Three–Dimensional Rock Fall Simulation in the Mining Environment Using Hy_Stone

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Abstract

Quantification of risk of rock fall is an important part of improving the safety of rock slopes in open-pit mining. Pit slope benches have traditionally been designed using simplified criteria (such as the Ritchie criteria) or one of several available two-dimensional software programs. Historically, 2D modelling tools have provided adequate guidance on catch bench width and berm designs for a variety of slope materials and bench face angles. However, in the real world, slopes rarely conform exactly to these designs. Actual open pit slopes are mostly convex or concave along a slope sector, and are thus affected by convergence or dispersion of actual rock fall paths. In addition, weathering, freeze/thaw action, back break, small/medium scale slope failures and other forms of erosion, acting over time along with geologic structure, modify the conditions from the “ideal” designs, thus making a reliable rock fall assessment difficult. Moreover, the mining environment is characterised by peculiar features affecting rock fall occurrence and dynamics (e.g. back break, bench failure causing rill to form, rock masses disturbed by mining). Important to safety is whether personnel and equipment should be allowed to operate below slopes that no longer meet the original design. 2D analysis can provide some insight into rock travel paths, but rock fall is a 3D process and travel paths may vary significantly from the 2D case. In this perspective, we applied the 3D rock fall simulation program Hy_Stone in different open-pit environments. The software, which has been used since 2001 to assess natural rock fall hazard, operates within the ArcGIS environment and can be used to account for complex 3D conditions. Using accurate digital terrain models (DTM’s) and calibration to known events or field tests, Hy_Stone is capable of statistically predicting a range of outcomes including travel paths, energy, rock size distribution and the distribution of rock fall among other factors. In addition, a fragmentation module has been added to Hy_Stone to assess the break up of rock particles and evaluate the travel paths of the fragments. An example of a Hy_Stone analysis along with a semi-quantitative risk analysis is presented which demonstrate how this tool can improve the understanding of rock fall hazard incorporating the peculiar characteristics of the mining environment.

1 Introduction

To evaluate open-pit slope conditions, an operator uses a variety of analyses, management plans, and operational methodologies’ that attempt to quantify, manage and ultimately reduce the risk to workers potentially exposed to geotechnical hazards. A fundamental question that is posed to an operator of an open pit mine involves the question, “are the slopes safe?” To this effect Rio Tinto has supported research and sought out new methodologies to understand, quantify and manage geotechnical risk, specifically rock fall risk. This paper discusses one new methodology that can be utilized, amongst a variety of tools available to both the designer and operator, in assessment of rock fall hazard. Understanding and quantification of the hazard can then be utilized in a slope management program to reduce risk of such occurrence. Although this paper primarily discusses a 3D rock fall analytic technique, it must be stressed that this new tool is just one aspect of an overall integrated risk based approach to the management of geotechnical hazards. In the example that is presented, extensive risk analysis, mitigation management and proactive measures were utilized so that an open pit area that was initially
assessed as having a high risk, was managed in such a way to both avoid hazards and provide mitigation measures.

Rock fall constitutes one of the biggest risks to an open pit miner. Rock fall is controlled in the mining environment by designing appropriate catch benches for a set of berm angles and bench heights which culminates in the inter-ramp slope angle. Better understanding of rock fall behavior and being able to model and best limit this exposure/risk represents a major contribution to the business.

Catch bench design width is often based on empirical approaches (Ritchie, 1963), “Modified Ritchie Criteria” (Call, 1992), local code (minimum berm width design) or a combination of empirical and analytical approaches, such as the use of 2D modelling tools (Pfeiffer and Bowen; Azzoni et al., 1995; Stevens, 1998; Bartingale et al, 2009). These methods essentially model slopes as straight line segments in 2D. As most practitioners are aware, catch benches are not excavated exactly according to design. Furthermore, as a result of back break, spillage on benches, ravelling, blast control and other factors, the effective catch bench width can result in dramatic changes from the original catch bench design. In these cases, a 3D methodology is clearly required to better assess the rock fall hazard. This paper summarizes a case study of 3D rock fall modelling using the Hy_Stone code in a open-pit mine to discuss the advantages and challenges of using this approach in the mining environment.

1.1 Rock fall modelling approach

In this work, a special version of the 3D rock fall simulator Hy_Stone (Agliardi and Crosta, 2003; Crosta et al., 2004; Frattini et al., 2008; Agliardi et al, 2009) has been used to simulate mathematically rock fall frequency and run out. The code computes rock fall trajectories in 3D with a multi-scale, spatially-distributed stochastic approach. It takes advantage of increasingly available high-resolution 3D topographic data, obtained by topographic survey or remote sensing techniques (e.g. aerial LIDAR, Terrestrial Laser Scanning, and Terrestrial Digital Photogrammetry).

In the Hy_Stone code, topography is represented by vector triangulate network derived by raster Digital Elevation Models at any cell size. The DEM is provided to HY_Stone as a raster grid file, with the size of the grid constraining the accuracy of the topography. The spatial resolution of topography exerts a major control on modeling results, since it affects the ability/need to explicitly represent slope roughness (Agliardi and Crosta, 2003). Therefore, model resolution must be carefully defined before undertaking a modeling task, depending on required detail and available budget.

Hy_Stone incorporates a hybrid (i.e. mixed kinematic-dynamic) simulation algorithm, allowing to model free fall, impact and rolling with different damping relationships available to simulate energy loss. Raster maps of relevant parameters (e.g. impact energy restitution and rolling friction coefficients) are derived by reclassifying GIS maps of surface lithology, vegetation and land use. Parameter values need site- and resolution-specific calibration to fit field observations (e.g. historical, experimental) in order to optimize modeling results. The stochastic nature of rock fall processes and all the related parameters are introduced by random sampling from different probability density distributions (e.g. uniform, normal, exponential).

Rock fall starting locations are detected combining different information, including mapping of bedrock outcrops on steep terrain, failure evidence, detection of recent rock fall deposits and active scree slopes, geomechanical characterization, and slope stability analyses. In the example provided herein, 3D FLAC simulations along with geologic structure mapping were used to define the probable zones of rock fall initiation. Rock fall sources can be represented as point-like (i.e. single rock fall source or mapped instability), linear (i.e. cliff band or outcrop) or polygonal objects (i.e. areas generating rock falls), and possibly assigned different relative probability (i.e. susceptibility) of rock fall onset. The size distribution of expected falling blocks can be introduced in the analysis by using different probability distributions (either a normal distribution around a mean or more usually an exponential decay from a given rock size). Other input including the starting velocity, and the direction of block release can be specified, although these parameters are held constant in most applications.
The Hy_Stone model is able to account for the interactions between blocks and countermeasures or structures by introducing their geometry and energy absorption capacity. A dedicated simulation module has also been specifically developed for Rio Tinto (Wang et al., 2010) in order to model the process of block fragmentation processes at impact, which represents a major concern in open-pit mining environments. The module exploits either a neural network (NN) or a multi-dimensional linear interpolation approach to detect the onset of fragmentation and the resulting block size distribution by interpolating the results of Discrete Element (DEM) simulations (Wang and Tonon, 2009).

The code accepts spatially distributed input data as raster matrices, including: location of source cells, number, shape and mass of simulated blocks, initial conditions and values of damping coefficients accounting for energy loss. Results are provided in raster and vector format, including rock fall frequency, bounce height, rotational and translational velocity and kinetic energy, as well as information about motion type and impact locations.

Accurate calibration of the input coefficients is required to lend credence to simulations and considerable discussion of the calibration process is presented herein. During the calibration process it must be remembered that the observed or actual rock fall events are a subset of the potential paths and run out distances that could be realized in the field. Hy_Stone provides output data including bounce height, velocity, kinetic energy, rotational energy, moment of inertia and allows for calculation of the distribution of rock sizes. In the example presented herein, rock fall simulations were utilized to generate hazard maps using a “zonal statistics algorithm” that was developed within ArcGIS.

Figure 1. Data layers required for Hy_Stone analysis (after Reichenbach, 2006).
The input files are schematically shown on Figure 1. The output files contain grid files containing information relating to travel paths, velocity, bounce height, rotational and kinematic energy. In addition, ASCII files are generated for each travel path of an individual rock fall path. As would be expected, the individual ASCII files can become quite large for simulations and are difficult to manage due to their size; usually a number of ASCII files are generated. An automated means of handling these files and counting the individual occurrences was developed using a VBA script in ArcGIS (9.2), herein termed a “counting grid.”

2 Case study: Rock fall associated to large-scale wedge failure

A case study of using the Hy_Stone software is presented. The location was in a pit wall where a massive quartzite unit was underlain by softer sedimentary units and a shear / fault zone. Wall dilation undercut the quartzite beds, which tended to form large blocky material. Structural control on the failure was along jointing and the shear zone. A multi bench, progressive wedge failure developed which caused an interruption of mining at the pit base. The slope failure involved about 20,000 m³ in September 2009 and involved undercutting and local failure of the quartzite unit (Figure 2), which in turn resulted in an unconsolidated talus (rill) with one very large boulder (1,000 m³, herein named the “big rock”) coming to rest. This event was termed the “September event.” The mine’s initial request was actually to just evaluate the risk presented by the large rock and the potential travel paths of that singular rock. Moreover, 3D FLAC analyses of the slope had been completed by others and the expectation was that the slope would continue to dilate. Similar events to the “September event” were expected as the slope continued to dilate and the risk of rock fall resulting from further wall dilation needed to be quantified. As the failure developed, a large amount of rill covered several benches and the concern was that this debris would form a “ski jump” leading to increased rock fall risk at the toe. A conservative step out at the slope toe was under evaluation by the mine. In addition, large safety bunds and berms were to be constructed. The mine wanted to understand whether the selected mining limit was conservative and whether the planned berms would be of sufficient size and at appropriate location to provide worker safety.

Figure 2. An understanding of source zones was critical to the hazard assessment. In the above situation, a quartzite outcrop was being undercut by slope dilation. The direction and magnitude of the dilation was well understood by independent modelling using FLAC-3D.
Rio Tinto T&I was requested to provide assistance on this complex multi-bench failure/rock fall risk that tested the uniqueness of the Hy_Stone software capabilities and its potential in the open-pit engineering context. The initial objective of 3D rock fall analysis using Hy_Stone included calibration to observed rock fall events. The mine had developed a detailed DTM of the slope (1m cell size) and also carefully surveyed the locations of 30 or so rocks that had fallen and come to rest at various locations on the slope, including benches and the slope toe. A view of the slope presenting the rock fall hazard is shown on Figure 2. The stratigraphy of the site is clearly understood with the cliff forming unit being a quartzite and the underlying deposits consisting of siltstones and mudstones. Further to the left, a similar stratigraphic sequence exists. Figure 3 shows a detail of the “big rock” that remained on the slope following the initial break out. Also evident is both the “hard” and “soft” rill that formed from the wedge failure.

3 Rock fall Model Development and Calibration

3.1 2D Analysis background

Prior to the failure, 2D rock fall analyses using the CRSP code (Pfeiffer and Bowen, 1989; Bartingale et al., 2009) had been completed by the mine geotechnical staff under controlled conditions (i.e. rolling boulders down a slope to calibrate the model to the observations). Based on these analyses, three representative slope profiles were initially considered for rock fall analysis from the toe of the cuts to the ramp. However, it was difficult to assess the overall rock fall hazard due to the complex geometrical conditions of the slope, in particular, “out of plane” (i.e. channelled or diverging) trajectories.

The slopes on the sections are predominantly composed of rill toeing into a raised bank of fill on which a ramp sits. Although the 2D coefficients are not identical to the 3D coefficients, they provided an initial basis for 3D Hy_Stone analysis, along with values published in the literature for similar geologic materials. It should be
noted that similar to “back calculation” in slope stability, the coefficients derived from rock fall calibration are essentially coefficients unique to that particular problem, also depending on the adopted modelling approach/algorithms, the accuracy of the topographic description, and other factors (e.g. block shape, account for block fragmentation, etc.). The coefficients are not intrinsic properties of the geologic materials and must therefore not be treated as such.

In the 2D simulation one wanted to assess the location and berm height required to contain rock fall resulting from rill filling the benches. A number of simulations were required to assess the potential for containing rill and rock fall, yet uncertainty in travel paths remained. A number of limitations were therefore identified in the 2D approach due to the complex geometry and other factors.

### 3.2 3D Model Development

3D rock fall modelling involved a process of calibration to observed rock fall events in the wedge dilation area and then undertaking predictive simulation runs to assess the rock fall hazard based on those calibrations. Key to understanding the hazard was the 3D stress-strain numerical modelling undertaken (Geonet 2009) to understand the slope dilation that was characterising the ongoing large-scale wedge failure, and identify the probable evolution with time of the locations of rock fall sources. This was a major point since rock fall hazard was developing in a quickly changing environment, and not in a “static environment,” as is usual. In this case, the slope was a quartzite band underlain by softer sedimentary units. Wedge failure and associated slope dilation caused the quartzite to be undercut forming a cliff roughly 30 m high and 100 m long. The cliff top envelope provided the rock fall source input for most simulation runs. All analyses were based on a raster DEM with 1 m cell size, derived from TLS (terrestrial laser scan) point cloud provided by the mine. The mine also provided a detailed geological survey of the mine slope, that was implemented for the analysis based on the latest rock fall evidence (e.g. soft and hard rills associated to slope failure), as well as “rocks files” (i.e. AutoCAD files with the surveyed position of each rock on either the bench or toe of slope).

As indicated above, critical to development of the Hy_Stone model is calibration of the input model parameter values to observed events. Several approaches can be adopted to this aim:

- Completion of rock fall trials in the field by rolling rocks down a slope to calibrate a model to those observations. This should ordinarily be the preferred approach when possible, but is not always viable depending on the particular situation.
- Completion of simulations to match the distribution of observed events. For this project, this approach was taken and the rock fall simulations were “calibrated” to a distribution of rocks observed in the field. This approach possesses some challenges, as one is attempting to calibrate to a subset of all possible rock fall permutations. Judgement is required in regards to the adequacy of the calibration.
- Likewise, using either a 2D or 3D approach, one can calibrate to the percent of rocks retained on benches, matching rock size, distribution and other observations.

In the initial set of simulations, the primary rock fall initiation zone is shown on Figure 2 and 3. Of particular interest for the mine were the potential travel paths of the larger quartzite blocks which were periodically released and the potential hazard that their travel path may pose. A lognormal rock size distribution was used for our analysis, which was based on photographic interpretation of the rill that had formed to estimate distribution of particle size. Moreover, specific simulation runs were performed in order to assess the propagation potential for the intact “big rock”, allowing a stochastic description by means of topographic accuracy and parameter variability.

To develop the model, the pit geology polygons were draped over the slope and assigned initial values of restitution and friction coefficients, based on the literature and the 2D analyses that were previously completed (Figure 4).
Initially, a visual approach was taken to calibrate simulated rock fall densities to the observed events. Although this approach has merit and provides a first-order calibration match between observations and simulations, it was felt that such an approach lacked rigour. Figure 5 shows an initial comparison between the observed events and simulated events. The conclusion reached is that the simulation “matches” in one location, while not in another. Calibration therefore results in a judgement call. To obtain a more statistically sound calibration process, it was decided to develop a “zonal statistics algorithm” to calibrate the observed events to the simulations. A means to utilize the point files of individual rock fall events was devised so that all occurrences of the output data could be captured in 5 by 5 to 10 by 10 meter grid spacing (Figure 6). This “counting grid” was used to statistically determine the number of rocks stopping within the uniform 10 by 10 meter grid area. For predictive simulations, the zonal statistics algorithm was color coded to show the areas having the highest incidence of potential rock fall occurrence.

We emphasize that both model calibration runs and predictive simulations were completed during a period of time where there was inactivity in this sector of the pit (partly due to weather conditions) and ravelling continued to occur. Therefore, following the initial calibration, the “big rock” eventually rolled down the slope. Interestingly, or perhaps fortuitously, the “big rock” came to rest in one of the higher density grids (Figure 7).
Figure 5. Initial calibration results trying to match simulation to observed rocks on benches. [red dots indicate observed events]

Figure 6. Distribution of the observed rock fall blocks within a 10 by 10 meter “counting grid”. Warmer colors indicate higher simulated density, empty grids indicate no rocks were retained within that grid.
Figure 7. Slope model (DTM) and distribution of rocks (red dots) observed in the field. Faintly shown is a 10 by 10 meter zonal statistics algorithm, color coded to those areas with the highest observed rock incidence.

The calibration stage of the project allowed some key lessons to be learned for a better application of rock fall modelling in open-pit mining environments. Initially, improvements in the accuracy of the TLS-derived DEM were needed. The initial scan was made from an opposing pit wall, so some of the bunds or berms present on the slope were “blind” to the laser scanner. A problem arose because rocks were observed on benches in the field that were contained by the remaining bunds, while the DTM did not model those benches. The resolution was to combine the available survey geometry with the DTM point cloud information so that these small scale features were incorporated. Over time, the geometry of the slope itself changed due to the formation of additional rill (talus) forming on the slope. Additional DTM data were needed to correspond to these slope changes. The performance of the numerous simulations then became an accounting issue and good documentation of each simulation, the input assumptions made, the rock size distributions completed, etc. proved to be necessary.

Since complex geology supported using a variety of coefficients across the slope, it was difficult to assess the impact of minor changes in a set of coefficients to the results. In this perspective, it was a useful exercise to assign uniform coefficients to the entire slope (i.e. take the geology and coefficients out of the equation) to assess the impact of the geometry alone on simulation results. After sufficient permutations of a reasonable range of coefficients have been made, a degree of comfort arises that the calibration has been achieved. The most efficient means at arriving at a calibration was to first attempt to “bound the problem.” This could be accomplished by running the simulations using the expected range of the coefficients.

Finally, mine or survey grids in which the problem was developed were generally skew to the slope, and should ideally have been orthogonal to the slope. To evaluate rock fall on individual benches, the rocks coming to rest on a given bench were manually summed. When rock retention and run out distance was assessed perpendicular to the slope, the calibration supported the 3D view. A comparison of the observed and simulated events by bench is shown on Figure 8.
Assessment of rock fall hazard potential

Once the calibration runs were completed, the coefficient files were used to make forward assessment of rock-fall hazard, here expressed in terms of probability of reach (i.e. propagation to a specific location on the slope; Crosta and Agliardi, 2003). As additional rill formed on the slope, a new DTM was developed to describe the changed geometry. The additional rock fall events resulted in new field distributions of rocks, which could be used for additional calibration, or to test previous coefficient file combinations. As these additional simulations were completed, it became evident that some coefficient files consistently yielded conservative results (i.e. a tendency to over predict run out). Knowing that coefficient files would yield conservative results provided a degree of security in making recommendations, as the best fit coefficients could be used to make risk based predictions and then tested using the conservative input files. In addition, different starting zones were tested included line (cliff) sources and polygon sources (rock outcrops or bands) to make forward projections. An example of forward projections is shown on Figure 9.

Lastly, trials were completed using a fragmentation module developed for Hy_S tone by the University of Texas (Wang et al, 2010). It was found that most of the fragmentation occurred higher on the slope corresponding to areas of greatest velocity.

Once we had satisfied ourselves that the most probable permutations of rock fall hazard had been evaluated, the distribution of predicted rock fall at the toe of the slope was developed (Fig. 10). This allowed the mine to avoid too conservative mining limits to be established, which would have finally resulted in a loss of profit for the mine. Figure 11 shows the predicted rock fall hazard as mining continued. By this time, the initial mining limit had been successfully completed and remotely operated equipment was used at a mining limit set closer to the toe of the slope.
Figure 9. Forward simulations with uniform coefficients. The color coding represents velocity with red being highest (40-50 m/sec) and blue lowest (5 m/sec).

Figure 10. Predicted distribution of rock fall extending from the toe of the slope.
Figure 11. The method A (best estimate coefficients) and Method B (conservative coefficients) simulations (left and right) showing variation of possible hazard based on varying the coefficients. Purple dots are observed, brown and green are simulated rock fall events. The white lines represent equal distances from the slope toe (line 1 = 1m, line 2 = 15 m, line 3 = 30 m).

It was observed that the majority of the rock fall hazard was within 40 meters of the slope toe. However, inspection of both figures indicates that there is a small distribution of rocks that exceed these “average” distribution values up to 60 meters from the slope toe. For this case, the conservative coefficients were used to generate the maximum run out. Offsets were then developed for mining to proceed safely using remotely operated equipment, in the framework of a wider risk mitigation strategy used by Rio Tinto. Simulations indicated that rock fall should not encroach on the protective berms that were constructed and the field observations also found this to be the case. In all cases, mining equipment was provided with extensive protection and reinforcement measures. In closure, the mine plan was completed without incident and with re-assurance that the likely 3D distribution of rock fall had been analytically determined.
5 Key learnings

This wedge rock fall assessment project is one of the first major implementations of 3D rock fall mathematical modelling in a mining environment, and was successfully completed using Hy_Stone. Although the software has been used at a number of natural slope locations and results are well published, the amount of rock fall and the means of calibrating Hy_Stone on the current project were challenging, and outlined the following points:

- The software relies on accurate topography information to simulate the travel paths. The ability to exploit the information provided by modern “point cloud” information obtained by Lidar, TLS and other techniques is very powerful. Experience indicates that the more accurate the DEM, the greater the potential accuracy of the results with a one by one meter resolution grid resolution being the target.

- Accurate calibration of rock fall model parameters is required to confirm reasonableness of the obtained results. Numerous sensitivity analyses indicate that possessing accurate topography is more important than other input parameters. Nevertheless, 3D model calibration requires a much greater effort and methodological rigour than for 2D models.

- Although the Hy_Stone program can be used as a design tool for unique catch bench/bench height/bench face angle geometries (i.e., inter-ramp slope designs), the authors believe that the primary utility of the software relies on its ability to predict hazard based on the actual slopes, which at times may vary significantly from the planned design condition. Such analysis can dramatically improve the operator’s understanding of rock fall safety of the slopes.

- The “zonal statistics algorithm” developed within ArcGIS was one method to evaluate rock fall hazard and risk on a statistical basis. The authors consider that the use of statistical analysis to develop probability density functions provides a powerful means of assessing rock fall hazard and maintaining a safe work environment. Despite our fortuitous success on predicting the path of the “big rock”, this approach should be used statistically and not deterministically.

- Calibration of Hy_Stone involves primarily “adjusting” the three coefficients (Et, En, At) and starting parameters to match the observed distribution of rocks. The calibration process is not linear and involves numerous iterations. If possible, it would be more straight-forward to perform actual trials of rolling rocks down a given type of material and determine the coefficients uniquely for that material and for small groups of individual rocks.

Overall, it was determined that Hy_Stone is a very robust, peer reviewed software using a geographic information system (GIS) environment as its graphical interface. Unique to Rio Tinto is a proprietary module developed by the University of Texas at Austin (Wang et al., 2010) adding a fragmentation subroutine to the model. The fragmentation module adds the ability for Hy_Stone to model the fracture of individual intact rocks and then to track the location of these fragments (up to 10) in space. Findings from the “fragmentation module” are considered to be a “beta” version of software; initial results suggest that the highest fragmentation hazard occurs immediately below the cliff areas where velocities are greatest. The presence of the remaining batters and bunds reduces the fragmentation hazard towards the toe.

6 References


