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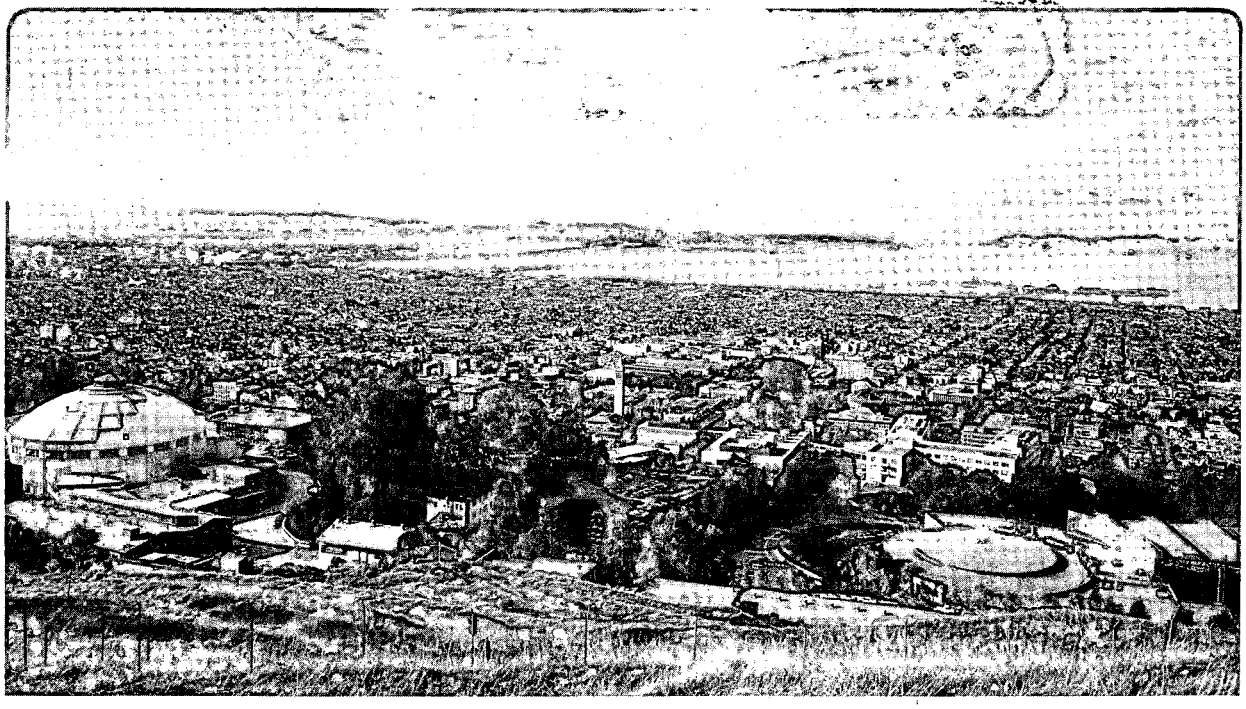

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Borehole Breakout and Stress Measurements

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Borehole breakout and stress measurements

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ABSTRACT: Elongated breakout cross sections for different rock stresses and strengths have been produced using a numerical simulation based on boundary element methods and a micromechanics model of extensile splitting. Although these breakout cross sections are completely stable for an elastic-brittle rock they are not related uniquely to the stresses and strengths, and depend upon the sequence in which holes are drilled and the stresses applied. The depth of any breakout depends mainly on the initial breakout angle. The same initial breakout angle can result from many different combinations of stress. We conclude that breakout shapes cannot be used to infer the magnitudes of the stresses orthogonal to a borehole. The interpretation of hydraulic fracturing measurements based on the stress around a circular hole does not result in large errors if the hole has moderate breakouts. Large breakouts result in tensile fractures that preclude measurements of breakdown pressures.

1 INTRODUCTION

The phenomenon of rock fracturing by spalling from the walls of boreholes, is referred to as "borehole breakout". The breakout problem has been the subject of intensive field studies and observations (Leeman 1960; Cox 1970; Bell and Gough 1979,1982; Hickman et al. 1985; Plumb and Hickman 1985; Kim et al. 1986), laboratory experiments (Gay 1976; Mastin 1984; Haimson and Herrick 1985) and theoretical analysis (Gough and Bell 1982; Zoback et al. 1985; Zheng and Cook 1985, Ewy et al. 1987, Guenot, 1987 and Maury, 1987). All the studies agree that breakouts take place in regions of high stress concentration and that the elongation of the diameter of a borehole is parallel to the direction of the minimum principal stress orthogonal to the borehole axis.

In this paper, we wish to report recent theoretical results concerning the effect of borehole breakouts on in situ stress measurements. We investigate the possibility of finding the magnitudes of the in situ stresses from borehole breakouts and the effect of breakouts on the results of stress measurement by hydraulic fracturing. Results from the numerical simulations show that borehole breakouts are stress history dependent, that is, the shape and size of a breakout depends on the sequence in which the hole is drilled and the stresses are applied. Results also show that the initial breakout angle is the main factor that controls the breakout depth and the same initial breakout angle can be obtained from different stress-strength combinations so that there is a non-unique relationship between the in situ stresses and the breakout shape and size. The effect of borehole breakout on the hydraulic fracture technique, however, is not important for moderate breakouts but for larger breakouts, in which tensile fractures have already been generated, only the "shut in" pressure can be obtained.

2 NUMERICALLY GENERATED BREAKOUTS AND THEIR NONUNIQUE RELATIONSHIP TO IN SITU STRESSES

When a borehole is drilled, the original stress field changes and results in concentration of tangential stress around the borehole boundary. The stress distribution around a circular borehole can be obtained from the Kirsch's solution (Jaeger and Cook, 1979). In the case of zero internal pressure, the rock close to the boundary is essentially subjected to biaxial compressive stress. Farther away from the borehole, the stress conditions will be triaxial in nature, with the maximum stress being the tangential stress, which decreases with radial distance from the borehole wall, and the confining stress being the radial stress, which increases with radial distance from the borehole wall. For vertical boreholes, the axial stress is usually equal to that produced by the weight of the overburden and is taken as the intermediate of the three principal stresses.

When a rock is under uniaxial compression or triaxial compression with low confining pressure, extensile splitting fractures are usually observed (Jaeger and Cook, 1969, Wawersick and Fairhurst, 1970 and Wawersick and Brace, 1971). Many fracture mechanics models have been proposed to study the mechanisms responsible for axial splitting and the transition to shear faulting at higher confining stresses (Brace et al. 1966, Fairhurst and Cook, 1966, Horrii and Nemat-Nasser, 1985, Ashby and Hallam, 1986 and Kemeny and Cook, 1987). The model for two dimensional sliding cracks proposed by Kemeny and Cook (1987) is used as the basis for the results presented in this paper. The rock adjacent to the free surface of a borehole in the direction of the minimum far field stress is subjected to the greatest values of tangential stress and the least value of radial stress. Therefore, rock fracture is most likely to occur at this location. A slab of rock formed by extensile splitting cracks will spall off so that the boundary of the borehole is no longer circular but becomes extended in the direction of the minimum principal stress. In general, this will cause further stress concentration in front of the spalled region and further breakout will take place. To model this continuous spalling, a numerical method that can systematically change the boundary cross section shape and calculate the stress distributions around the new shape has been developed (Zheng and Cook, 1985, Ewy et al., 1987 and Zheng, Kemeny and Cook, 1987). In this model the borehole boundary is divided into many small elements and the stresses are calculated using an elastic boundary element technique (Crouch and Starfield, 1983). The tangential stresses in the elements are compared with the strength of the rock and elements in which the calculated stress exceeds the strength of the rock are removed from the mesh so that a new borehole boundary is formed. The stresses on the new boundary are calculated and compared with the strength of the rock and the "failed" elements are removed again. By repeating this procedure, a stable breakout cross section can be formed. Stability of the final breakout cross sectional shape is reached when the boundary tangential stress everywhere is less than the biaxial compressive strength or the tensile strength of the rock, whichever is appropriate and the stresses inside the rock are everywhere less than the limiting values from a Mohr-Coulomb shear failure criterion. This criterion is used outside the borehole because shear the most probable mode of failure inside the rock due to the presence of a confining stress (Zheng, Kemeny and Cook, 1987). Different breakout cross section shapes produced from various stress-strength combinations are shown in figure 1. In this figure two breakout cross sections are shown for some stress-strength combinations. These represent results from different loading histories. The larger of the double breakout shapes and the single breakout shapes are produced for the condition of a borehole drilled into a pre-stressed rock. To some extent, this represents the case when a borehole is drilled in field. The smaller ones are produced for the condition where the stresses are gradually increased on a rock in which a borehole has been drilled. This could represent the condition of laboratory produced breakouts.

Figure 2 shows contours of half of the differential stress, or maximum shear stress and the contours of mean stress. The breakout cross section used is the final stable cross for stresses of 30.3 MPa and 15.15 MPa, respectively, and a rock with a coefficient of internal friction of 0.7 and strength of 75 MPa. The numbers in the left column represent the values of the stress contours. The numbers in the right column represent the values of the

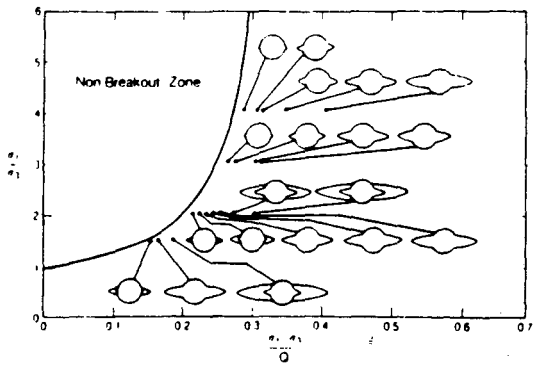

Figure 1. Simulated stable breakout cross sections for different values of field stress in relation to the biaxial compressive strength.

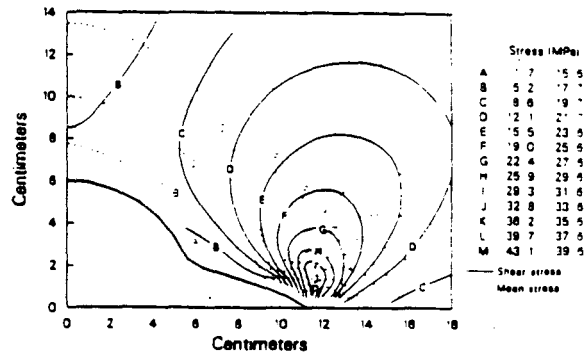

Figure 2. Contours of maximum shear stress and mean stress around a stable breakout cross section. The breakout cross section is generated with a stress ratio of 2 and stress-difference/strength of 0.22.

shear stress required to cause a Mohr-Coulomb shear failure with these rock properties at the mean stress given in the left column. It is clear from the stress contours that shear stresses at points around the "broken out" borehole are everywhere less than those required to cause Mohr-Coulomb failure. To insure that the stress contours produced by the numerical method are correct, experiments using a photoelastic stress analysis were conducted and the maximum shear stress contours from the experiments (figure 3) have the same shapes as those in figure 2.

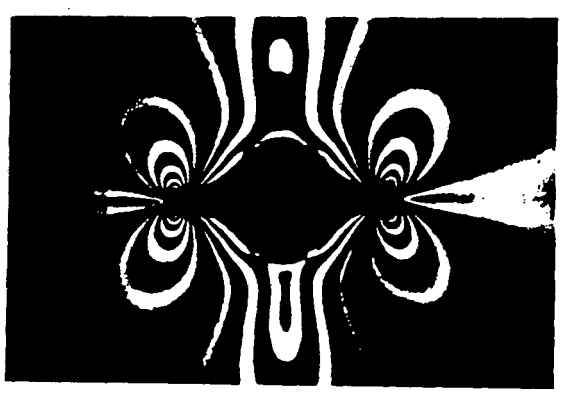

Figure 3. Photoelastic stress analysis show maximum shear stress contours around the breakout cross section shape in figure 2.

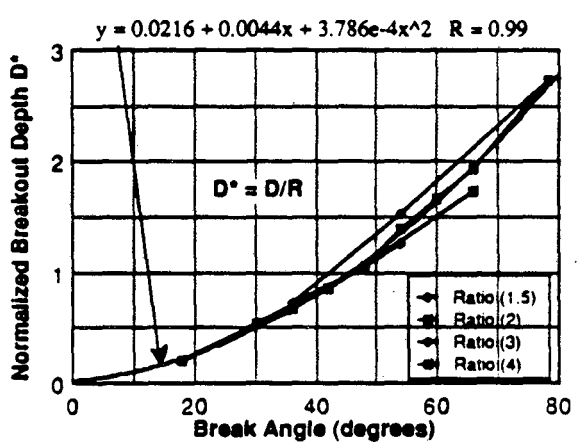

Figure 4. Breakout angle vs. normalized breakout depth (D*) for combinations of all stress and strength for breakouts generated in a pre-stressed rock shown in Figure 1.

Some researchers have observed borehole breakouts having with bottoms (Zoback et al., 1985). Careful examinations of these breakout shapes show that most of the flat bottoms actually have a sharp notch at their deepest portion. The rock located at the corner, where the breakout wing and the original borehole join, is essentially free of confining stress so that it it possible that the rock could fall off the corner, forming flat bottomed breakouts.

One important result from the breakout cross sections produced by the numerical simulation, is that once a breakout is initiated within a certain angle, the breakout generally will not widen but will deepen until it reaches its stable state. This is because the stress

concentration zone always moves away from the original boundary and the area it occupies decreases. As a result, the tangential stress at locations on the unbroken portion of the borehole, never exceeds the strength of the rock. The depth of a breakout depends on both the initial breakout angle and the current stress state but mainly on the former; the larger the initial breakout angle, the greater the breakout depth. The initial breakout angle can be calculated directly from the Kirsch's solution for a given stress state and the same initial breakout angle can be obtained for different states of stress, that is, different stress states can create similar stable breakout cross sections. Figure 4 shows plots of breakout angle vs. normalized breakout depth for all breakout cross sections generated for different combinations of stress and strength shown in figure 1. The normalized breakout depth is the ratio between the distance between the two tips of the breakout and the diameter of the borehole. The breakout angle is the angle subtended at the center of the borehole by the intersection of the breakout and the circumference of the borehole. Each solid curve correspond to a constant stress ratio σ_1/σ_3. The near-superposition of the curves indicates that the in situ stress magnitudes cannot be determined uniquely from the breakout size , shape and the strength of the rock, although the orientation of the breakout indicates the directions of the in situ stresses. The dashed line in the figure is the correlation between the breakout angle and the depth.

3 DEPENDENCE OF BREAKOUT SHAPES ON THE STRESS HISTORY

To study the effect of loading history on the shapes of breakout produced, we modified our numerical method to produce breakouts around boreholes in rock subjected to gradually increasing stresses. During the calculation, the ratio between the maximum and the minimum far field stresses is kept constant and the stresses are increased in steps starting from values on the curved line in figure 1 which correspond to the minimum stresses necessary to initiate any breakout. During each episode of spalling on the borehole boundary, the stress values are kept constant and the failed boundary elements are determined by comparing the tangential stress in the elements to the biaxial compressive strength of the rock. After each episode, the failed elements are removed so that the boundary of the borehole is redefined. The stress values are then increased by one step in order to start the next episode. This procedure is repeated until the final stress values are reached and the breakout reaches its stable state, that is, the tangential stress everywhere on the boundary is less than the biaxial compressive or tensile strengths of the rock and the stresses inside the rock are less than the limiting values given by the Mohr-Coulomb criterion. The breakout shapes resulting from gradually increasing stress are shown in figure 1 as the inner of the two breakout shapes at the same point. The stresses at these points correspond to final values of the stresses in the gradually increasing stress condition. The difference between the breakout shapes produced by the two different stress histories is remarkable. The breakout shapes produced from the gradually increasing stress condition are much smaller than those from the condition of a borehole drilled into a pre-stressed rock although the final stress values are the same. Breakout shapes can have different sizes for different rates of stress increase. This is because the initial breakout angle (the arc on the borehole boundary that the breakout occupies) is small when the initial stress values are small and the breakout shape relieves the stresses at points behind this arc before the far field stresses reach final values. Nevertheless, as the far field stress values are increased so the stresses inside the rock also increase, which tends to make the smaller breakouts less stable than the larger ones at the same final values of stress. As a result, the degree of the stability of the breakout produced under the gradually increasing stress condition, is less than that produced for the condition of a borehole drilled into a pre-stressed rock.

4 EFFECT OF BOREHOLE BREAKOUT ON THE HYDRAULIC FRACTURING MEASUREMENTS

The interpretation of hydraulic fracturing, one of the most frequently used techniques for

the measurement of in-situ stresses (NRC, 1983), has been developed on the basis of stress distributions around a circular opening, induced by in situ stresses and internal pressure. However, if a borehole breakout occurs, the boundary of the borehole is no longer circular and the stress distributions around it, is different. Therefore, the interpretation of the hydraulic fracturing results based on the Kirsch solution may not be valid. Two questions have to be answered when the hydraulic fracturing is used in a borehole within which breakout has taken place. First, will the presence of breakout affect the stress measurement? Second, if there is an effect on the measurement, how great is it? To answer these two questions, we conducted a theoretical analyses of stress distributions around an elliptical opening in a infinite, linearly elastic body, induced by internal pressure applied on the boundary and the far field stresses. In addition, we have used numerical modeling to analysis hydraulic fracturing in a borehole within which breakout has occurred.

4.1 Stress distribution around an ellipse with internal pressure and far field stresses

When a stable borehole breakout takes place, the diameter parallel to the minimum in situ stress orthogonal to the borehole axis will elongate. This elongation of the axis will reduce the compressive boundary tangential stress induced by the minimum in situ stress at the ends of the short axis. An ellipse should have an effect similar to that of a breakout on the boundary tangential stress at this same point. Hence the study of the stress distribution on the boundary of an ellipse, induced by internal pressure and far field stresses can help to understand the effect of a change in the borehole cross section by a breakout. The tangential stress around an ellipse with longer axis 2a and shorter axis 2b, induced by far field stresses σ_1 and σ_3 parallel and orthogonal to the short axis of the ellips is know (eg. Jaeger and Cook, 1979) and the effect of internal pressure P, can be derived using the superposition principle (figure 5). The minimum tangential stress is:

$$\sigma_{tB} = \sigma_3(\frac{2b}{a} + 1) - \sigma_1 + (1 - \frac{2b}{a})P \quad \text{at the ends of the shorter axis} \qquad (2)$$

when this axis is parallel to the direction of the maximum principal stress.

The term "break down pressure" used in hydraulic fracturing is the fluid pressure required inside the borehole to generate a tensile fracture on a circular wall. In the case of an elliptical opening, however, the internal pressure required to generate a tensile fracture on the elliptical wall is:

$$P_{be} = \sigma_3(\frac{2b}{a} + 1) - \sigma_1 + (1 - \frac{2b}{a})P + T_o \qquad (3)$$

where T_o is the tensile strength of the rock. From equation 3, it is clear that if the difference between the two axes a and b is small, the "break down pressure" in ellipse is not much different from that for a circular borehole. This is because the compressive tangential stress at point B, induced by the far field stress is less than in the case of a circular opening and the tensile tangential stress induced by the internal pressure is also less than that in the case of circular opening. The two effects compensate one another so that the pressure required to open a tensile fracture is not changed much if the difference between the axes is small.

4.2 Numerical modeling results of the effect of borehole breakout on hydraulic fracturing measurements

To simulate a hydraulic fracturing test in a borehole, within which a breakout has taken place, we conducted numerical modeling using boundary elements (Crouch and Starfield,

1982). The test is simulated by taking the breakout cross sections shown in Figure 1 and applying a normal stress on the boundary to simulate the fluid pressure. The rock is assumed to be linear elastic, homogeneous and isotropic. For a given tensile strength T_o, the internal pressure required to create a tensile fracture at location B is calculated. Because the whole system is linear, the required internal pressure can be obtained by extrapolating the result from any two different internal pressures. Table 1 shows the results from this numerical modeling:

Table 1. Comparison of the internal pressure required to open tensile fractures in a circular borehole (P_{bc}) and a borehole with breakout in it (P_{bb}).

Borehole Breakout Shapes	σ_1/σ_3 $(\sigma_1-\sigma_3)/Q$	P_{bc} P_{bb}	Borehole Breakout Shapes	σ_1/σ_3 $(\sigma_1-\sigma_3)/Q$	P_{bc} P_{bb}
	1.50 0.15	37.9 39.0		3.00 0.26	6.9 7.7
	1.50 0.16	40.0 46.2		3.00 0.28	6.9 6.7
	1.50 0.18	30.3 ----		3.00 0.30	6.9 5.9
	2.00 0.21	21.4 21.3		3.00 0.31	6.9 5.3
	2.00 0.22	22.1 20.4		4.00 0.28	0.455 1.304
	2.00 0.23	22.7 19.6		4.00 0.30	0.0 ---
	2.00 0.24	23.4 17.9		4.00 0.31	--- ---
	2.00 0.25	24.1 15.2		4.00 0.32	--- ---
	2.00 0.27	25.5 ----		4.00 0.34	--- ---
	2.00 0.30	27.6 ----		4.00 0.40	--- ---

where P_{bc}, is the commonly referred breakdown pressure if the borehole is circular and P_{bb} is the calculated hydraulic pressure required to create a tensile fracture at the same locations, if the borehole has breakouts. As shown in the table, for small and moderate breakouts, the difference between the regular breakdown pressure, P_{bc}, and that with breakout, P_{bb}, is negligible. For large breakouts, however, tensile fractures have already been generated by the far field stresses. The breakdown pressure cannot be measured but only the shut-in pressure which equals to the minimum principal stress orthogonal to the borehole axis.

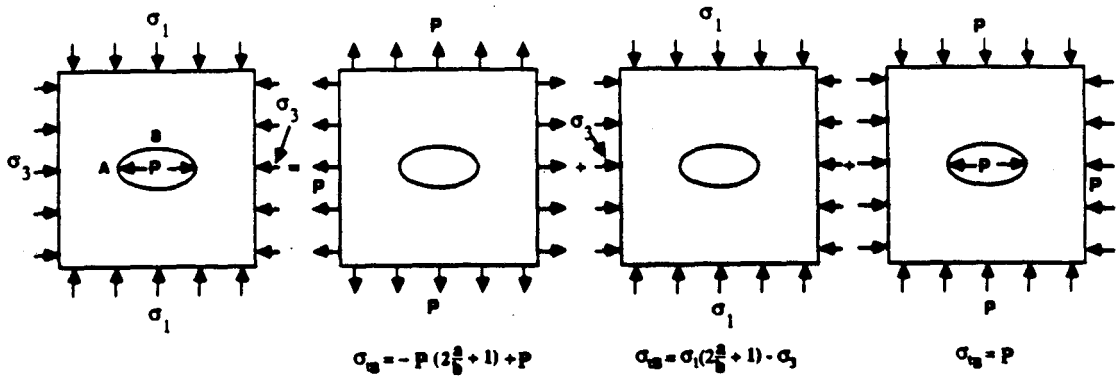

Figure 5. Superposition principle used to obtain the stress distribution around an elliptical opening with both far field stresses and internal pressure.

5 CONCLUSIONS

The numerical results show that borehole breakout cross sections are not uniquely related to the magnitudes of the in situ stresses. The initial breakout angle, which can be obtained from different combinations of stresses and strengths, is the dominant factor that determines the breakout depth. The shapes and the sizes of breakout cross sections are stress history dependent, that is, a breakout will be small if the tangential stress that causes the initial breakout is small because of the strong dependence of the breakout depth on the initial angle.

The effects of breakout on hydraulic fracturing are: For large borehole breakouts where tensile fractures have already been generated at the locations of hydraulic fractures, only the minimum stress orthogonal to borehole axis can be measured. For moderate and small breakouts where no tensile fractures are generated, however, the effect of breakout on hydraulic fracturing measurements is not significant. In practice, it would be difficult to set packers for hydraulic fracturing in holes with extensive breakouts.

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