KEYNOTE TALK

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Developments in Open Pit Slope Design since 2009

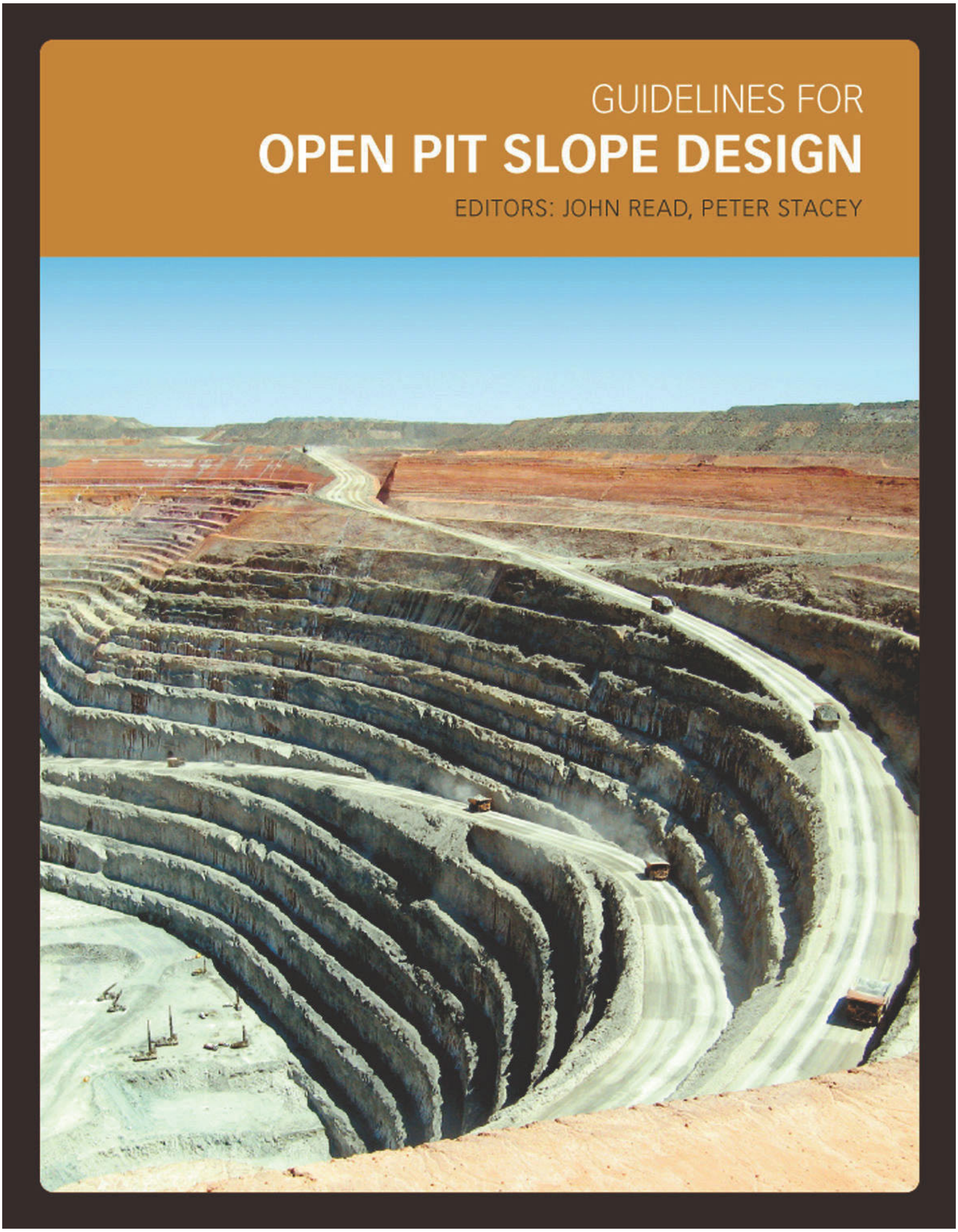
ABSTRACT

The objectives of Slope Stability 2018 are to i) consolidate the knowledge gained and show how techniques have improved since the book Guidelines for Open Pit Slope Design was published in 2009, ii) to provide real and evidenced results, and iii) to provide direction for further improvements beyond 2018. The objective of this keynote address is to set the scene for the conference by over-viewing what has taken place in the open pit slope design world since 2009 by critically examining what has worked, what is not working, and what is considered to be the best approach to satisfy best practice beyond 2018

1. INTRODUCTION

Slope Stability 2009 marked the publication of the book Guidelines for Open Pit Slope Design (Figure 1). The objective of Slope Stability 2018 is to consolidate the knowledge gained and show how techniques have improved since then to provide real and evidenced results: it also aims to provide direction for further improvements beyond 2018.

The guidelines book was an outcome of the CSIRO Australia research project the Large Open Pit (LOP) project. The project commenced in April 2005. Its purpose was to address critical gaps in the industry's knowledge and understanding of the relationships between the strength and deformability of rock masses and the likely mechanisms of failure of rock slopes in large open pit mines. The 2005 agreement envisaged the project would last for at least four years. In the event, it continued until June 2014, courtesy of the support of 12 international large open pit mining companies. Since then it has entered Phase II with the support of the University of Queensland and funding from eight international mining companies.



GUIDELINES FOR
OPEN PIT SLOPE DESIGN
EDITORS: JOHN READ, PETER STACEY

Figure 1: Guidelines for Open Pit Slope Design (*source: CSIRO Publications*)

When setting up the project, feedback from mining companies and slope design practitioners indicated without question that the time had come for the preparation and publication of authoritative, new generation pit slope design guidelines that linked innovative mining geomechanics research with best practice and clearly outlined the best approach to satisfy best practice in a range of situations.

The subsequent success of the book underlines how correct this feedback was. Another key to the success was that the book brought together the experience of the sponsors and a number of industry and academic practitioners who willingly shared their knowledge and experience by either preparing or contributing their knowledge to chapters in the book. It is noteworthy that although a great deal of the information in the book was drawn from material published by academics, none of the research was done by or in universities.

I have been asked and it is my privilege to set the scene for the conference by overviewing how the geomechanics world has fared in the open pit mining industry in the years since 2009. I will do so first by outlining what in 2009 was considered to be the standard approach to data gathering and then by outlining what I consider to be significant advances and significant shortcomings since then, and what I consider to be the best approach to satisfying future best practice.

2. INVESTIGATION METHOD

Geotechnical investigations are an integral part of large open pit mine development. They should follow an orderly path of data gathering aimed at providing as much information as possible about the engineering characteristics of the ore body, which is encapsulated within the four parts of the geotechnical model illustrated in Figure 2; the geological, structural, rock mass, and hydrogeological models.

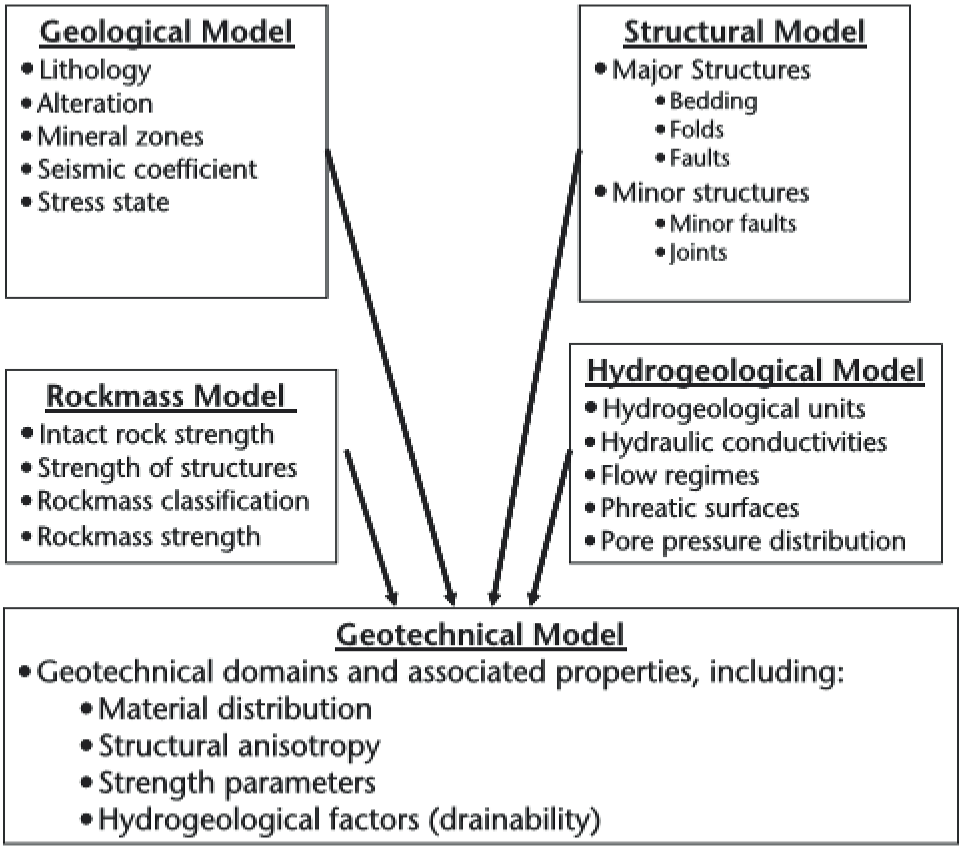


Figure 2: Component information and output from the geotechnical model (source: Read & Stacey, 2009)

As indicated in Figure 2, the key information included in any slope stability analysis can be grouped as follows.
The material type(s), including weathering and alteration variants (type and/or degree).

The orientation, spatial distribution and shear strength values for the major structures, including the shear strength of the individual faults, bedding planes and any laminated structures associated with metamorphic rocks such as slate, phyllite and schist that are continuous along strike and down dip within each domain.

The orientation, spatial distribution and shear strength values for the rock fabric within each domain, including the strength of micro-bedding, minor faults, joints, schistosity and cleavage.

The rock mass strength values, including the point load (Is50), uniaxial and triaxial strength test values for the intact rock, the rock mass classification information and the estimated shear strength values of the rock mass.

The elastic moduli values for the rock mass in each domain, for use in the numerical slope stability analyses.

The pore water pressure data derived from regional, mine and pit slope scale groundwater flow models that have been calibrated with pore pressures observed in vertically discretised slope piezometers during mining.

Ultimately, the assembled information is used in limiting equilibrium and numerical stability analyses that, in parallel with cost benefit and risk analyses, are aimed at estimating the optimum wall design. The final part of the package normally will include recommendations for monitoring pit wall performance, rainfall and groundwater during mining.

The question is, what have we done since 2009 to improve the certainty of the data collected in the Geotechnical Model and increase the reliability of our slope designs?

3. SIGNIFICANT ADVANCES

SYNTHETIC ROCK MASS MODEL

The rock mass phi and cohesion values used in limiting equilibrium and numerical stability analyses of rock slopes usually are obtained empirically from one of a selection of rock mass classification schemes, of which the Hoek-Brown GSI criterion (Marinos & Hoek, 2000; Hoek et al. 2005) is usually the criterion of choice. In this empirical world rock bridges that occur between intersecting structures in the rock mass are assigned empirical phi and cohesion values and are assumed to behave as a continuum, that is, they do not break up.

Unfortunately, in deforming rock slopes the empirical approach does not represent geological reality. In the real world rock bridges within the rock mass do break up, either in tension or across the joint fabric within them, which highlights a fundamental need to look beyond Hoek-Brown and i) create an “equivalent material” that honours the strength of both the intact rock and the joint fabric with the rock bridges, and ii) simulate the brittle fracturing that occurs within the rock bridge as the rock mass deforms (Read & Stacey, 2009).

In response to this need the LOP project initiated a research program that went back to basics to seek a more geological approach to the brittle fracture of the rock bridges. This lead to the application of the Synthetic Rock Mass Model (SRM), initially developed by the Itasca Consulting Group, Inc. (Itasca), for block caving applications to the brittle fracture process (Pierce et al. 2007).

In the SRM model the intact rock is represented by an assemblage of bonded particles numerically calibrated using UCS, modulus, and/or Poisson’s ratio values to those measured for an intact sample (Potyondy & Cundall, 2004; Figure 3, lower left). A discrete fracture network (DFN, Figure 3, upper) that captures the geometry and connectivity of the fracture network within the rock bridges is then imported into the particle assembly. In the model the fractures are represented by a smooth joint model (Figure 3, lower right) that allows associated particles to slide through, rather than over, one another and so represent joints that slide and open in the normal way.

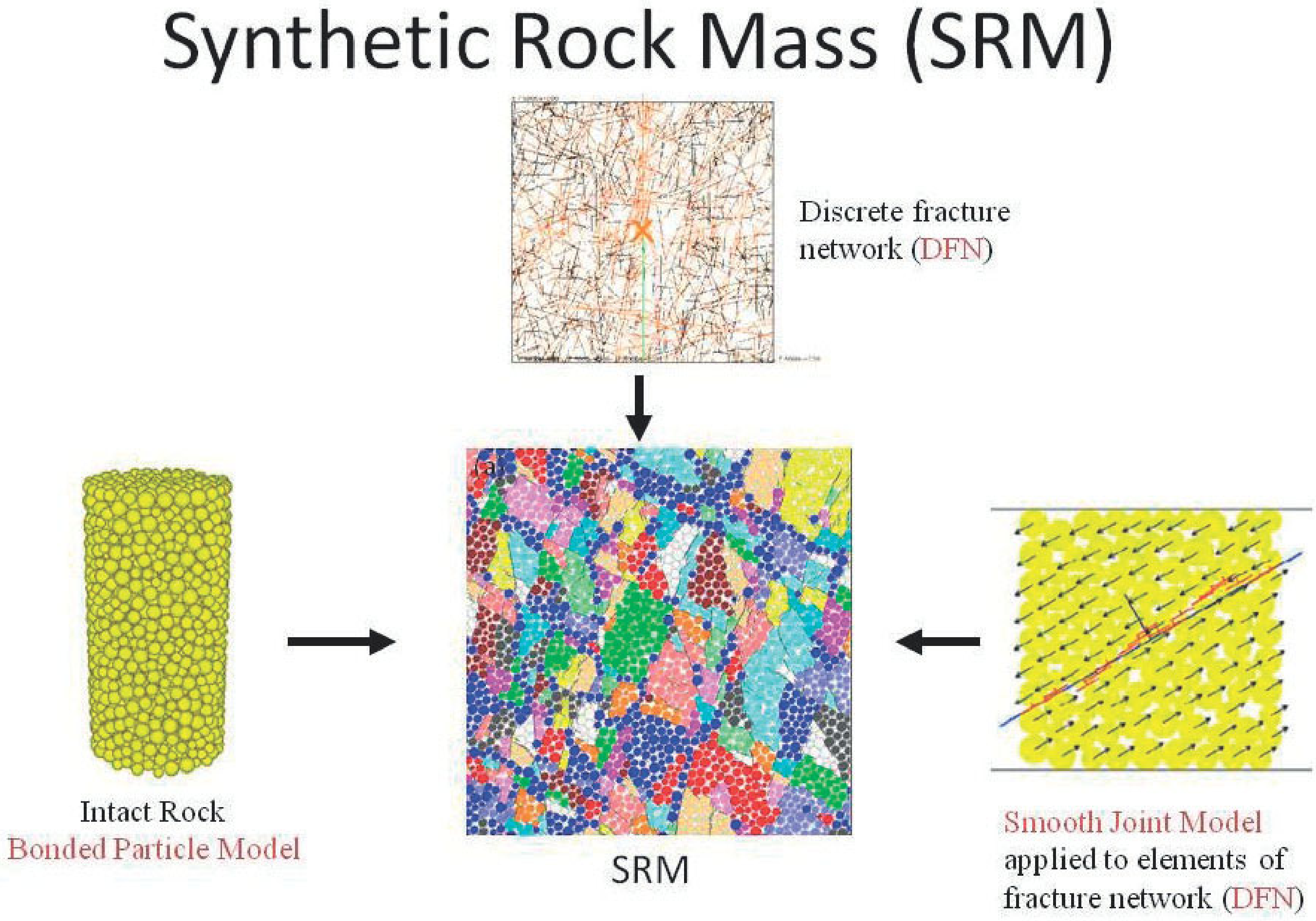


Figure 3: Synthetic rock mass (SRM) assemblage (source: courtesy Itasca Consulting Group, Inc.).

As demonstrated during laboratory testing, the SRM approach is able to supply information that is missing from empirical strength estimates. Notably, it provides (Read & Stacey, 2009):

a constitutive model (strength envelope) for the material in the rock bridges that is not reliant on either Mohr-Coulomb or Hoek-Brown criteria;

a strength envelope that honours the strength of the material in the rock bridges at different scales;

a strength envelope from which the Hoek-Brown parameters can be derived, that is, it provides a means of calibrating the Hoek-Brown strength envelope.

In a review of the SRM model for block caving studies being performed by the Mass Mining Technology project (MMT II), Evert Hoek and Derek Martin (Hoek & Martin, 2010) noted that “the SRM approach has provided an outstanding set of tools which promise a far more realistic and reliable method of modelling rock mass behaviour than has been available in the past. At the very least this approach should enable us to calibrate traditional rock mass classification approaches used to estimate rock mass properties, but the approach also has the potential, in the long run, of replacing these empirical approaches”.

Studies of slope failures at project sponsor mine sites using the 3D numerical modelling code Slope Model, developed by Itasca for the LOP project (Beale & Read, 2013, Appendix 6), together with Slope Model validation studies (Damjanac, 2013), demonstrated that the Slope Model/SRM approach does capture the correct physics of rock mass behaviour. The studies also demonstrated that validation of the DFN model and its ability to truly represent the bench scale structural fabric within the rock bridges was a challenging task, being totally reliant on data provided by high quality bench-scale structural mapping.

As discussed in the Significant Shortcomings section of the paper, high quality bench-scale structural mapping is an under-performing aspect of the today's field data gathering process and is restricting our ability to prepare the necessary DFN models. In turn, this is holding back the full potential of the SRM approach for estimating the geological 3D strength of a rock mass. Long familiarity with the less exacting Hoek-Brown and other empirical rock mass strength criteria may also be creating a road block. However, although empirical methods may suffice for shallow pits where an experienced practitioner is preparing the strength estimates, they definitely do not suffice when we are dealing with pit slopes that are now ranging in heights upwards of 1200 m.

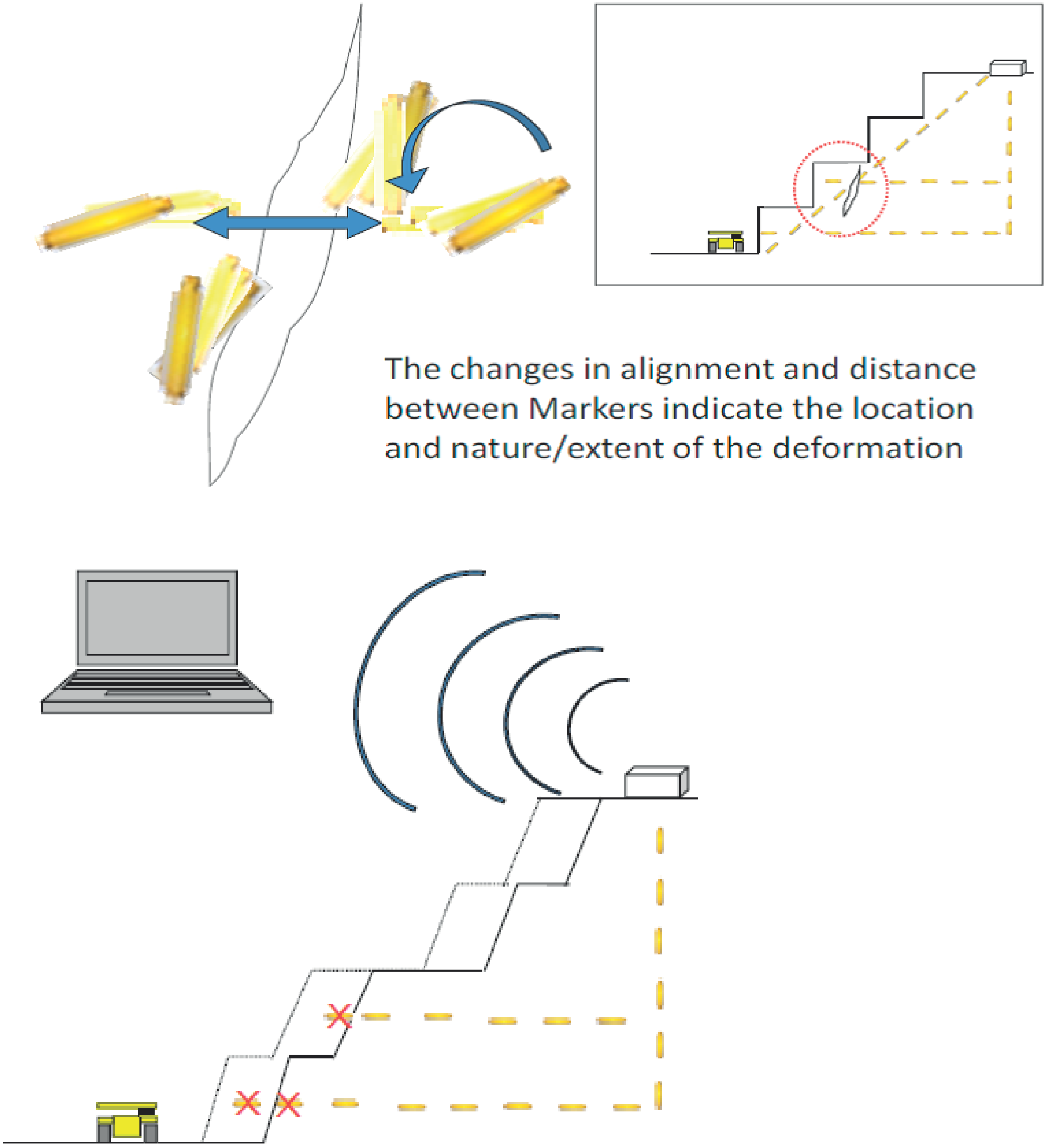
REAL TIME SUBSURFACE DEFORMATION MONITORING

Standard methods of monitoring surface displacement in open pits, including visual observations at the surface, measuring pins and extensometers on observed tension cracks at the surface, total station survey monitoring of surface prisms, and radar monitoring, collectively can provide a trustworthy real-time 3D record of any surface movements that may be taking place in the walls of the pit.

Conversely, instruments used to monitor subsurface displacements, typically including shear strips and/or TDRs, extensometers and inclinometers, rarely, if ever, are able to detect in real time subsurface deformation when it develops and propagates to the surface.

To overcome this limitation, a subsurface deformation system has been developed in Chile in a joint venture between CSIRO Australia and the University of Chile, with sponsorship from mining companies in Chile. The system is based on subsurface Smart Markers that are used for monitoring ore recovery performance in block caves. The manufacturers have enhanced the Smart Marker's on-board radio transmitters to enable the markers to be networked in a chain located behind the pit wall. Every marker in the chain measures the strength of the radio signal between other markers in the chain. Changes in radio signal strength over time track changes in the alignment and distance between the markers, so locating the nature and extent of the deformation. This information is reported in real time by "hopping" it from marker to marker to the surface reader (Figure 4). A feature of the system is continuous operation during cutbacks: although the cutback will remove the markers closest to the pit benches (right hand schematic in Figure 4), the remainder of the system will continue working after the cutback due to the continuing wireless communication between the remainder of the markers in the chain (Read, 2013).

The initial trial of the system behind a vertical double bench at a mine site in Chile (Figure 5), successfully demonstrated that a chain of markers can be grouted into location in vertical boreholes behind a pit wall, record the deformation information, and report it to the surface as mining progresses (Fredes, 2016; Hölk, 2016; Widzyk-Capehart, 2018).



The changes in alignment and distance between Markers indicate the location and nature/extent of the deformation

Figure 4: Smart Marker chain installed within the slope to detect subsurface deformation (source: Read, 2013)

Figure 5: Trial Smart Marker site. 2x marker chains installed behind the vertical double bench on the LHS of the photo (source: Fredes, 2016)

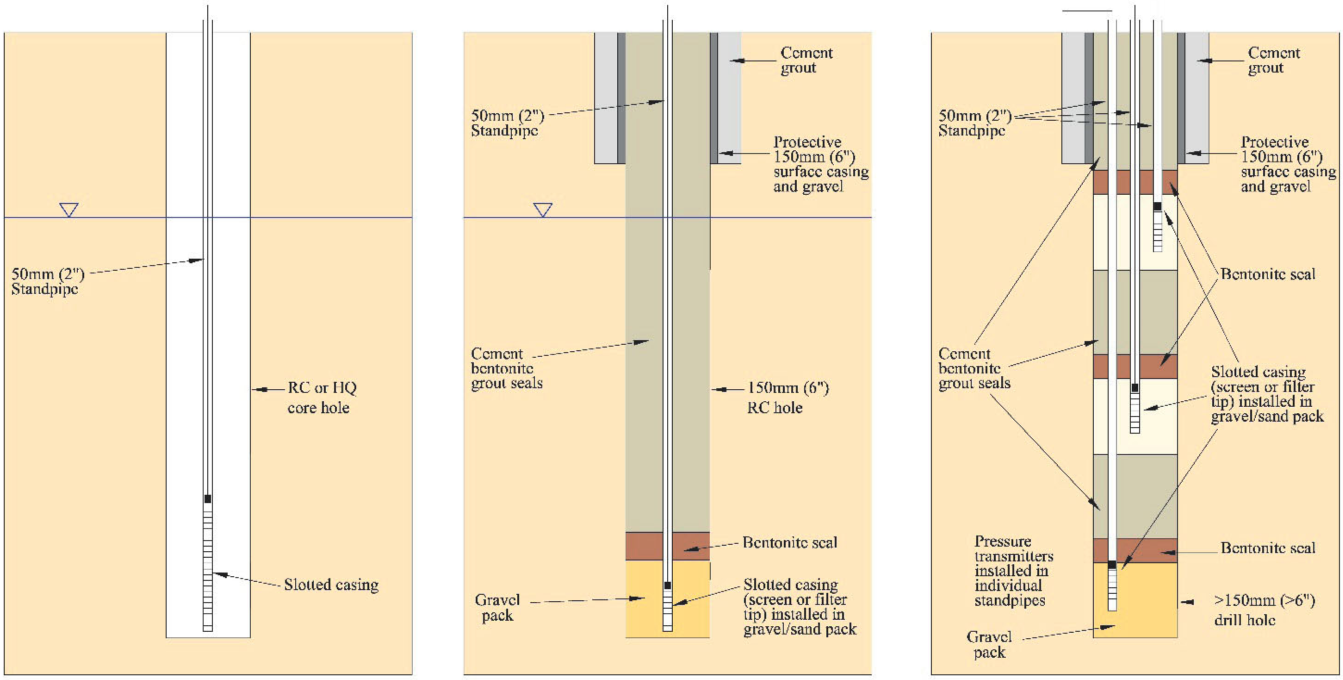
Since the trial accelerometers and pore pressure sensors have been added to the markers and, together with improvements in movement accuracy and range, the system is now able to i) provide real time identification of when and where subsurface deformation behind a pit wall develops, ii) provide real time measurement of any pore pressures associated with the deformation and iii), transmit that information to the surface as it propagates to and ultimately is observed at the surface. These outcomes provides a major breakthrough in identifying and linking deformation and associated pore pressure changes at depth behind a pit wall in real time.

PORE PRESSURE MONITORING USING GROUTED-IN VIBRATING WIRE PIEZOMETERS

The presence of groundwater and the potential detrimental effects of the resulting pore pressures on the performance of open pit slopes has long been recognised, but it is not so long ago that estimating the pore pressure distribution with any certainty was something of a black art. Estimates could be made provided the elevation of the water table was known. But that was not always the case, so assumptions were made and applied to the stability analyses. A default frequently applied to the analyses was that the slopes were "dry" and should water be encountered it would be possible to "drain" them by some means, usually assumed to be horizontal drain holes. This inadequate understanding of pore pressures led not to over-designed slopes that were flatter than necessary but mostly to steeper, under-designed slopes that failed.

Probably, many of you, like me, began life installing simple standpipe piezometers such as that exampled in Figure 6a. We then progressed to the use of a sealed filter pack (Figure 6b) as we gained more experience and understanding of the need to prevent cross-connections or determine the pore pressure where, for whatever reason, heads varied with depth. If we were very clever, we graduated to multi-level sealed filter packs, as in Figure 6c: given that mostly we were dealing with deep, diamond drilled boreholes, not relatively shallow RC boreholes, this was rarely the case.

Figure 6: Standpipe piezometer installations (source: Beale & Read, 2014)



A simple standpipe
Slotted pipe installed in geology
exploration drill hole.

B Sealed standpipe piezometer
Smaller perforated interval.
Sealed below the water table.
Installed in RC drill hole.

C Multilevel standpipe piezometer
Using required larger drill hole.
Necessary to use tremmie pipe
to place ground packs and seals.

Life became easier with the introduction of vibrating wire piezometers (VWPs) and a simpler installation of the sensor within bentonite sealed filter packs, as in the left hand side of Figure 7. Yet it remained a field intensive, time consuming and expensive operation which, unless owners had hands-on experience of under-designed slopes that had failed, made it difficult to convince them either of its rightful place in the slope design studies or its cost effectiveness. How often have you arrived on a site to review the investigation and slope design procedures to find only a handful of piezometers and an inadequate "best guess" at the groundwater levels, or where the discovery of water came as a surprise?

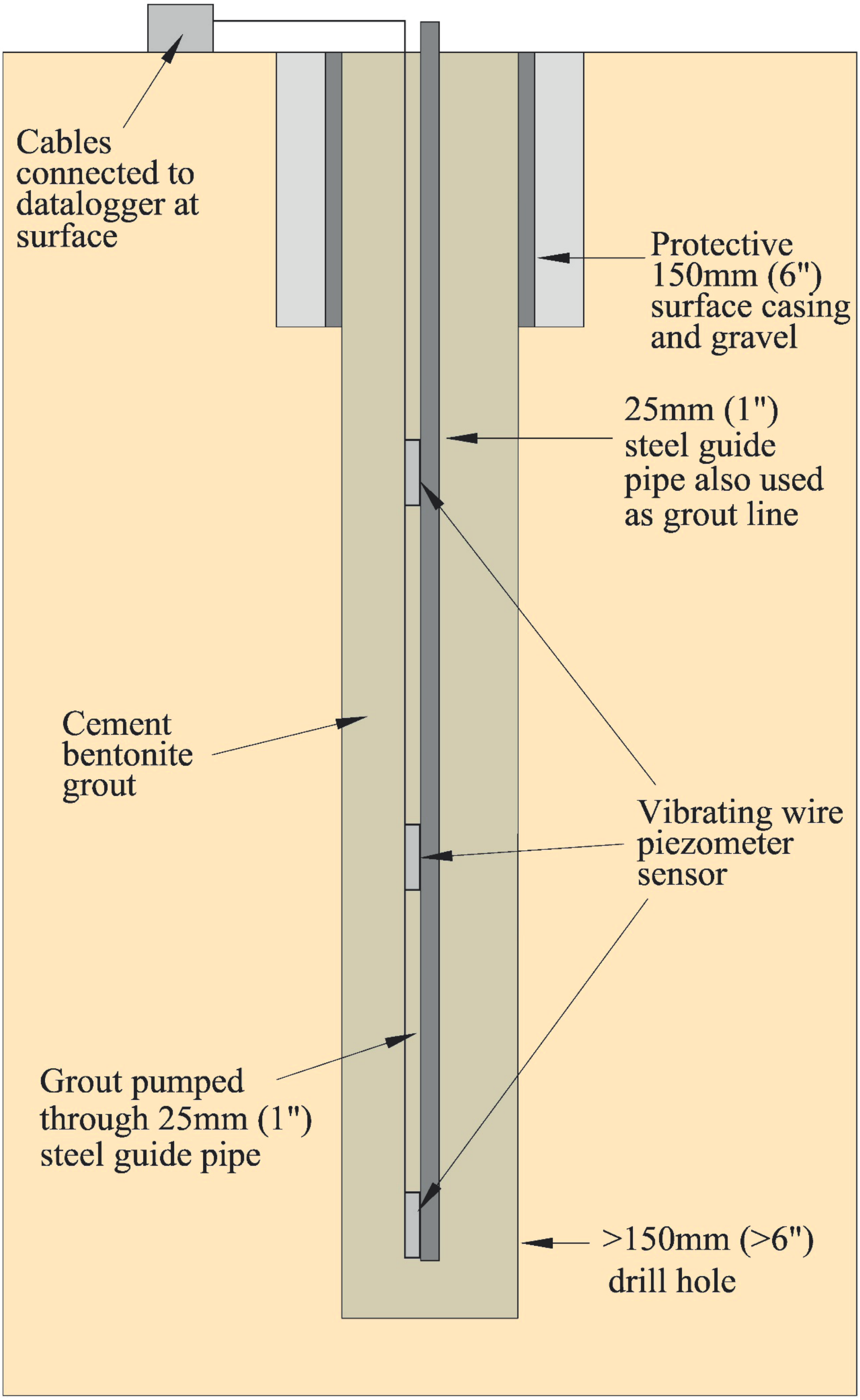


Figure 7: LHS, Vibrating wire piezometers in sand packs; RHS, Grouted-in vibrating wire piezometers (source: Beale & Read, 2013)

The game changer was the introduction of grouted-in VWPs in the late 1990s, which enabled the installation of a string of sensors without the use of a filter pack, as illustrated in the right hand side of Figure 7. Vibrating wire piezometers are now routinely installed by piggy-backing on exploration or geotechnical boreholes rather than in dedicated boreholes, which has reduced costs significantly and made it possible to install many sensors rapidly at any given mine site (Beale & Read, 2013). This has not just benefited slope designs at individual mine sites. Data gathered from mine sites worldwide by the Large Open Pit project since 2009 has enabled us to improve our understanding of the occurrence and the role of pore pressures in pit slope engineering, as will be outlined by Geoff Beale in his keynote address at this conference.

RISK AWARENESS

Section 9.4 in the Open Pit Slope Design book (Read & Stacey, 2009), addressed the need to quantify the risks that may be associated with slope failure, outlining risk model procedures that had the objective of providing a basis for management decision by:

- defining the risk in terms of safety and economics;
- quantifying the risk levels for different slope configurations
- quantifying the economic value added for increased levels of risk.

Since the book was published there has been a concerted geotechnical effort to follow these procedures, recognising that safety must not be compromised as the economic value of selected slope angles is optimised. Operational risk management and decision making processes such as those illustrated in Figure 8 are now required standard practice: hazard management plans that include at a minimum hazard inventory, risk reduction procedures, trigger action responses (TARPS), and emergency response procedures are mandatory.

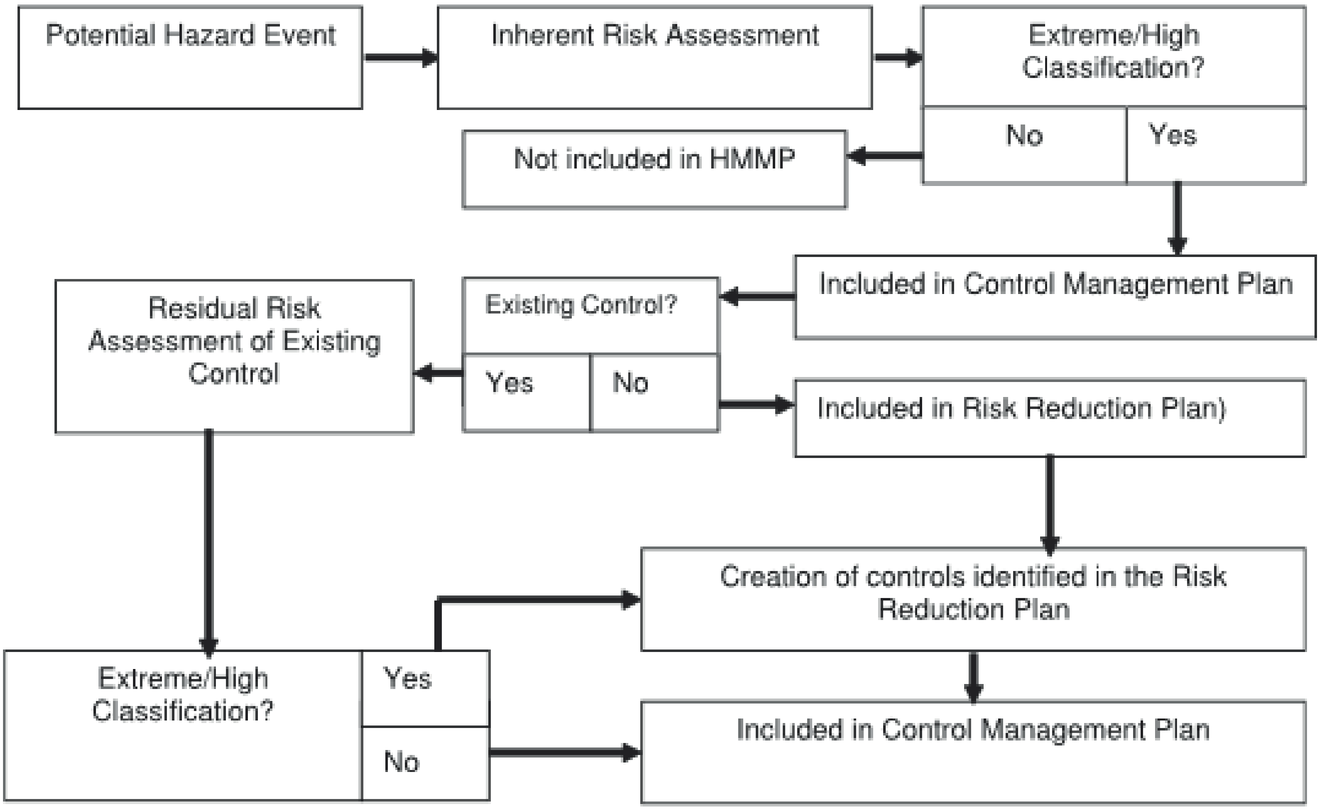


Figure 8: An operational risk management decision-making process (source: Read & Stacey, 2009, Figure 13.4; courtesy Newcrest Mining Limited)

In the exploration field, codes for reporting exploration results, mineral resources and ore reserves to the stock exchange have also been updated, as for example in Australia where the 2004 JORC code (JORC 2004) was updated in

2012 (JORC 2012) with the expressed intent of ensuring that the code's defined terms were aligned to the Committee for Mineral Reserves International Reporting Standards (CRIRSCO) Standard Definitions as revised in October 2012. After a transition period the 2012 Edition of the JORC code came into mandatory operation in Australia from December 1st 2013.

4. SIGNIFICANT SHORTCOMINGS

FIELD MAPPING

As pointed out in by Read and Stacey (2009, Section 2.2), outcrop mapping is fundamental to all activities pursued by the teams responsible for designing and managing the pit slopes. This includes not just regional and mine-scale surface outcrop mapping during development prior to mining, but bench and inter-ramp scale mapping as mining progresses. In particular, as hard rock slope failures will always be controlled by the nature of the defects that occur in the wall (cf., Figure 2), constant field mapping and updating of the structural model is a must for the geotechnical section. In a large open pit this necessary but time consuming activity can be a daunting task, even for a well-resourced geotechnical group. The 3D digital photogrammetric and laser imaging technologies that are now firmly established as routine methods that back-up structural mapping at bench and inter-ramp scale can and do reduce field mapping time. They also help meet current OH&S field mapping safety requirements. But this does not entirely resolve the human resource issue; there are two Catch 22s.

1. Geological maps prepared by digital photogrammetric and/or laser imaging must be ground proofed. More often than not the co-dependent issues of time and resources have led to a map that has been prepared remotely in the office being committed to the database without adequate and, in some instances, any ground proofing having been performed. The potential consequences of this short coming are a diminished hands-on understanding and ownership of the structural model, and a structural database lacking in quality and practical value.

2. Digital photogrammetric and laser imaging mapping techniques do provide reliable defect orientation, frequency, and spacing data. They do not provide reliable information on the persistence, roughness, aperture width and nature of infilling of defects. This information is required at both inter-ramp and bench scale to i) provide reliable structural models for LE and/or numerical stability analyses and ii) reliably characterise the connectivity of the fracture network assembled within the DFN model used in the SRM approach to estimating the geological 3D strength of a rock mass.

In my view, the widespread use of digital photogrammetric and laser imaging mapping has inevitably led to what I will call a "smart technology mindset" amongst some practitioners, where the emphasis is on office rather than field based activities.

A stand-out example is the current application of radar (RAR and SAR) in slope monitoring and the management of the software that is used to help identify potential slope failures. First introduced into open pit operations in 2002, its main use has been for production-critical monitoring where potential slope instabilities are located above mining activities.

The software used for operating the radar and reducing the data is not straightforward and usually is managed 24/7 by an on-site team of contracted specialist technicians reporting to the geotechnical superintendency. An unintended consequence of this procedure is that increasingly, rather than being the production-critical monitoring tool it was intended to be, radar data is being used as a diagnostic tool for potential structurally controlled slope failure mechanisms. This trend includes a research project recently initiated by the LOPII project to collect point cloud data from laser scans and then process them in a semi-automatic way to characterise the main structural features. The initiating project proposal included the statement that, once identified and characterised, the structures **could also** (my emphasis) be validated through a comparison with data acquired by conventional geomechanical surveys (Farina et al. 2016). In my view the outcome of this mindset not only puts the cart before the horse, but effectively has geotechnical personnel spending more time sitting behind a computer in the office rather than being in the pit mapping the benches and inter-ramp slopes, gaining an understanding of the geology that drives structurally controlled slope failures. The site ownership gap will become even wider if recent moves by some companies to move the radar monitoring team off-site continue. I agree with and strongly support the concept that smart technologies and keyboard expertise are a "must have" in the geotechnical toolbox, but I also consider there is absolutely no substitute for observant, well trained and well equipped boots on the ground who can read a compass and follow a map (Figure 9).

Figure 9: Co-dependent activities (sources: LHS, internet photo: RHS, J Read)

EDUCATION AND TRAINING

A concern related to the technology mindset issue, but which is not a Catch 22, is that many mine site "geotechnical engineers" have been educated as mining engineers, or sometimes as civil engineers, not geological engineers (aka, engineering geologists). Consequently, they lack core geological skills, particularly field mapping skills. Which raises the question, what is an engineering geologist's skill set?

The question of what constitutes good engineering geology has been discussed by Baynes who, in a paper addressing engineering geology and quality (Baynes, 1999), listed five guiding principles that are central to how engineering geology is practiced.

1. Geological knowledge (regional and site specific).
2. Spatial and temporal distribution of the geological attributes (the model).
3. Encoding of data in geotechnical language (engineering geological description systems).
4. Transformation into an engineering framework (application of soil and rock mechanics).
5. Communication of knowledge in cognisance of the project objectives and limitations due to any uncertainties attached to knowledge.

These principles are part and parcel of the studies for a degree in engineering geology, which usually will take an undergraduate student four years to complete. In contrast, a mining or civil engineering undergraduate will be fortunate if he is subjected to one semester dealing with "Geology for Engineers". Their background training is so different that expecting mining or civil educated geotechnical engineers to perform engineering geological related tasks such as outcrop mapping and/or ground proofing digitally prepared geological maps is akin to expecting to receive pennies from heaven.

Section 2.2.1 of Read & Stacey (2009) noted that preferably, outcrop mapping and logging should be carried out only by properly trained geologists, engineering geologists, geological engineers or specialist geotechnicians, assisted by specialists from other disciplines as needed. In hindsight, the use of the word preferably was a mistake.

USE OF KRIGING

Kriging is a form of regression analysis which estimates that the value at an unknown point should be the average of the known values at its neighbours, weighted by the neighbours' distance to the unknown point (Matheron, 1993). Figure 10 examples a simple one-dimensional data interpolation by Kriging.

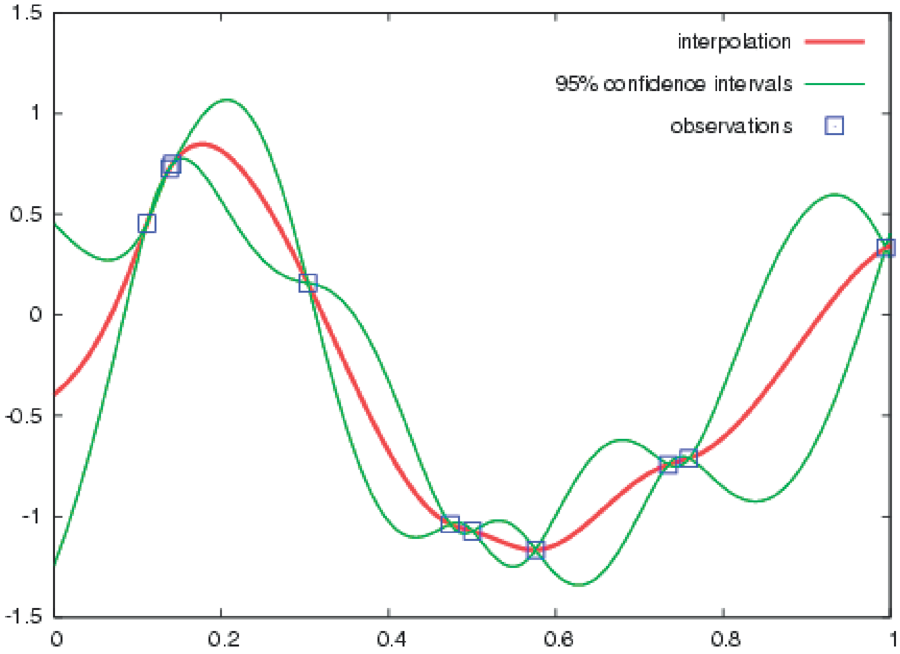


Figure 10: Simple example of one-dimensional data interpolation by Kriging, with confidence intervals. Squares indicate the location of the data (source: Wikipedia; example.krig.png)

Kriging and variograms are essential tools for ore body block modelling, where grade information is obtained from drill holes set out in orderly and closely spaced grids: typically, drill hole spacings are 25 m to 50 m.

Kriging has become popular with statistically minded geotechnical engineers, but caution must be exercised if it is to be used to help prepare a Rock Mass Model. Statistically, the process is not suited to geotechnical applications, where information, be it for RMR, RQD or fracture frequency, typically is obtained from scattered and/or widely dispersed and differently oriented drill holes. As pointed out by Read and Stacey (2009, Section 7.2.4), such values are calculated from a range of overlapping data sets, some with well-defined domains and others with poorly defined variability. Kriging of such data is unlikely to produce a meaningful result.

DRILLING AND CORE LOGGING

Methods of core drilling and logging are explicitly set out in Section 2.4 of Read and Stacey (2009), and are well supported across the industry by in-house manuals prepared by mining companies and geotechnical consultants. Despite the ready availability of this information, regrettably my experience and that of many others is that the quality of core drilling and logging too often can only be described as inadequate. Given that core drilling is the most commonly used means of obtaining the geotechnical relationships and engineering properties of the rocks that will form the walls of the pit, this situation is indefensible.

An example of this state of affairs is given in Figure 11. Much of the broken core in the interval shown (110 m to 127 m) was caused by poor drilling, despite the use of triple-tube core barrels. Close inspection of the core showed that many of the fragments had been ground and rounded, which could only have been caused by poor drilling, not the occurrence of poor quality rock. This situation had not been recognised by the loggers. To add to the logger's difficulties, although recorded on the core blocks, core losses had been spaced up by the drillers, not blocked out. Given that the loggers were recording RQD per metre drilled, this resulted in numerous errors in the depths registered on the logs, compounding the already incorrect RQD values recorded: I will leave it to the reader's imagination to visualize the representativeness of the final logs

Figure 11: Drill core between approximate depths of 110 m and 127 m (source: J Read)

The question is, why did this occur? I consider that answers to this question can be grouped under three main headings: the competence of the drillers; core recovery procedures; and the competence of the loggers.

DRILLING COMPETENCE

Geotechnical drilling in civil engineering has long been a specialised field, in Australia dating back to the 1960s when Longyear triple-tube core barrels with split inner tubes were adopted by the Australian Snowy Mountains Hydro Electric Authority (SMHEA) to ensure that core was extracted with minimum loss and remained undisturbed when placed in the core box (Moye, 1967, Endersbee, 1999). Regrettably, the expertise developed by the SMHEA has never been transferred efficiently to the mining industry, and for that matter was a long time coming into civil engineering practice in North and South America and other countries, where double-tubed core barrels sometimes still are used. In this context it is always worth remembering that RQD, long since adopted by the geotechnical community as a rock mass quality parameter, originally was introduced in 1964 by Don Deere and his colleagues not as rock mass parameter but simply to account for core loss (Deere et al. 1967, Deere & Deere, 1988): core loss remains a common event when single and double-tubed core barrels are used.

Poor drilling results in the acquisition of poor geotechnical data. Selection of a properly experienced drilling contractor and the maintenance of appropriate QA/QC contract procedures is the responsibility of the owner.

CORE RECOVERY PROCEDURES

Understandably, mining industry drilling focusses primarily on exploration. Good recovery is stated to be a prerequisite, but ensuring that the core is not disturbed when placed in the core box often is not of concern to the drillers who are aware that, when logged, most likely the core will be split for assay and thus completely disturbed: hence, carefully boxing the core is not foremost on their list of priorities. Additionally, double-tubed core barrels are often the norm, so that many drillers have little experience in the use and purpose of triple-tubed barrels with split inner tubes.

The quality of the geotechnical logging data very largely depends on the core being kept as nearly as possible in its original state. When removing the core from the split inner tube of a triple-tube core barrel QA procedures must be followed strictly if the core is to remain as undisturbed as possible. Standard QA procedures are outlined in Section 2.4.7.1 of Read and Stacey (2009), and I specifically repeat two important ones here.

1. When transferring the core to the core tray, the best results are obtained by replacing the upper split with a PVC pipe that has been cut in half, rolling the combination over to transfer the core from the split tube into the cut PVC pipe, then placing the cut PVC pipe containing the core directly into the core tray.
2. Spacers such as the red coloured PVC sticks shown in Figure 12 must be used to mark core loss zones. In Figure 11 spacers have not been used, with the lengths of core retained and lost in the run being written on the core lift markers, which have been closed up. Closing up core lift markers so that only the length of core retained is visible fails to highlight the core loss and potentially introduces measurement errors when logging.

Figure 12: Core loss zones marked by red coloured lengths of PVC (source: D Martin)

LOGGING COMPETENCE

Core loggers must have a geological background and be professionally trained not just to collect the required geotechnical data, but also to recognise bad drilling such as that in Figure 11 when confronted with it. They must also have the presence of mind to draw on other available sources of data to help them overcome difficulties such as those presented by the broken core in Figure 11.

As an example of utilising other sources of data, it transpired that the drill hole from which the core in Figure 11 was recovered had been logged with a televiewer (Figure 13), which enabled a more reasonable evaluation of the rock mass than could be provided by the core logs.

The televiewer log showed core loss at approximate depths of 105.8 m to 106.7 m, 112.0 m to 112.5 m, 118.0 m to 119.0 m and below 124 m, and small losses elsewhere. Otherwise, the wall rock appeared to be intact, with structures and fracture frequency recorded. This information provided a clearer understanding of the rock mass properties than was possible from the drill hole log. In addition to the structural information gained, because the televiewer log recorded fracture frequency, it was possible to use Bieniawski's method to make an empirical estimate of the RQD of the rock mass in the badly broken section of the core.

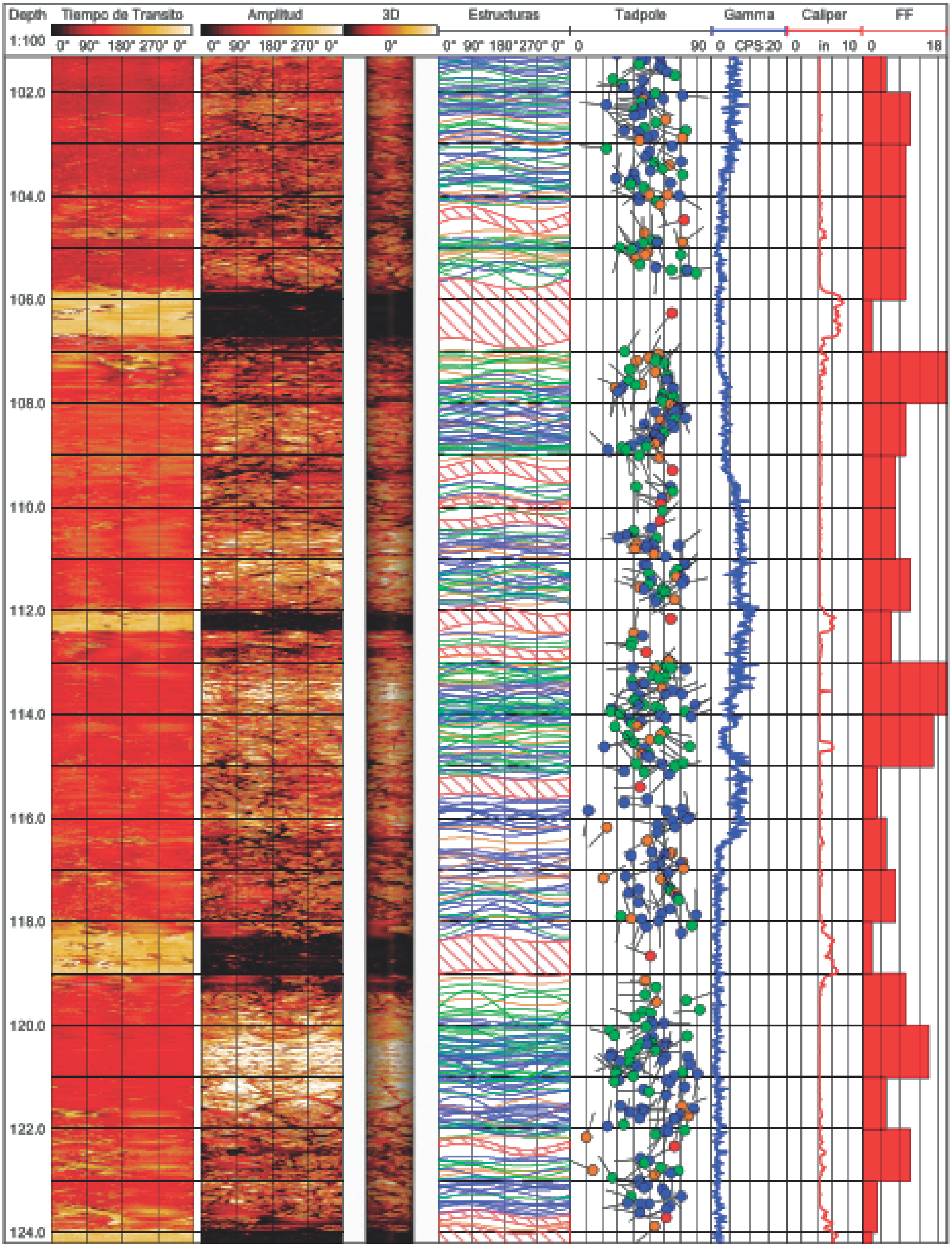


Figure 13: Televiewer log of core in Figure 11 between depths of 102 m and 124 m (source: Andes Geofísica S.A.)

5. SATISFYING FUTURE BEST PRACTICE

TRAINING

As highlighted in the Significant Shortcomings section of the paper, quality field mapping, including mine-scale, inter-ramp and bench-scale structural mapping, is an under-performing aspect of today's field data gathering process. In my view, this can only be resolved by corrective skills training on site, not off-site.

Off-site training and course work has a number of drawbacks. It reduces the site resources, the question always being, "can he/she be spared"? And the learning gained tends to benefit the individual not the site team, as it is often not transferred to the team members when the individual returns to the site.

On-site training brings the trainer to the site, which enables the training to be directed at and performed as part of the day-to-day activities: for example, inter-ramp and bench mapping, and core logging. This will not only enable the building of both individual and team skills, but will help build an understanding and ownership of the site geotechnical model. It will also build the confidence of the planning and operations groups in the skills of the geotechnical team.

RESEARCH

The outcomes of the LOPI project clearly demonstrated that, to be effective, future applied research must be a partnership between sponsoring mining companies, industry and academic practitioners, and the researchers; it will not be advanced in the isolated corridors of academia.

The research initiated and promulgated by the LOPI project is being continued by the LOPII project. Ongoing LOPII research projects include: the use of data from different mine sites in Bayesian and empirical approaches to estimate geotechnical uncertainty in risk-based slope designs; combining numerical modelling and field data to provide practical guidelines for quantifying the empirical Hoek-Brown wall damage factor "D"; and the aforementioned application of radar, integrated with laser and total station data, to support structural mapping. A detailed monitoring guidelines book is also being prepared, with publication intended towards the end of 2018.

Currently, the LOPII Sponsor Management Committee is assessing future research priorities and funding to enable the LOPII project to be succeeded by an LOPIII project. I would strongly urge mining companies to continue their support of these initiatives so that the link between innovative geomechanics research and best practice forged by the publication of the open pit slope design guidelines book and the subsequent LOPI project publications can be maintained.

TECHNOLOGY APPLICATION

Since the 1960s there have been a number of key step changes in the equipment used by civil and mining geotechnical engineers to obtain geotechnical data from outcrop mapping and drilling. Foremost was Longyear's development in the 1960s of triple-tube core barrels with split inner tubes to ensure that core could be extracted with minimum loss and remained undisturbed when placed in the core box. The parallel development by the SMHEA in conjunction with Triefus Pty. Ltd. of a spring loaded extending nose cone attached to the triple tube core barrel to help retain undisturbed samples of completely to highly weathered rock within intervals of fresher rock (granite) was an associated step change.

Other key step changes have included: the adoption in the early 1990s of downhole televiewers, first developed by the oil industry (ATV, 1960s; OTV, 1980s); the introduction of 3D digital and laser mapping technologies in the early 2000s (Sirovision, 2001; Adam 3DM Analyst, 2003); and slope instability radar (2002).

The two technologies that I believe will provide step changes in the future are the Smart Markers outlined earlier in the paper and drones (UAVs).

The step change provided by the Smart Markers is their ability not just to record in-ground deformation behind the pit wall as it occurs and report it to the surface in real time but also, with the addition of pore pressure sensors, record and report in real time any pore pressures changes that are associated with the deformation. This outcome is not just a breakthrough, but a step change as, for the first time, it enables us to link deformation with pore pressure changes in real time.

Surfing the net whilst preparing this paper I came across a 2014 article that cited 192 future uses for UAVs listed in 24 categories, ranging from early warning systems through emergency services, delivery, business activities and marketing, to farming. One potential hazardous material delivery mechanism that caught my eye was the UAV with a robotic arm pictured in Figure 14.

Figure 14: UAV with robotic arm (source: www.futuristspeaker.com)

The only mining related use of UAVs listed in the business activities category was geological mapping, but if you browse through some of the mining company web sites you will find a wide range of UAV activities cited. Commonly, these will include the provision of real time aerial footage and 3D site maps, measuring stockpiles, traffic monitoring, and safety monitoring activities. Notably, a high proportion of the activities cited highlight the UAV's contribution to one of a mine manager's key performance activities, cost savings.

Given the proliferation of UAVs in mining you may wonder why I have included them in the step change category. I do so with one particular application in mind, pit wall mapping. I have already lamented that high quality structural mapping of our benches and inter-ramp slopes is an under-performing aspect of today's field data gathering process. I believe this is one area where UAVs can be not just a cost saver, but a game changer that helps site teams improve the quality of the information held in the structural model.

Discussions with hands-on users of the technology indicate that it adds significant new dimensions to current wall mapping practices (P Craine, M Zelic, RTIO, Western Australia, pers.comm.), particularly the following.

1. The ability to observe images across a range of scales without loss of resolution.
2. Multipoint image capture, enabling:
    a) the change of perspective and the elimination of shadows. Digital 3D mapping images (Sirovision and/or AdaTech) are recorded from one position, usually the pit floor, making berms invisible and/or leaving certain parts of the wall in shadow;
    b) the mapping and measuring of linear structural features such as a fold plunge, a striation on a fault plane, and mineral lineation. Mapping linear features is critical for understanding structural architecture and potential wall instabilities. When looking only at photographs it is an extremely difficult task.

In the discussions it was emphasized that the accuracy of UAVs is not the same without survey ground controls. Although the need for ground controls may not meet short term objectives of reducing costs by removing people from the pit, in my view the improved accuracy and reduced uncertainty in the structural model, together with the consequent long term gains in the reliability and safety of the pit walls, far outweigh such concerns.

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