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Modeling Validation of Mechanical and Thermal Borehole Breakouts from Polyaxial Laboratory Tests to Determine Maximum Horizontal In Situ Stress

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ABSTRACT: To accurately assess rock behavior in the deep subsurface, it is necessary to measure the in situ stress directions and magnitudes. The current methods for measuring the in situ stress state in the deep subsurface primarily include hydraulic fracturing tests (i.e., the minimum horizontal stress) or occasionally observing existing compressive borehole breakouts (i.e., the maximum horizontal stress) that have occurred naturally from drilling. If there are no existing compressive breakouts in a borehole, the maximum horizontal in situ stress cannot be estimated with much confidence. In response to this data gap, a new thermal breakout technology is being developed that will provide a method for thermally inducing borehole breakouts and obtaining consistent measurements of the maximum horizontal stress magnitude. This thermal breakout technology involves heating the borehole and increasing the thermoelastic compressive stress in the rock until a breakout develops, which is directly correlated to the maximum horizontal stress magnitude.

In support of developing the thermal breakout technology, polyaxial laboratory tests have been performed on small-scale boreholes within rock blocks where mechanically- and thermally-induced borehole breakouts have been created. Numerical models along with the principal of superposition were created and used to analyze the polyaxial laboratory tests to predict the maximum horizontal stress, given the same data that would be obtained in an actual subsurface borehole thermal breakout test. Multiple failure criteria were used to evaluate the best prediction of the breakout onset and maximum horizontal stress. The maximum horizontal stress predictions were compared to the actual maximum horizontal stress applied at breakout using acoustic events recorded from emission sensors in the polyaxial tests. The results showed consistent results that could be used to refine the modeling approach and failure criterion that are used to make the maximum horizontal stress predictions. This study provided insight and validation for the thermal breakout stress measurement concept.

1. INTRODUCTION AND BACKGROUND

The most common in situ stress measurement method is hydraulic fracturing, which measures the stress state by creating a tensile fracture that opens normal to the minimum horizontal stress direction (Zoback, 2007). Using the minimum horizontal stress and fracture reopening pressure provides a basis for approximating the maximum horizontal stress, provided that the stress concentration around both the borehole and fracture can be assumed from linear-elastic theory. Considerable confidence exists in using the shut-in pressure to determine the minimum horizontal stress; however, recognition of fracture mechanics and pore pressure effects as well as a general uncertainty in fracture initiation processes have eroded the confidence in approximating the maximum horizontal stress magnitude based on hydraulic fracturing (Rutqvist et al., 2000).

Unlike hydraulic tensile fractures, borehole breakouts result from compressive fractures in the direction of the minimum horizontal stress. These compressive borehole breakouts develop from the high stress concentrations created by the borehole, strength of the rock, and in situ stress field (Moos and Zoback, 1990; Peska and Zoback, 1995). By using a combination of hydraulic fracturing and breakout measurements, the minimum and maximum horizontal stress profiles as a function of depth can be estimated with reasonable accuracy (Molaghab et al., 2017).

While breakouts are not uncommon, they do not appear in most wellbores. Breakouts are only observed when the magnitude of the maximum stress and its ratio to the minimum stress are sufficient to create stress concentrations that exceed the compressive strength of the rock. Other than drilling in regions prone to breakouts, a method does not currently exist for consistently creating breakouts where they do not naturally occur. The lack of borehole breakouts severely limits the potential areas where the traditional breakout technology of measuring the maximum horizontal stress can be applied; therefore, the current state-of-the-art technology for deep-borehole, in situ stress measurement needs to overcome this major limitation.

The United States Department of Energy (DOE) is currently sponsoring a project to develop a new approach for measuring the maximum horizontal stress. This approach induces breakouts by heating the borehole surface and controlling the rock's thermoelastic expansion. To develop and refine this thermal breakout technology, the project research focuses on numerical modeling, laboratory testing, small-scale field testing, and full-scale field testing in a deep borehole (Nopola et al., 2020; Trzeciak et al., 2020; Voegeli et al., 2020).

This paper presents select results from numerical modeling in support of understanding observations from laboratory polyaxial breakout testing. The overall approach discussed in this paper involves several tasks, including the following:

- Discuss the fundamental thermal breakout concept
- Review laboratory polyaxial borehole breakout experiments performed by the University of Wisconsin at Madison
- Perform numerical modeling to predict the maximum horizontal stress based on the onset of breakouts
- Compare the model-predicted maximum horizontal stress to the laboratory applied maximum horizontal stress

2. FUNDAMENTAL DEVELOPMENT

The theoretical development of the thermal breakout concept is based on analyses of the classic Kirsch solution, which is a set of equations that are commonly used to evaluate the three-dimensional (3D) stress state around a borehole that is drilled within an isotropic, linear-elastic medium (Kirsch, 1898). Figure 1 illustrates the horizontal in situ stress components, azimuth orientation, and breakout definition for a vertical borehole. Although only a vertical borehole is considered in this paper, the thermal breakout concept can be easily extended to an arbitrarily oriented borehole within an in situ stress field (Peska and Zoback, 1995).

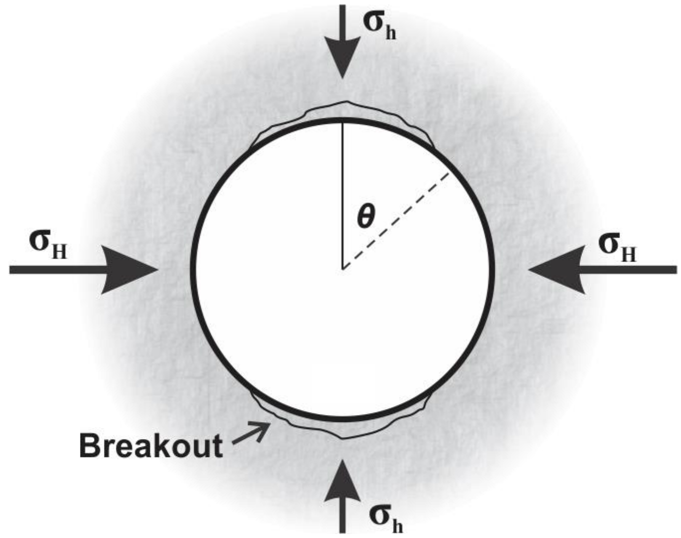


Fig. 1. In situ stress components and breakout orientation around a vertical borehole.

Based on Figure 1 and the Kirsch solution, the effective hoop stress acting on the borehole surface in the case of an applied temperature change is given by the following equation:

$$\sigma_{\theta\theta} = \sigma_H + \sigma_h + 2(\sigma_H - \sigma_h)\cos 2\theta - P_0 - P_m + \frac{\alpha_t E \Delta T}{1-\nu} \quad (1)$$

where:

$\sigma_{\theta\theta}$ = tangential stress ("hoop stress") around the borehole
σ_H = maximum horizontal in situ stress
σ_h = minimum horizontal in situ stress
θ = azimuth from σ_h direction
P_0 = pore pressure
P_m = mud weight or internal borehole pressure
$\alpha_t,\ E,\ \nu$ = rock properties that correspond to the coefficient of thermal expansion, Young 's modulus, and Poisson 's ratio, respectively
ΔT = change in borehole surface temperature

For a borehole breakout to occur, the compressive stress on the borehole surface must exceed the rock's compressive strength. As evident in Eq. (1), an induced temperature increase on the borehole surface will lead to a corresponding increase in the hoop compressive stress, which provides a controllable means for initiating breakouts and is the basis for the thermal breakout technology that is currently in development. Thermoelastic effects on the hoop stress around boreholes have long been recognized as an important factor in calculating safe drilling mud windows (Gholilou et al., 2017).

3. LABORATORY POLYAXIAL BREAKOUT TESTING SUMMARY

The University of Wisconsin at Madison (UW) performed six polyaxial stress tests on Berea Sandstone (Berea) samples to create mechanically- and thermally-induced borehole breakouts. Trzeciak et al., 2021 provides a detailed description of the polyaxial borehole breakout tests, but a summary is provided here.

Blocks of Berea, with dimensions 139.7 x 139.7 x 203.2 mm, with a 19.1 mm borehole drilled through the center in the long direction were prepared. Three external stresses were independently applied to each block to approximate the principal in situ stresses that a borehole would experience in the subsurface. These in situ stresses include a vertical stress (σ_v), a minimum horizontal stress (σ_h), and a maximum horizontal stress (σ_H).

Eight acoustic emission sensors (AE sensors) were used to monitor the position and magnitude of acoustic emissions created from rock failure. Two AE sensors were on each of the four longest sides and their location was used to locate acoustic events recorded. Twelve thermocouples were installed in holes drilled from the outside of the block to different radial distance to record the sample's temperature distribution. The three, independently applied external stresses were calibrated and recorded throughout the tests.

Three tests did not include borehole heating and induced borehole breakouts through the application of only the external mechanical stress (i.e., mechanical tests). In these mechanical tests, all three external stresses were gradually applied from the unloaded stress state to an initial stress state. After this point, σ_v and σ_h were held constant while σ_H was increased until breakouts formed.

The other three tests induced borehole breakouts from thermally-induced stress from heat applied inside the borehole (i.e., thermal tests). Heat was applied to the borehole using a 1000 watt cartridge heater. The borehole was air-filled at atmospheric pressure in all tests. These thermal tests first loaded the blocks to an initial stress state, like the mechanical tests. After this point, σ_v and σ_h were held at the constant initial stress while σ_H was increased to a value just below the critical value that would initiate borehole breakouts. Next, the borehole heater was activated, which increased the borehole temperature. The resulting compressive thermoelastic stress continued to increase with additional heating until borehole breakouts formed, even though the applied external stresses remained constant.

Three different σ_v and σ_h stress combinations were applied in the mechanical and thermal tests and ranged from 10 to 20 MPa. Each mechanical test was paired with a thermal test at the same σ_v and σ_h stress combination. All six tests successfully created borehole breakouts. Following the completion of the tests, the acoustic emission data was processed to obtain a distribution of normalized acoustic energy localized in the σ_h direction around the borehole, which is where the breakouts initiated. Using the accumulated acoustic energy through the duration of the test and video of the borehole for the mechanical tests only, the breakout time was determined to be used in modeling to predict σ_H.

4. MODELING APPROACH

A thermo-mechanical model was developed and simulated to approximate the laboratory test results, with the objective of developing a method to predict σ_H from a borehole thermal breakout test. Specifically, the thermo-mechanical model was used to back-predict the applied σ_H, which provided validation for the thermal breakout stress measurement approach. The following sections discuss the modeling approach.

Model: To adequately predict σ_H, an accurate and efficient 3D finite difference model was developed to approximate the polyaxial test conditions. Figure 2 shows the model that was created to match the polyaxial test sample dimensions.

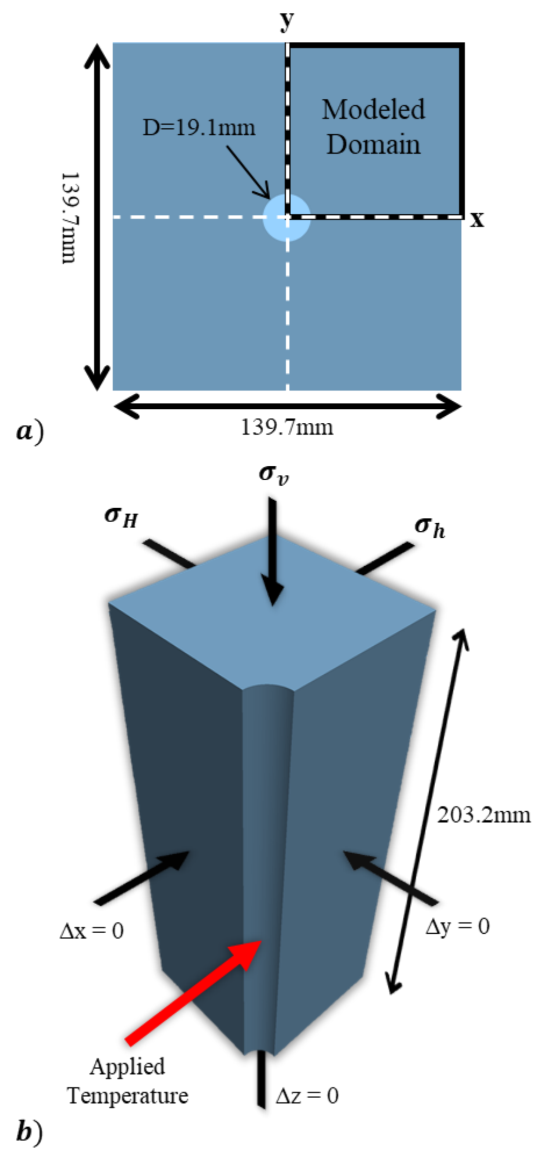


Fig. 2. a) Top view of the polyaxial test sample. b) Isometric view of the quarter symmetry model. Applied external principal stresses and roller boundary conditions are labeled by black arrows. Red arrow points to borehole surface where the temperature boundary condition was applied.

Boundary Conditions: The full sample block and loading conditions in Figure 2 are symmetric about the x and y axes. Therefore, the full model was simplified to a quarter symmetry model (as shown in Figure 2b) by applying roller boundary conditions to the planes of symmetry.

The external principal stresses were applied as time-dependent surface tractions based on the laboratory testing measurements. Table 1 lists the maximum applied principal stresses for the pairs of matching mechanical and thermal tests.

Table 1. Maximum applied external stresses for polyaxial tests.

		Maximum Applied External Stress		
Test #	Type	σ_H (MPa)	σ_h (MPa)	σ_v (MPa)
Ber2	Mechanical	69	10	10
Ber5	Thermal	26		
Ber3	Mechanical	74	20	20
Ber7	Thermal	35		
Ber6	Mechanical	73	20	10
Ber4	Thermal	31		

To approximate the application of the borehole heater, a time-dependent temperature boundary condition was applied to the borehole surface based on thermocouple measurements from the test sample. The height of the heater covered 94% of the borehole height; therefore, the temperature of the entire borehole surface was assumed to be uniform.

Model Properties: The model behavior was defined as a linearly elastic, isotropic, and thermally-conductive material to incorporate the effects of applied mechanical and thermal stress. To model these effects, it is necessary to specify appropriate elastic and thermal properties. Table 2 lists the measured Berea elastic and thermal properties, which were obtained from laboratory testing performed by RESPEC and are discussed in greater detail by Trzeciak et al., 2021.

Table 2. Elastic and thermal properties of Berea Sandstone used in the 3D model.

Property	Average Value	Unit
Elastic		
E	20	GPa
v	0.19	—
Thermal		
k	2.2	W/m-K
c_p	730	J/kg-K
ρ	2.05	g/cm^3
α_t	1.48E-5	1/K

Two failure criteria were used to predict the onset of breakout (and subsequently, σ_H), the Mohr-Coulomb criterion and Mogi criterion. Historically, the Mohr-Coulomb criterion has been widely used to analyze borehole breakouts. In its simplest form, the Mohr-Coulomb criterion is a linear relationship that defines the maximum allowable σ_1 (i.e., the strength) for a given σ_3. Note that the Mohr-Coulomb criterion does not consider the influence of the intermediate principal stress (σ_2) on the rock strength. The Mohr-Coulomb relationship is shown in Eq. (2).

$$\sigma_1 = UCS + q\sigma_3 \tag{2}$$

where:

UCS = Unconfined Compressive Strength

$$q = (\sqrt{1+\mu^2} + \mu)^2 \tag{3}$$

μ = Internal friction factor

The Mogi criterion is a linear relationship that defines the maximum octahedral shear stress (τ_{oct}) for an applied two-dimensional mean stress ($\sigma_{m,2}$) as shown in Eq. (4) (Mogi, 1971). Note that the Mogi criterion includes the influence of σ_2 on the rock strength.

$$\tau_{oct} = a + b\sigma_{m,2} \tag{4}$$

where:

$$\sigma_{m,2} = \frac{1}{2}\,(\sigma_1 + \sigma_3) \tag{5}$$

Traditional triaxial tests were performed on Berea samples to obtain a Mohr-Coulomb strength fit. The Berea was found to have a UCS=59.9MPa and a μ=0.77. The Mohr Coulomb strength parameters were recast into the Mogi stress space, which produces the criterion values a=11.01MPa and b=0.575.

σ_H Prediction: If a thermal breakout test was conducted in a subsurface borehole, the following data would typically be available: borehole temperature, acoustic emissions, and the mechanical and thermal properties of the rock. Additionally, σ_h would be available from hydraulic fracturing tests, and σ_v would be calculated from the overburden weight. Similar to the laboratory polyaxial tests, the precise time at the onset of the breakout development can be determined from processing the acoustic emission data. Based on the breakout onset and the borehole temperature data, the borehole wall thermal stress can be approximated. With rock strength limiting the maximum allowable hoop stress, σ_H is then left as the only unknown to be determined in Eq. (1).

Based on the polyaxial test data, a σ_H prediction method was developed. The method involved iterating through values of σ_H in the model until the onset of borehole breakout was predicted at the same time as indicated in the acoustic emission measurements. Stress superposition and an optimization algorithm was used to minimize the solution time.

5. MODELING RESULTS AND DISCUSSION

Each of the mechanical and thermal polyaxial tests were modeled, and σ_H was predicted using the Mohr-Coulomb and Mogi criteria. The predictions of σ_H for the mechanical tests, using the Mogi criterion, are compared to the polyaxial test measurements in Figure 3. Figure 4 shows the σ_H predictions, using the Mogi criterion, compared to the polyaxial test measurements from the thermal tests.

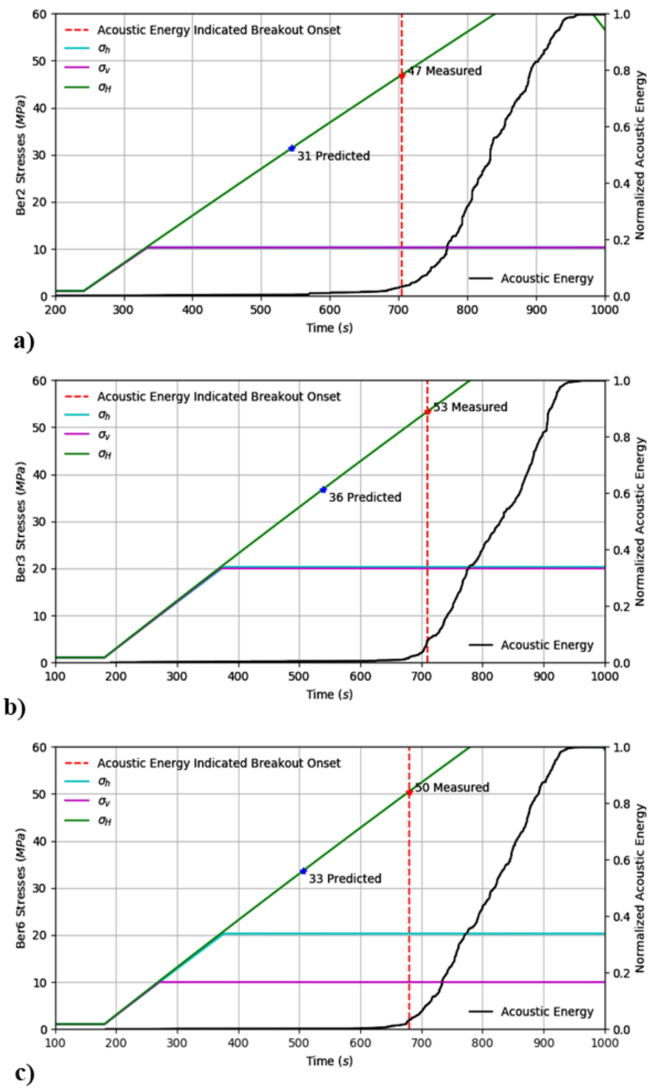


Fig. 3. Polyaxial mechanical breakout test data. Primary y-axis shows applied external principal stresses. Secondary y-axis shows the normalized acoustic energy. The onset of breakout indicated by the acoustic energy is labeled by the red dashed line. The predicted σ_H (blue star) and measured σ_H (red star) are labeled for each of the tests: a) Ber2 b) Ber3 and c) Ber6.

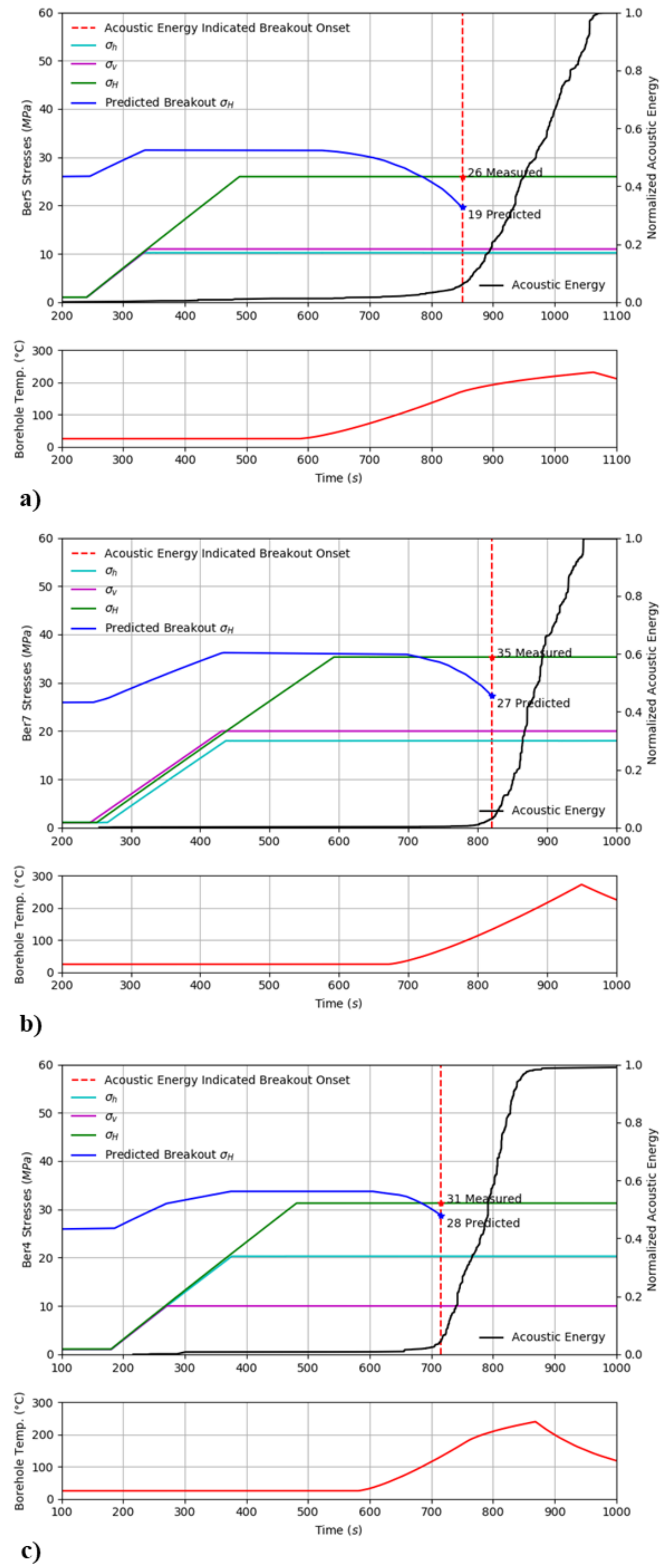
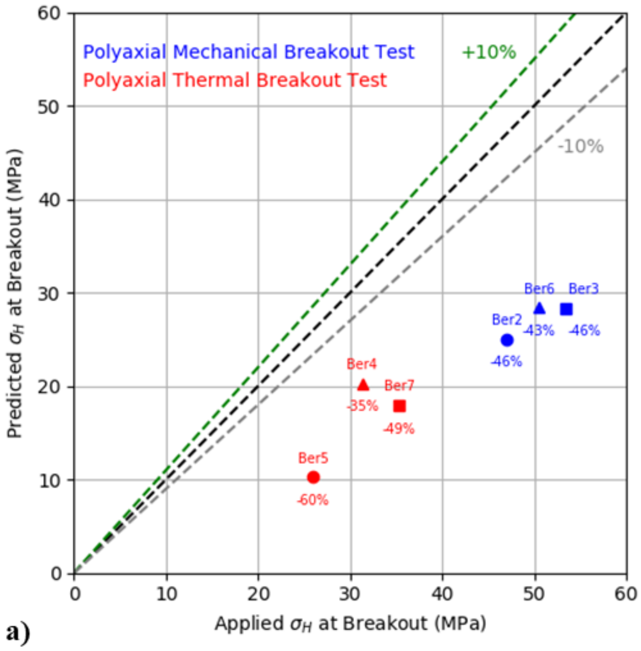
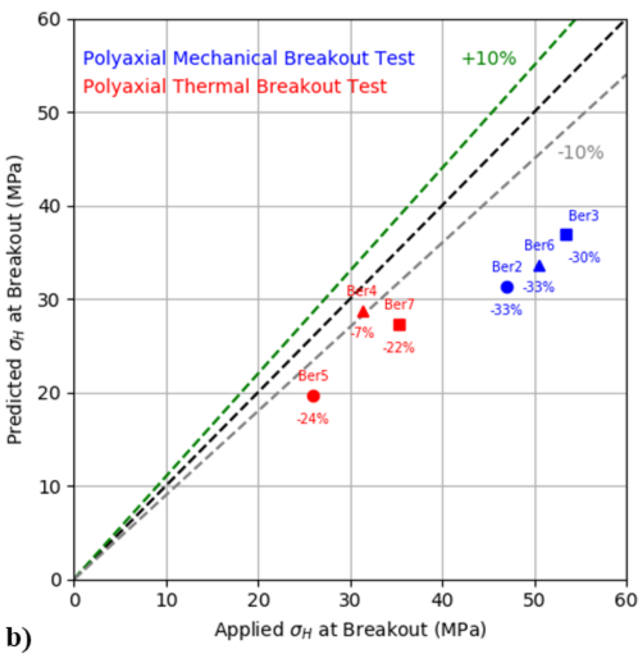


Fig. 4. Polyaxial thermal breakout test data. Primary y-axis shows applied external principal stresses. Secondary y-axis shows the normalized acoustic energy. The onset of breakout indicated by the acoustic energy is labeled by the red dashed line. The predicted σ_H to cause breakout through time is shown by the blue line. The predicted σ_H (blue star) and measured σ_H (red star) are labeled for each of the tests: a) Ber5 b) Ber7 and c) Ber4. The second plot for each test is the measured temperature applied to the model borehole.

The predicted σ_H and applied σ_H magnitudes were compared, as shown in Figure 5 for both Mohr-Coulomb and Mogi criteria. The percent error for the predicted σ_H was calculated and labeled for each test.



a)



b)

Fig. 5. Predicted σ_H vs. applied σ_H using a) Mohr-Coulomb and b) Mogi criterion. Matching symbols indicate tests with matching σ_h and σ_v magnitudes. The percent error and test name are labeled next to each symbol. The black dashed line indicates 0% error between the predicted and applied σ_H. The green and grey dashed lines bound the +10% and -10% error, respectively.

The Mohr-Coulomb criterion consistently underpredicted σ_H by an average of approximately 50% for both the thermal and mechanical tests. This percent error is too large and suggests that the Mohr-Coulomb criterion may not be suitable to predict σ_H in this study. The Mogi criterion also consistently underpredicted σ_H, however the average error is approximately between 20-30%. The consistently underpredicted σ_H for both criteria could be explained by several aspects of the prediction method. These aspects include the triaxial strength fit, influence of σ_2, borehole size effects, and the dependence of elastic and strength properties on temperature.

The current strength fit for the Berea was based on four triaxial tests to characterize the Mohr-Coulomb strength. Because only four triaxial tests were performed, the rock strength may not have been adequately characterized, especially given the inherent variability of geologic materials. If more strength tests were performed, a potentially more accurate average strength could be determined, which could provide potentially better σ_H predictions.

The influence of σ_2 (which is the vertical stress acting on the borehole wall at the breakout location) likely explains the difference between the Mohr-Coulomb predictions and Mogi predictions. This behavior can be seen in Figure 5a where the Mohr-Coulomb failure criterion underpredicts σ_H significantly. The Mohr-Coulomb criterion does not include the strengthening effect of σ_2, which causes a significant underprediction of σ_H (i.e., a lower σ_H would cause a breakout when using the Mohr-Coulomb criterion). In contrast, the Mogi criterion does incorporate the strengthening effect of σ_2, which prescribes a higher strength and results in a higher σ_H prediction that is closer to the applied value. Therefore, a strength criterion that includes the influence of σ_2, like Mogi or similar criteria (e.g., Colmenares et al., 2002), is likely required when using the thermal breakout concept to measure the in situ stress state.

Another explanation for the consistent underprediction of σ_H is the influence from the relatively small size of the borehole (i.e., size effects). Cuss et al., 2003 and Meier et al., 2013 suggest that the borehole strength increases as the borehole diameter decreases. This might suggest that the small borehole diameter (19.1 mm) in the polyaxial breakout tests increases the rock's strength, which could explain the consistently underpredicted σ_H shown in Figure 5 for both the Mohr-Coulomb and Mogi criteria. If the boreholes were similar in size to actual deep subsurface boreholes, the predicted σ_H could potentially be closer to the applied σ_H. This suggests that a correction to the failure criterion based on the borehole size could more accurately predict σ_H. However, an appropriate size correction would need to be determined through additional laboratory experiments.

The error in σ_H predictions could also be explained by the potential dependence of the elastic and strength properties on temperature, which was not included in this study. Including the effects of temperature on the elastic properties (i.e., Young's modulus, Poisson's ratio, and thermal expansion coefficient) might suggest that the borehole experiences a different stress state at the time of breakout than predicted in the models. Similarly, the models assumed that the rock behaved as a linear elastic material up to the breakout onset. If the rock's elasticity is not perfectly linear, then a different stress state would be predicted around the borehole. Additionally, a temperature-dependent strength criterion could result in a different prediction of σ_H.

6. SUMMARY AND CONCLUSIONS

This paper summarizes numerical modeling of laboratory polyaxial borehole breakout tests. This modeling was performed to help interpret the laboratory measurements and aid in developing a method to predict the σ_H in situ stress from thermally induced breakouts. In the polyaxial tests, three external stresses were independently applied to a block of Berea Sandstone to approximate the principal in situ stresses that a borehole would experience in the subsurface. For half of the tests, σ_H was increased until breakouts formed on the borehole surface. For the other half, σ_H was held constant, and a cartridge heater was used to heat the borehole until breakouts formed.

The numerical models used the Mohr-Coulomb and Mogi criterion to capture the breakout onset and predict the applied σ_H. The numerical models consistently underpredicted σ_H when compared to the applied σ_H

While the σ_H predictions did not show perfect agreement with the recorded values, the study results revealed important considerations for accurately predicting σ_H. These considerations include a comprehensive triaxial strength fit, the influence of σ_2, borehole size effects, and the dependence of elastic and strength properties on temperature. Based on the study results, the authors suspect that the influence of σ_2 and borehole size effects are critical factors for interpreting laboratory-scale borehole breakouts.

Despite the need for more research, the study presented in this paper provided a crucial proof of concept for thermally inducing borehole breakouts, which were shown to depend on the applied in situ stress. As this DOE-sponsored project advances, more detailed and complex analyses, testing, and validation will be performed to further refine the thermal breakout σ_H in situ stress prediction method.

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