical relationship) of hazards in terms of their relative weightings can be represented in the following formula:

\[ \text{Hazard}(x,y,z,time) = f(\text{hazard1}, \text{hazard2}, \text{hazard3}, \ldots, \text{hazard}(n)) \]

GeoHazmap has the ability to rerun a workflow quickly with different parameters to efficiently explore multiple scenarios, and gauge the impact of a hazard criterion’s weight on the overall hazard index.

An example of a typical workflow to derive the hazard index is highlighted on Figure 1. In this example, 4 main hazards (rock code/type, rock quality, faults, and seismicity) are included in the overall hazard index. Each hazard has an individual rating and two of the hazards (faults and seismicity), have their own sub-rating criteria that depend on perceived consequences.
For summing the hazard index for any point in space (and time), the individual hazard rating criteria can be normalized based on the distance of the point to the location of the hazard. In GeoHazmap, the hazards are imported as block models, wireframes, strings, or points which can be produced from any conventional 3D modeling software.

An example of the overall hazard index plotted on a pit shell is shown on Figure 2. The hot colors (reds) signify areas on the planned pit with higher hazard ratings. In this example, the north wall of the pit shows relatively high potential hazard. With this one-off assessment, it would then be worthwhile to look in more detail at the causes of this increased risk in the north wall, and whether mitigative measures might be required to help reduce the potential impacts to operations. Mitigative measures in this example might include consideration for increasing the berm widths thus reducing the angle of the slope, or moving the ramp configuration to the south wall of the pit.
2.4 Development of the geotechnical block model

For clarification purposes, it is common practice to have the geotechnical attributes obtained from geotechnical core data, such as RQD and RMR (or Q), added to existing geological or mineral resource block models using the same statistical principles and techniques as those used in resource estimation. The resulting block models can make up most of the 3D Engineering Geology Model (EGM), including geological, structural, rock mass classification, and sometimes, hydrogeological data. The 3D EGM can be built in GOCAD (or imported from other modelling programs into GOCAD), where the faults and other major structure are entered as wireframes, and the geotechnical properties related to the rock mass can be applied within the statistical block model framework.

In application of the geotechnical parameters from the block model to the GeoHazmap hazard model, a weighted hazard scale is incorporated, for instance, for the RQD and/or RMR values.

The advantage of using GeoHazmap compared to other programs is that it allows not only the mapping of mine hazards, but also the correlation of these hazards either by summing them up to obtain an overall hazard index (as presented in this paper), or by using other mathematical relationships.

3 GeoHazmap applied to the Detour Lake open pit project

The Detour Lake gold project is a large scale, low-grade gold reserve currently being developed by Detour Gold Corp. (www.detourgold.com) in northeastern Ontario, approximately 180 km northeast of Cochrane. The feasibility study mine plan includes the development of a large pit, with approximate dimensions of 2.5 km length, 1.5 km in width, and up to 550 m depth. The results of the feasibility study, completed in 2010, indicated that Detour Lake contains an estimated open pit mineral reserve of 11.4 million ounces of gold, capable of producing nearly 650,000 ounces of gold annually over a mine life of 16 years. Following a successful drilling campaign in 2010, Detour Gold increased the mineral reserves to 14.9 million ounces of gold. Construction of the mine started at the end of 2010 with gold production expected in early 2013.

The pit geology mainly comprises hanging wall massive and pillow theoilitic flows and komatitic flows and footwall volcanicleastic, quartz wacke, and mafic volcanics. The hanging wall and footwall rock units are transected by the Sunday Lake Deformation Zone (SLDZ), which is the main east-west striking geological structure in the pit. The rock mass within the pit walls is generally anticipated to be very competent, and of good to very good quality (e.g., RQD > 75% and RMR > 70). The SLDZ deformation zone is known to consist of sheared talc chlorite and chloritic greenstone rock masses, with reduced strengths and fair quality. The talc chlorite units are thickest towards the eastern pit area. Here the Talc Chlorite Zone will be used to define the weaker portions of the SLDZ and the locations of fair (and in localized places poor) rock mass quality within the planned pit shells. This means that, except where faults with broken core occur, within the Talc Chlorite Zone, the rock mass is of fair/poor quality and elsewhere of good quality.

Several smaller faults and shears have been inferred to transect the pit. Review of exploration core for identification and geotechnical characterization of these structures helped identify design sectors where the intensity of faulting and shearing is more prevalent. Ongoing data collection aims to more accurately characterize such fault structures.

The Detour Lake mine was operated by Placer Dome from 1983 to 1999. The site has seen both underground mining and a relatively small pit (labelled the Campbell pit) at the eastern extent of the currently planned super pit. The underground stopes follow the east-west trending of the SLDZ, plunging towards the west. The mine site was closed in 1999.

Golder Associates Ltd. has been assisting Detour Gold with the design of the open pit through the Pre-Feasibility and Feasibility design stages. Data collection has included; review of historical information, oriented core geotechnical drilling, borehole televiewer imaging, and hydrogeological (packer) testing.
A preliminary GeoHazmap hazard model was developed for the open pit during the Feasibility Geotechnical Study. Several criteria were used to evaluate hazard potentials for the various phases of planned pit development. Based on the results of the geotechnical investigations discussed previously, the hazard criteria were identified, evaluated and subsequently weighted to produce an overall hazard index for visualizing areas on the pit walls of increased risk.

The hazard criteria and weightings incorporated into the Detour Lake hazard map included (Fig. 3):

- Rock quality represented by the occurrence of the Talc Chlorite Zone - a hazard rating of 1 was applied for the Talc Chlorite Zone, and 0 to rock outside it.
- Proximity to major faults and shear zones. For the case presented here, the orientation of the faults was not considered in relation to the pit shell. Rather, the occurrence of a fault was used as an indication of zones with lower rock mass quality.
- Presence and proximity of existing underground openings (i.e., stopes and drifts).
- Wall orientation in relation to the main discontinuity/foliation sets (set Fo1A has a mean dip / dip direction = 79°/000° for the footwall, while set Fo1B has mean dip/direction of 77°/185° for the hanging wall).

![Hazard Rating Criteria Diagram](image)

**Overall Hazard Index**

- Away from Fault
- Away from U/G Openings
- Outside Talc Zone
- No influence Foliation

Figure 3. The preliminary GeoHazmap workflow and hazard criteria developed for the Detour Lake Project.
3.1 Overall hazard index on the intermediate (Phase II) shell

The overall hazard index was defined as the sum of the individual hazard ratings (Rock quality + Proximity to Faults + Proximity to U/G openings + Wall Orientation in relation to foliation set). It varies from 0 to 5 (note that separate ratings were applied to stopes and drifts, increasing the total ratings to 5). As shown on Figure 3, a value of 0 for a pit wall section would indicate that it is away from the faults and underground openings, outside the talc zone, and with minimum to no influence from the foliation. On the other hand, an overall hazard index of 5 would represent an area close to faults and underground openings (both stopes and drifts), within the talc zone, and fully impacted by the foliation.

With additional information and interpretation, the hazard rating criteria used for the preliminary hazard maps could easily be modified for better delineation of perceived ‘high hazard’ areas.

Overall hazard indices were estimated with and without the hazard index for proximity to fault locations. This was done because there was higher confidence in the location and occurrence of the Talc Chlorite Zone, underground openings and dip direction of the foliation sets Fo1A and Fo1B, compared to the fault locations. This reduced the overall hazard index up to 4 when without the influence of faults, as represented on Figure 4. The figure shows the distribution of the individual hazard ratings on one of the intermediate (Phase II) pit shells, as well as the overall hazard index obtained by adding these individual ratings.

The immediate application of the hazard ratings can be viewed singly or in combination. Figure 4a shows in light/dark red which design sectors will be impacted by the dominant foliation set, while Figures 4b and 4c show where the stopes and drift would daylight into or be in close proximity to the pit shell. Figure 4d shows where the Talc Chlorite zone will daylight on the pit shell. Figure 4e presents the overall hazard index, which is the summation of each hazard. Comparison of the single hazard maps with Figure 4e, which highlights the main areas of risk, suggests that design attention needs to be given to optimizing the position of the ramp in the south wall, as discussed next.

Figure 4. Application of GeoHazmap on the Phase II pit shell (excluding the influence of faults).
3.2 Example of ramp location

The overall hazard index, draped on an intermediate (Phase II) pit shell shown on Figure 5, suggests that, without the influence of the faults, the initially proposed ramp location would traverse areas with higher hazard indices (due to the foliation, proximity to an existing underground stope and proximity to the fair/poor quality Talc Chlorite zone). This representation allowed the Detour Gold team to move the ramp to a higher elevation to reduce exposure to this hazard and avoid the use of ground support. This simple application of GeoHazmap has also been useful for other projects, for planning the switch backs of the ramps, and deciding which wall sections for developing the ramp would present fewer hazards.

Figure 5. GeoHazmap draped on the Phase II pit shell (excluding the influence of faults) emphasizing the hazards on the initial ramp location.

3.3 Overall hazard index on the ultimate (Phase III) shell

Several iterations of hazard assessment were carried out using various weightings and hazard parameters. Because the rock quality at the site is generally good to very good, it was determined that the hazard rating for RQD (or RMR) did not change the hazard distribution, since rock quality was already accounted for by the Talc Chlorite Zone factor. This is what made it possible to reduce the number of hazards to the four hazards described on Figure 3.

The overall hazard map for the ultimate pit, shown on Figure 6, includes the delineated fault traces with perceived low shear strength characteristics. The zones of the pit showing the highest perceived hazards are reddish in colour, corresponding to the intersection of the weak talc chlorite rock units with the existing underground workings at the planned pit floor. The intersection of mine workings were also interpreted to be one of the main design challenges going forward, and extensive 3D numerical modeling was carried out to assess these potential instabilities.
Figure 6 also suggests that the western portion of the pit has potential to be significantly affected by the faults with potential for wedge failures mechanisms to occur. As a result, the inter-ramp angle was slightly reduced in that sector, despite the positive contribution of pit wall curvature.

Because the current pit design is at the feasibility level, the majority of the hazards are based on interpretations from historical records, drillcore, and geological mapping. As the pit moves into production, geological and geotechnical data collection from the exposed pit walls will allow for updates to the hazard map, and reorganization of the hazard workflow criteria. There will also be the opportunity to incorporate real-time monitoring data into the GeoHazmap.

3.4 Probabilistic kinematic assessment

Stability assessment through kinematic analyses is usually carried out using either a deterministic or probabilistic approach. In the deterministic approach, the major (or dominant) and minor peak set orientations established through structural fabric analysis are considered representative of the orientation of controlling failure surfaces. In the probabilistic approach, all the measured discontinuities for a given structural domain are used in the evaluation of potential planar or wedge failures. Cumulative frequency distribution curves for all the potential planes or wedges encountered are then generated. These are each assessed for a given factor of safety in order to build the cumulative density function (CDF). It is common practice to then establish threshold values of acceptable probability of failure for defining inter-ramp and/or bench face (or batter) angles.

The ability to conduct probability assessment has been incorporated into GeoHazmap application plug-in, where the geotechnical engineer provides: i) the stereonet for each structural domain, ii) the shear strength along the discontinuities, iii) the target factor of safety and iv) the threshold probabilities of failure. The GeoHazmap solver takes into account the wall dip direction using the initially planned pit shell (or pit design).

For illustration purposes, Figure 7 shows an example of the probability of planar failure for one of the Detour Lake design sectors. For the bench face angle (BFA), assuming an allowable probability of planar failure of 40%, for instance, Figure 7 indicates the potential for bench face angles of up to approximately 70°. Similarly, for an allowable probability of ramp failure less than 20%, Figure 7 suggests an inter-ramp angle of no more than 55°.
Based on the stereographic projection of the structural data obtained from eight core-oriented drill holes and 10 televiewer surveying holes, structural domains were identified. Using GeoHazmap, inter-ramp angles were estimated for each structural domain, considering an allowable probability of ramp failure of 20%, and the results are plotted on the pit shell (Fig. 8), allowing quick identification of wall sectors where further refinement stability analyses were required for the pit slope design.
4 Final remarks

Use of GeoHazmap© as a workflow procedure to highlight high hazard potential problems has been incorporated in Golder’s pit slope design approach for large open pits. Its use has enhanced standard pit design procedures by allowing rapid integration of a large amount of data into an overall hazard index. This simplifies and improves initial understanding of potential hazards for pit slope design. As the process facilitates pit optimization, the benefits of visualizing potential hazards in 3D around any phased pit shell have been well received by mine planners.

As the Detour Lake project advances to design implementation during mine operation, GeoHazmap procedures will be used to: a) reconcile planned and actual slope geometries, b) compare areas with high predicted displacements from 3D numerical modeling to actual (measured) displacements, and c) monitor slope deformations in real-time.

While not used in the Detour Lake case study, it is important to note that many other criteria (such as microseismic events) within the GeoHazmap workflow can be reconfigured to accommodate new data. The workflow can be automatically rerun in near real-time as new data is fed into the model.

The use of GeoHazmap techniques in conjunction with appropriate hazard registers have the potential to highlight all major hazards for pit development, but like all enhanced sophistication in modern computer-aided design and enhanced 3D graphical presentation techniques, it must always be remembered that they are only as good as the input data. Increasing the sophistication of presenting information does not in itself reduce potential geologic risk – only drilling, wall mapping and additional data, in conjunction with appropriate design modifications, can achieve that (Carter, 1992). Essentially, the GeoHazmap is an additional tool for the mine planner and engineer, but does not replace good investigative practices and engineering judgment.

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6 References
