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Rock strength obtained from core samples and borehole wall instabilities - the effect of drilling induced damage

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ABSTRACT: Borehole breakouts are accepted as one of the best indicators of in-situ principal stress orientation. However, the estimation of the stress magnitude from breakouts is still controversial. One prerequisite to derive stress magnitude from borehole wall failure is to have an independent estimate of the strength of the borehole wall. Zoback et al. (2003) suggest assuming that the Uniaxial Compressive Strength (UCS) from core samples is an acceptable estimate of borehole wall strength, but it has been shown that when drilling in relatively high stress environments core may be damaged, resulting in significantly reduced core strengths (e.g. Martin and Stimpson, 1994). Such core damaging processes are highly probable in stress environments relevant for breakout formation. Thus, an underestimation of UCS due to core damage could lead to an underestimation of in-situ stress magnitude from breakout back-analyses. Preliminary results from the numerical analyses presented here suggest that damage in the core initiates long before any damage occurs in the borehole wall. It is thus suggested that in relatively high-stress situations, strength evaluation from borehole geophysics or from breakouts back-analyses (in situations where the complete stress tensor is independently estimated) delivers a better estimate of the in-situ intact rock strength than laboratory tests. Work is underway to propose solution for the unbiased estimation of in-situ intact rock strength from borehole observations.

1 INTRODUCTION

Proper estimation of the in-situ intact rock strength as well as an estimation of the in-situ stresses forms the basis for most geomechanical designs of underground openings. Borehole failure constitutes a well accepted stress orientation indicator, but its use for stress magnitude estimation is controversial. Indeed, in order to obtain a proper estimate of stress magnitude from borehole breakouts, an accurate and independent estimation of the in-situ strength of the borehole walls is required. Zoback et al. (2003) suggest that the UCS obtained from core samples provides an acceptable estimate of borehole wall strength. In relatively high stress environments, however, damage is created in the core while drilling, which may significantly reduce the core strength (e.g. Martin and Stimpson, 1994). Such core damaging processes must be expected in stress environments where breakouts form. Consequently, an underestimation of UCS due to core damage could lead to an underestimation of the magnitude of in-situ stress from breakout back-analyses. At depth, both the core and the borehole wall experience complex but not identical stress paths during drilling. Since these paths are not identical and may or may not result in damage and strength reduction in comparison to that of

the rock remote from the wellbore, the damage and strength reduction of the core may not be equal to that in the wall.

The reverse approach could also be applied: in a situation where the stresses are reasonably well constrained by independent means, borehole failures could be used to back-analyze the in-situ rock strength. This problematic introduces several questions: (1) How will this in-situ strength compare with the strength obtained from the testing of potentially damaged cores?, and (2) Is the strength back-analyzed from borehole failure a better estimate for the in-situ undisturbed strength than the one obtained from the testing of cores? This paper aims at bringing insight into this issue by investigating with numerical analyses the stress paths and damage creation generated during drilling.

2 BACKGROUND

Evidences of sample disturbance have been documented at the Underground Rock Laboratory (URL) in Manitoba (Canada) by Martin and Stimpson (1994) and Eberhardt et al. (1999). They showed that the UCS, Young's modulus, and the P-wave velocity measured on cores decrease and Poisson's

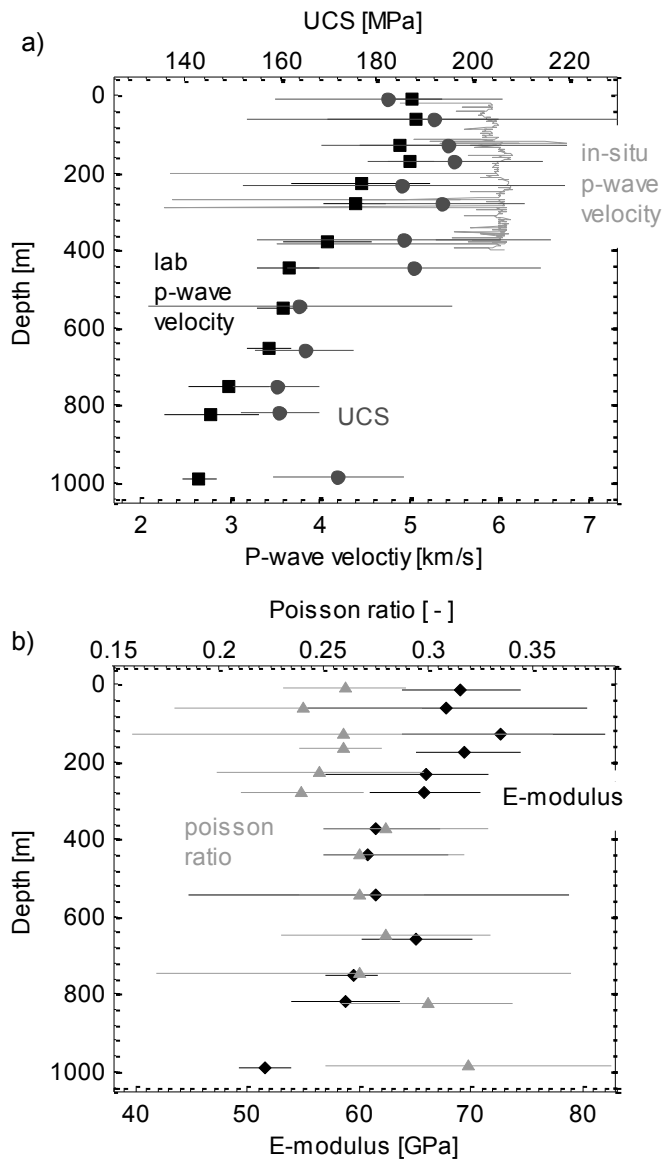


Figure 1. Laboratory and in-situ rock properties at URL (modified after Martin & Stimpson, 1994)

ratio increases as samples are obtained from rock at increasing depth and consequently increasing in situ stresses (Figure 1). They suggest that these effects are caused by increasing microcracking with depth. This is also supported by the strong non-linearity of stress versus volumetric strain from damaged samples, reflecting the higher volume of closing microcracks at the early stage of loading. Similar behavior was also observed on samples taken from deep mines in South Africa (Watson et al. 2009). Crack count using Scanning Electron Microscope (SEM) analyses support that samples from depth contains larger amounts of micro cracks. Lanaro et al. (2009) reported a strong negative correlation between sample strength and measured in-situ strength and explained this observation by sample disturbance. Interestingly, strength reduction in their case wasn't only a matter of depth but could also be related with high stress zone associated with fault zones.

At the URL, a proxy for borehole wall damage can be obtained by looking at in-situ sonic velocity logs. Contrary to the velocity measured on core sample, the in-situ velocity appeared to be depth

Table 1. In situ stress values used for numerical models

Domain	Depth m	Horizontal stress MPa	Vertical stress MPa
1	130	10.50	3.64
2	240	24.25	6.72
3	330	34.00	9.24

independent; drops in velocity seem related to fracture zones (Figure 1). This observation suggests that the intensity of drilling induced damage differs between core sample and borehole walls; being more pronounced in the core.

3 FINITE ELEMENT MODELING OF DRILLING-INDUCED CORE DAMAGE

Martin (1990), according to extensive in situ stress measurements conducted at the URL in Manitoba, defined three distinctive stress domains; stress domain 1 extending from surface to a depth of 200 m, stress domain 2 at 240 level, a transition from domain 1 to 3, and stress domain 3 extending to the deepest measurement point at 550 m. No sample disturbance was encountered in stress domain 1. However, samples retrieved from stress domains 2 and 3 were partially to severely damaged. In situ stress values assumed for the numerical modelling are given listed in Table 1.

The two-dimensional finite element software Phase² (Rocscience, 2009) was chosen to simulate core drilling and its consequent sample disturbance observed on the URL's samples. As a first approximation, a series of axi-symmetric analyses were conducted for three different depths inside three stress domains. Table 2 lists the intact rock properties of samples, taken from stress domain 1 and assumed to be representative of undamaged samples. To simulate the damage stage in the core and walls, a Mohr-Coulomb elastic, perfectly-plastic model with a tension cut-off was used for the analyses reported here. For axi-symmetric analyses, the stresses perpendicular to the borehole (horizontal stresses for a vertical hole) are assumed to be isotropic and equal to the average horizontal stresses.

In order to ensure that the numerical models provide results with an acceptable accuracy in terms of the distribution of induced stresses, especially close to the borehole wall where the stress concentration exists, elastic models were run and the stresses at the borehole wall were compared with those calculated with analytical solution. It was found that among all the types of mesh elements available in Phase²

Table 2. Intact rock properties used for numerical analysis

Cohesion	Friction angle	Tensile strength	Modulus	ν
MPa	Degree	MPa	GPa	
36	54	8	65	0.25

including three- and six-noded triangular and four- and eight-noded quadrilateral mesh elements, only the model meshed with the eight-noded quadrilateral elements provides reliable results. An error of less than 1% of the induced stresses at the borehole wall was obtained using this mesh type. The core and a zone close to the borehole wall were very finely meshed with equal-area quadrilateral elements with side length of 1 mm. Figure 2 shows the Phase² model including the geometry as well as the size of mesh elements in areas close to the core.

Since the results of the elasto-plastic model are stress path and consequently excavation size dependent, a series of sensitivity analyses were performed to optimize the discretization of the excavation increments while properly capturing the continuous drilling process. Several stages were used to capture the drilling process and an optimal excavation length of 10 mm was established with respect to yielding pattern formation, while keeping manageable computation times. For the total core length of 400 mm, 40 stages are used to simulate the drilling process (Figure 2).

The drilling-induced damage core was monitored by tracking the yielded element patterns. The simulation result suggests that as the drilling progresses and reaches a specific stress threshold, the tensile yielding initiates from the outer edge of the core and propagates toward the centre of the core when the drill bit passes this point. The yielding pattern is almost perpendicular to the borehole axis. This observation is consistent with the results of most of the published works (e.g., Corthesy and Leite, 2008). Figure 3 shows the yielded elements in the core while drilling in the three stress domains described earlier. This figure indicates that the amount of yielded elements in the core increases from domain 1 to 3; no yielding was observed in domain 1. Periodic tensile yielding occurred in the core in domain 2 and 3; being most pronounced in domain 3.

The images in Figure 3 are consistent with the core damage measured or inferred from laboratory

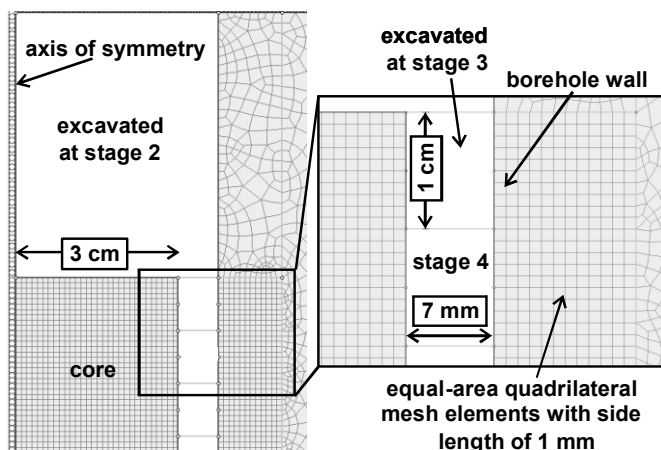


Figure 2. Geometry of Phase² model used for coring simulation

testing results reported by Martin and Stimpson (1994, Fig. 1) and Eberhardt et al. (1999).

Whether the tensile yielding appearing in the core actually implies macro fracturing (actual core breakage in the form of core discing) is a matter of strain required to cause crack coalescence and cannot be judged based on these elasto-plastic continuum analyses. However, since the tensile yielding in the elasto-plastic analysis indicates that the tensile strength is reached, it is assumed that it can be used as an indicator of damage (microcracking) that will affect the intact rock properties; the degree of property variation depending on the amount of yield in the sample.

The most important observation though, is that while extensive yielding is generated in the core (interpreted here as core damage), no sign of damage is present in the borehole wall at the simulated stress level. This suggests that the strength (and deformation) properties measured in the laboratory on core damaged by the drilling process will most probably underestimate the borehole wall strength. It must be remembered though that the adopted axi-symmetric models do not account for effects of differential stresses in the plan perpendicular to the borehole axis. This issue is to be tackled by 3D models.

4 EFFECT OF DRILLING FLUID PRESSURE

Based on the assumption that the tensile yield in the elasto-plastic model is an indicator of core damage, several models were run with the intact rock properties listed in Table 2, and vertical to horizontal stress ratios (σ_v/σ_H) of 0.25, 0.33, 0.5, 1, 1.6 and 3. For each stress ratio the horizontal and vertical stress magnitudes which resulted in tensile yielding at the outer edge of the core were determined using a trial and error procedure to define the undamaged – damaged core domains (Figure 4).

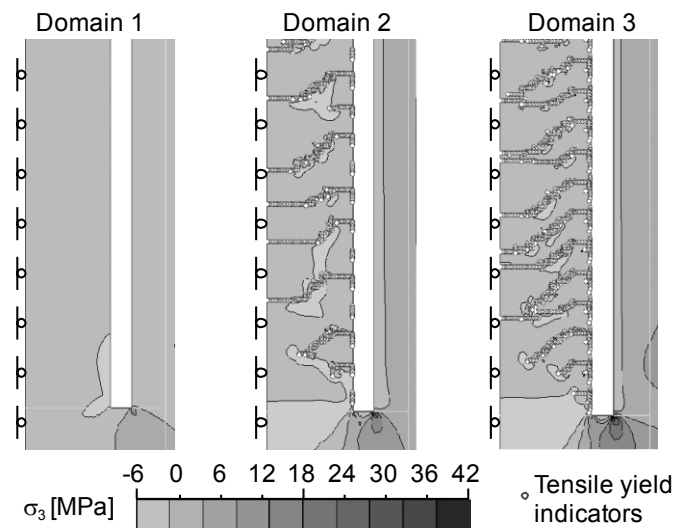


Figure 3. Increasing drilling-induced core damage from domain 1 to 3; no damage in domain 1, periodic tensile yielding in domain 2 and 3.

An important parameter that strongly influences the amount of damage in the core, but is often ignored in core discing literature, is the drilling fluid pressure. The analyses described above were repeated with internal pressure values of 1 MPa, 4 MPa and 20 MPa, and the undamaged – damaged core domains were defined for each pressure magnitude using the criterion described above. The results are presented in horizontal and vertical stresses space normalized to the intact rock tensile strength (Figure 4). For each analyzed borehole internal pressure (0, 1, 4 or 20 MPa), a contour is drawn separating a domain where no yielding is observed in the core (below the contour) and a domain where some yielding occurs (above the contour) and thus a potential for the core to be damaged during drilling exist and consequently the intact rock properties could be underestimated (e.g., both UCS and elastic modulus) or overestimated (e.g., Poisson's ratio). This figure reveals the importance of drilling fluid pressure on stabilizing the core by expanding the undamaged core domain. Furthermore, it suggests that the drilling fluid pressure is more effective in limiting damage when σ_v / σ_H is smaller than unity (below the dotted line).

The practical use of this chart is, for some given site stress conditions, to evaluate whether core damage might significantly influence the laboratory properties. If this is the case, test results on core sample will probably underestimate the in-situ strength.

5 CONCLUSIONS

The numerical results presented in this paper suggest that:

- Drilling-induced rock damage must be anticipated. If drilling-induced rock damage is neglected, the actual in-situ rock strength will likely be underestimated.
- Stress situations where core damage becomes significant can be evaluated with charts as shown by in Figure 4 (example is limited to axis-symmetric stress conditions).
- Core damage initiates before borehole wall damage is observed (again assuming axis-symmetric stress conditions). If combined with uncorrected laboratory strength data, this may lead to an underestimation of in-situ stress estimate when borehole breakouts are back-analyzed to derive in-situ stress magnitudes.
- The results presented here suggest that in-situ methods, e.g. wireline logs and/or breakouts back-analysis, if in situ stresses are obtained independently, could provide a more effective means to determine the in-situ rock strength than by laboratory testing, particularly if core damage is significant.

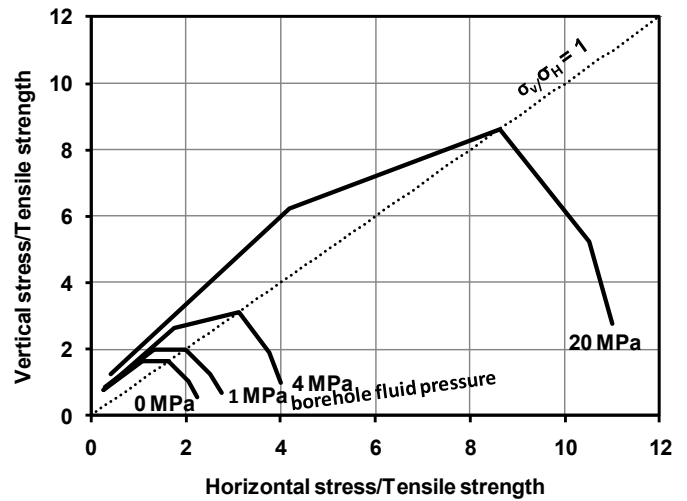


Figure 4. Undamaged (below black lines) – damaged (above black lines) domains in the normalized horizontal vs. vertical stress space for different values of internal pressure.

ACKNOWLEDGMENTS

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