Chapter 84

FAILURE MODES OF DEEP BOREHOLES

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Abstract

During drilling of deep boreholes, local mechanical failures of the wellbore walls may occur due to the inability of the incompetent overburden and reservoir rocks to withstand drilling-induced changes of the stress environment. At present, borehole failure mechanisms in three-dimensional stress fields are poorly understood. Our experimental investigations based on 3-D physical models demonstrate the stabilizing effect of the intermediate principal stress. The latter may play a dominant role in maintaining the integrity of the stress relieving failure zone around the borehole. However, this will depend on the stress anisotropy, the angle of hole deviation and on the angle of internal friction. Our tests also indicate that the failure zone can accomodate high extensional strains. Finally, relations between the physical models and closed-form elasto-plastic solutions are discussed.

Introduction

From the earliest days of exploration and production, petroleum engineers have been confronted with the difficult task of maintaining the stability of deep boreholes. Even today, the consequences of wellbore instability, ranging from increased drilling time to stuck pipe and sidetracking, contintue to cause a major yearly expenditure.

In general, the factors which affect the mechanical performance of an unsupported hole are:

(a) the in-situ stress components (including vertical stress and pore pressure)
(b) the angle of hole deviation
(c) the hole orientation (if $\sigma_V \neq \sigma_H \neq \sigma_h$)
(d) the rock strength and deformation characteristics, includng effects of anisotropy and fissuring.

Excess mud pressure acting across the mud cake assists in maintaining the stability of a hole, but this must be carefully designed to avoid tensile failure of the hole, mud loss and possible hole collapse.

Analytical studies of the stress state around boreholes are based on closed-form solutions derived from elastic theory (i.e., Miles and Topping, 1949, Hubbert and Willis, 1957, Fairhurst, 1964) or elastic/plastic theory (e.g. Westergaard, 1940, Gnirk 1972, Risnes et al. 1982). Various rock strength criteria have been applied in these studies, ranging from the linear Coulomb s yield criteria to poroelasticity equations (Geertsma, 1966, Cheatham, 1984). Limit equilibrium techniques have also been suggested for prediction of incipient yielding of the wellbore wall by utilizing the stress invariants (Bradley, 1979). Finally, stress analyses based on non-linear models of behaviour and finite element mdoelling have been reported by Desai and Reese (1970), Morita and Grey (1980) and others.

Greater production depths, exploitation of marginal reserves, horizontal drilling for production from thin oil zones, and increased use of strongly deviated wells from expensive deep sea gravity platforms has tended to refocus attention on borehole stability. Our understanding of wellbore stability appears to be limited, at least that appearing in the open literature.

Surprisingly, there seems to exist very little experimental work, to complement and validate the findings of the seemingly elegant and exact analytical and numerical techniques.

Gall and Wilhoit (1962) made a three-dimensional photoelastic study of the stress state around the wall and bottom of a wellbore, and obtained some data comparable with the analytical predictions for an elastic medium. A study of the possible forms of wellbore instability was reported by Darley (1969) on samples of reconstituted shale. Haimson and Edl (1972) examined experimentally the potential correlation between breakout orientation and principal stress direction and some further interesting results on this topic were recently produced by Haimson and Herrick (1985).

Forms of borehole instability

As a vertical borehole is drilled, the radial, horizontal stresses are relieved and the load is transferred around the circumference as a hoop stress. The radial component decreases from the far-field horizontal stress level and becomes equal to the pressure drop across the mud cake, or to zero, if there is no fluid overpressure. Wellbore failure results from the mechanical incapacity of the wall material to sustain the loss of radial support and the redistributed stresses. Excessive rock straining may lead to plastic flow or fracturing depending on the ductility of the material.

It is important that the extraordinarily high "stress to strength" ratios prevailing at the depths of current interest (3-5 km) are physically appreciated. The realistic ranges given in Table 1, indicate that the theoretical compressive (tangential) stresses at points of maximum concentration can be 2-10 times higher than σ_c, the uniaxial compressive strength.

Wellbore instability can be experienced both during drilling and production. During drilling, hole size reduction may be caused by plastic flow of an everstressed shale or salt. A repeated need to ream the hole, and in the worst case stuck pipe may result from this squeezing. In other types of rock, such as microfissured shale or sloughing sandstone progressive failure of the borehole walls can result in hole enlargement, poor directional control and difficulties when cementing (Cheatham, 1984).

TABLE 1. Approximate range of effective stresses and rock strength encountered in typical oil-well drilling (P_r = reservoir pressure)

STRESSES (MPa)			
	Far - field		
Depth	Initial	After 10 - 30 years	At boundary of hole
3-5 km	$\sigma_v' \approx$ 10-15 $\sigma_h' \approx$ 5-10 $\sigma_H' \approx$? $P_r \approx$ 30-40	$\sigma_v' \approx$ 30-35 $\sigma_h' \approx$ 20-25 $\sigma_H' \approx$? $P_r \approx$ 10-20	Theoretical Concentration factor 1,5-3,0 (uncertainties in 3-D stress field)

ROCK STRENGTH				
Rock types	Uniaxial compr.str. σ_c (MPa)	Young-s Modulus E (GPa)	Internal friction ϕ	Cohesion c (MPa)
Sandstones	0,5-30,0	0,2-10,0	25°-40°	0,0-5,0
Shales	1,0- 5,0	0,1- 3,5	5°-15°	0,0-1,0
Clays	0,5- 8,0	0,3- 3,0	2°-10°	0,0-3,0
Chalk	2,0-35,0	1,0-4,0	10°-20°	0,5-8,0

The above problems are confronted by approximate balancing of the weight of the mud column, which produces the radial support needed to maintain the hole open. (The chemical interaction between the wellbore fluid and the walls will not be considered here). However, the maximum mud weight will often be severely limited by hydraulic fracturing problems. Tensile splitting of the borehole wall can occur if the minimum stress is too low, if the ratio of maximum to minimum stress is too high, if the tensile strength is too low or if the pore pressure is too high. Severe mud losses to the formation can result in worse stability problems than the mud was supposed to correct, and in kicks or underground blow-outs.

Each of the above problems can occur both in vertical boreholes and in deviated boreholes. However, Bradley (1979) notes that in normally stressed regions ($\sigma_v > \sigma_h = \sigma_h$), deviated boreholes may fracture at lower wellbore pressure than the fracture pressure in vertical wells. Increasing the borehole angle from 0° to 60° may reduce the allowable mud weight by up to 3 lb/gal (0,36 Mg/m^3).

During production a different range of borehole stability problems can be encountered. In loosely cemented sandstones and weak overstressed chalk, produced fines nucleate from the perforations. This problem may be accentuated, if hydraulic fracturing (with or without acid) is used to stimulate the formation behind the perforations, due to cavity-fracture interaction in the zone of high fluid pressure gradients.

The local fluid pressure drawdown in the producing zone may be a critical factor in weak overstressed rock, due to the related increases in effective stresses. Fluid inflow related body forces may also be significant. In the long run, the reduction in the reservoir pressure may be compounded by vertical compaction of the formation, which may cause buckling and collapse of the casing.

The resistance to axial buckling would be reduced if the casing had suffered elliptical deformation under anisotropic horizontal effective stresses, and if these were increased in magnitude by local drawdowns.

Promoted by the interest of the oil industry, an extensive experimental and numerical investigation of hole stability during drilling and production is planned at the Norwegian Geotechnical Institute. This paper presents some preliminary findings of interest.

Research objectives and approach

The prime objective is a thorough investigation of the mechanical interaction phenomena that control borehole instability: (a) while drilling (stability of vertical, horizontal and deviated holes under compressive and tensile loading), and

(b) during production (fines production in holes $0^o < \beta < 90^o$, hydraulic fracturing through perforations, interaction of fines and fractures).

The approach entails three-dimensional physical model testing in parallel with numerical simulation techniques.

Numerical analyses

Predictions from closed-form elasto-plastic solutions have been examined and compared with the physical model test results (Bandis and Nadim, 1985). The solutions are based on a two-dimensional plane strain idealization of the problem and were obtained by solving the equation of equilibrium in the radial direction and satisfying the linear Coulomb's criterion in the plastic zone. Examples of the predicted stress state and width of plastic zones are illustrated i Fig. 1. No fluid flow towards or out of the borehole is being simulated.

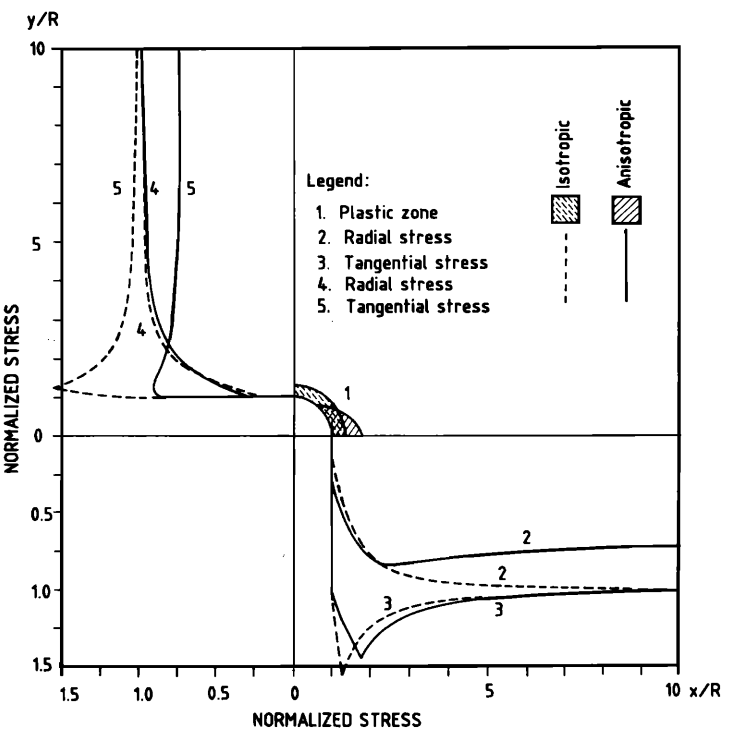

Figure 1. Typical examples of closed-form elasto-plastic analyses of borehole stability.

The uppper diagram illustrates the case of an isotropically loaded borehole with a relatively low internal pressure. The narrow symmetrical plastic zone is shown shaded. The lower diagram illustrates the case of a deviated hole in an anisotropic stress field. Note that the plastic zone is now relatively wide despite a higher internal pressure.

Three-dimensional physical model tests

(a) Experimental facility

A polyaxial test rig has been developed at NGI, which can accomodate prismatic blocks of up to 30x30x40 cm (Fig. 2). Pressure is applied in three dimensions by six flat jacks, each pair of which is independently steered by a hydraulic system. A hand-operated drilling device is used to drill horizontally or at an angle. The pressure in the flatjaks is monitored by transducers and all precautions are taken to minimize boundary friction. Internal borehole pressures simulating a balanced mud pressure, are provided by a reinforced rubber membrane that can expand radially but not longitudinally. So far, failure sensing has been visual or by monitoring changes in the internal borehole pressure. We are currently planning to instrument the blocks by miniature pressure cells. Seismic monitoring using tomographic analysis will also be used in the future by utilizing piezoelectric transducers. Seismic velocity, amplitude damping and frequency will each be analyzed as potential indicators of "plastic" zones, shear fracturing etc.

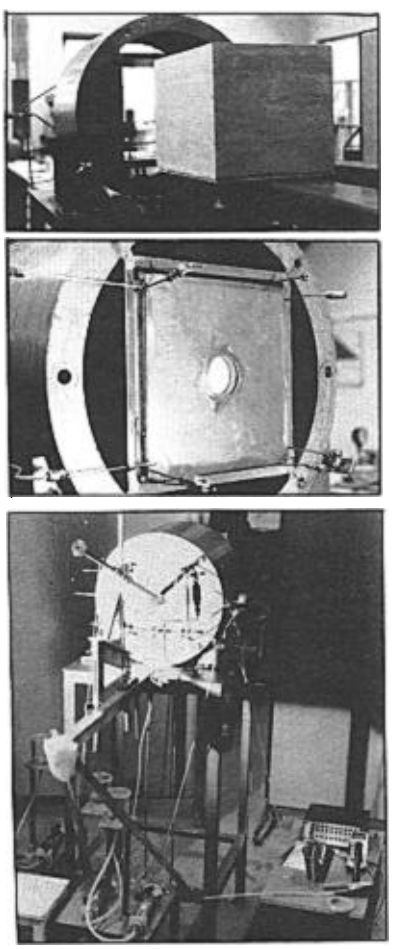

Figure 2. Views of the polyaxial loading facility for testing deep borehole models.

(b) Model materials

A suite of multicomponent rock-like materials has been developed. By varying the relative proportions of the dry and wet constituents of the gypsum-cemented, sand-based frictional/dense filler mixtures, and by selecting appropriate

curing temperatures, the mechancial properties of a range of prototype rocks has been simulated (i.e. weak sandstones, shales, chalk, marlstones, etc.). Figure 3 contains typical triaxial test results for a simulated shale.

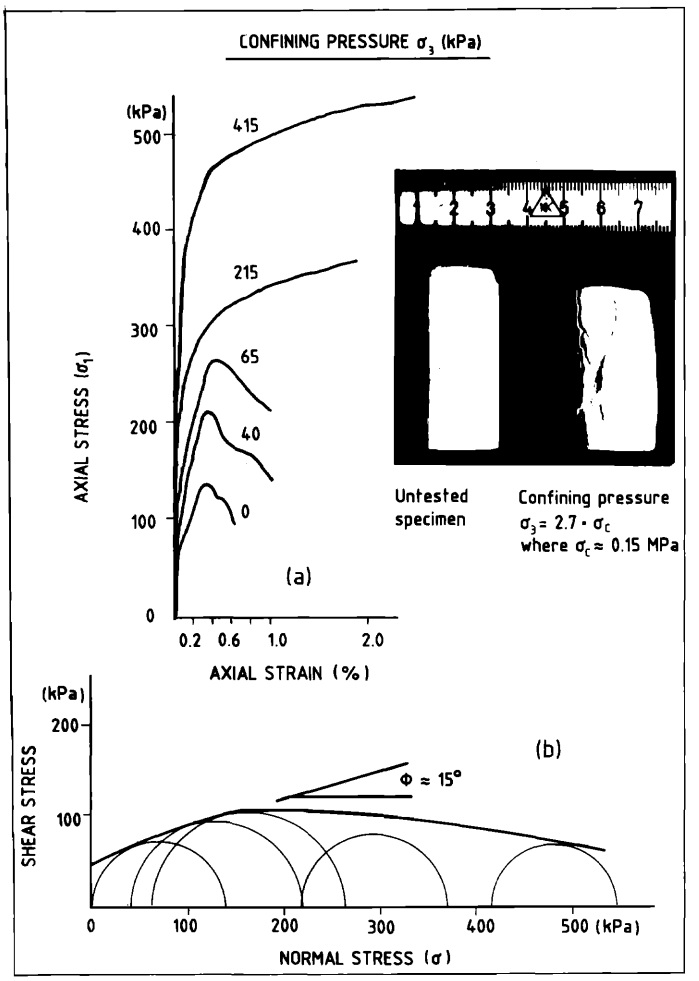

Figure 3. Triaxial test data for model material simulating shale.

A series of model experiments were conducted to investigate the influence of the following factors upon the mode of borehole failure:

(a) stress field
(b) rock type
(c) angle of hole deviation
(d) internal pressure

(c) Test procedure and results

Commencement of drilling was preceeded by a phase of block consolidation, until the boundary pressures were stabilized. A variety of stress fields were simulated, by adopting the classical stress scaling relationship.

$$\xi = \lambda \quad (\rho_p/\rho_m)$$

where ξ = stress scale factor (σ_p/σ_m)
λ = geometric scale factor (L_p/L_m)
ρ_p = density of prototype rock
ρ_m = density of model material

The test arrangement adopted at NGI overcomes the usual limitation of loading a prefabricated hole. However, the practical inability to simulate drilling under internal pressure still remains.

In general, the drilling was conducted in steps, thus enabling us to examine the performance of the hole with various stress combinations. If no collapse had occurred at the end of drilling, the hole was loaded to failure. A summary of the experimental results is presented in Table 2.

TABLE 2. Summary of results from model borehole experiments.

PROTOTYPE ROCK					STRESS RATIOS AT FAILURE								
Test No.	σ_c (MPa)	E_t (GPa)	ϕ	c (MPa)	$\frac{\sigma_v}{\sigma_H}$	$\frac{\sigma_v}{\sigma_h}$	$\frac{\sigma_H}{\sigma_h}$	$\frac{\sigma_v}{\sigma_c}$	$\frac{\sigma_H}{\sigma_c}$	$\frac{\sigma_h}{\sigma_c}$	$\frac{\sigma_v}{P_i}$	$\frac{\sigma_h}{P_i}$	$\frac{P_i}{\sigma_c}$
Vertical borehole (0°) - No internal pressure													
1	0,3	0,12	28°	0,2	1,5		1,0	6,5	4,3		-	-	-
Horizontal borehole (90°) - No internal pressure													
2	2,0	0,35	20°	0,3	5,3		1,0	1,3	0,25		-	-	-
3	0,3	0,12	28°	0,2	-	2,0	0	2,0	0	1,0	-	-	-
Deviated borehole (70°) - No internal pressure													
4	0,4	0,15	28°	0,3	1,6	2,4	1,5	8,0	5,0	3,3	-	-	-
Deviated borehole (70°) - With internal pressure													
5	1,5	0,40	15°	0,5	1.75		1,0	9,2	5,1		5,5	3,0	1,7

σ_c = uniaxial compressive strength
E_t = Young s Modulus
ϕ = angle of internal friction
c = cohesion
σ_v = effective overburden stress
σ_h = min. horizontal effective stress
σ_H = max. horizontal effective stress
P_i = borehole internal overpressure

Discussion of the results

It is apparent that, under the simulated 3-D stress fields, the borehole walls were able to sustain stresses exceeding by several times the unconfined strength (σ_c) of the material. Stress/strength ratios at failure of up to 3-5 are seen in the literature in plane strain model experiments, if an elastic stress distribution is assumed (e.g. Worotnicki et al., 1976, Kaiser et al., 1985, Haimson and Herrick, 1985). In our case, calculation of the stress peaks according to the Kirsch solution would give tangential stresses 5-10 times greater than σ_c at the hole boundary (Bandis, 1985).

However, at the stress/strength ratios pertinent to our studies, an elasto-plastic approach is more relevant (Bandis and Nadim, 1985). The plot in Figure 4 illustrates the effect of stress anisotropy on the calculated σ_θ/σ_c ratio at failure (σ_θ is the tangential stress). The nor-

malized maximum field stresses are also included for each case. It is shown that at the instant of hole collapse, σ_θ/σ_c could have ranged between 1,0 - 3,0 for the assumed stress distribution.

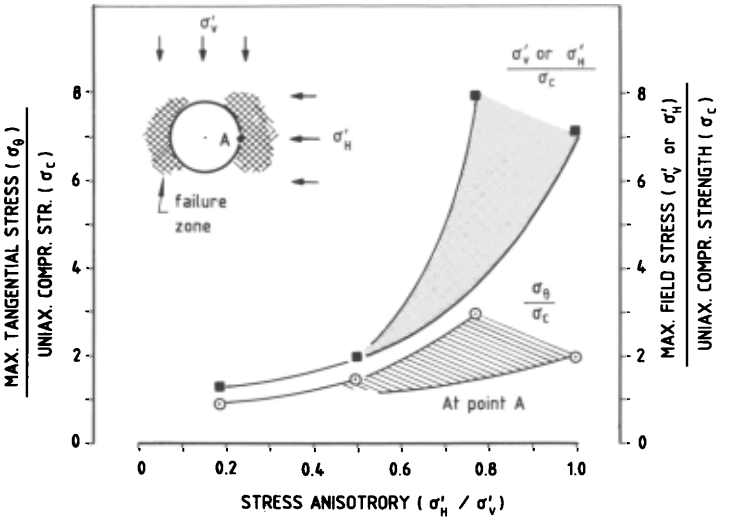

Figure 4. Effect of stress anisotropy on borehole wall stability assuming elasto-plastic stress distribution. The experimental field stress/strength ratios at failure are included for comparison.

Formation and role of the failure zone

Typical examples of the types of failure zones observed in the present experiments are illustrated in Figure 5. Certain differences and similarities can readily be distinguished:

- Low internal friction and stress anisotropy promote significant growth of failure zone (Fig. 5e). The same applies when σ_2 is absent (Fig. 5b). When ϕ is high the failure zones is of limited extent and failure is more brittle (Fig. 5d).

- Competent rocks may fail along well delineated shear fracture planes (e.g. Fig. 5a).

- Under anistropic stress fields the failure planes display the expected geometric relation with the principal stresses. Consequently, borehole breakouts may be a reliable means of identifying the direction of minimum principal field stresses. Absence of deviatonic stresses appears to favour random propagation of the failure zone (Fig. 5c).

Figure 6 illustrates the approximate stress-strain relationship of a borehole loaded to failure under constant internal pressure (P_i). It is seen that stages of yielding and plastic straining are identified prior to collapse. Plastic straining may begin prior to visible crack development along the wall of the hole. By implication, early activation of the stress relief mechanism will enable the borehole to sustain significant compression straining prior to collapse.

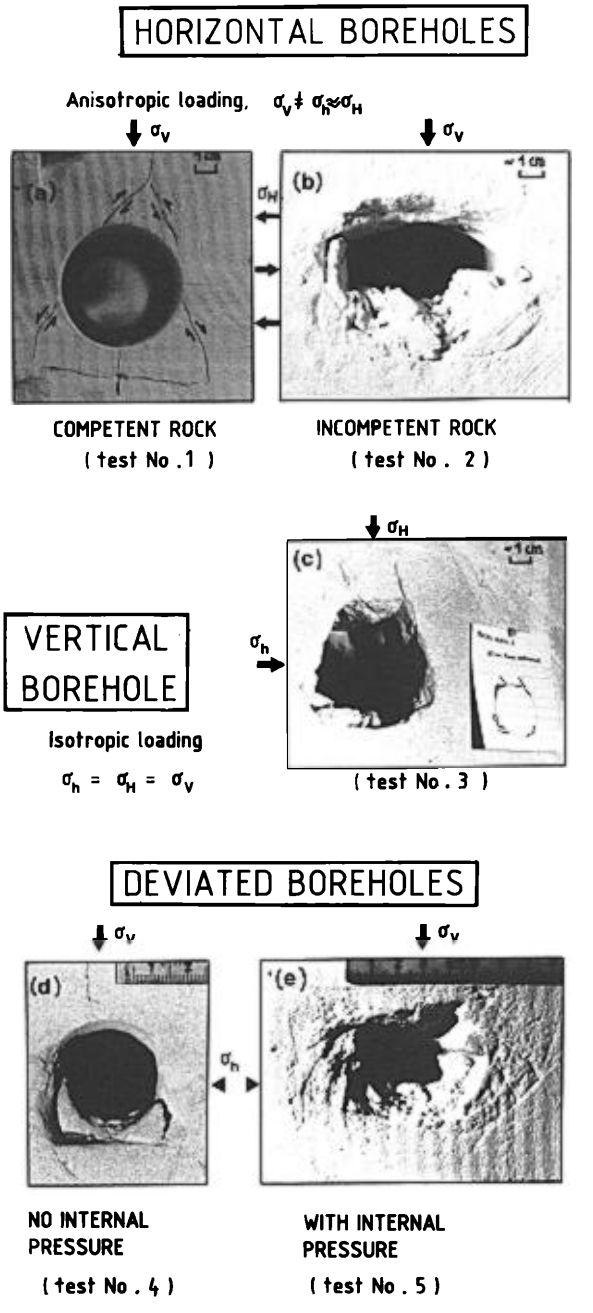

Figure 5. Illustrations of failure modes of deep boreholes in different rock simulants under various stress conditions.

Implications for wellbore drilling design

At present, both reasoning and experiment favour a concept of "failure zone growth". Intuitively, hole collapse would be kinematically initiated, when the zone extended beyond the size required for loss of matrix continuity.

Preliminary comparisons of our elasto-plastic solution with the physical models indicate that,

as long as the predicted normalized radius of the plastic zone is less than 2, the hole may be considered stable. When the normalized radii exceeded 4, complete collapse would occur. Intuitively, values between 2 and 4 would be indicators of potential instability.

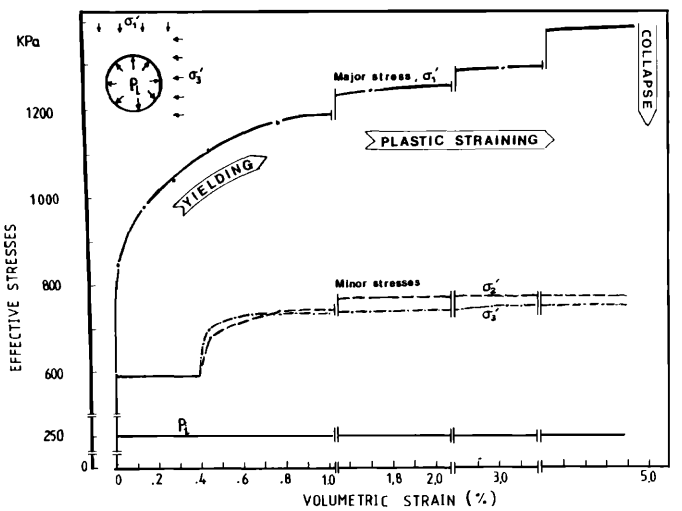

Figure 6. Approximate stress-strain relation for an inclined model borehole loaded to failure under constant internal pressure P_i.

An example of application of the above concepts in the design of drilling operations is given by the tentative stability charts in Fig. 7.

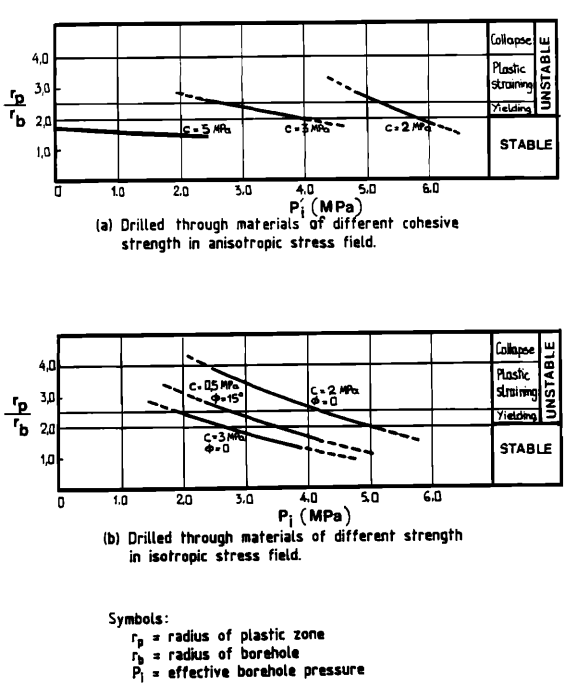

Figure 7. Stability charts for an inclined borehole (70°) $\sigma_H/\sigma_V \approx 0{,}60-1{,}00$
$\sigma_V/\sigma_C \approx 7{,}0$
$\sigma_H/\sigma_C \approx 4{,}0$

A potentially useful result is the apparently high resistance of a borehole to extension splitting, for the rock types considered. In one of our tests, the borehole pressure (P_i) was raised to almost double the overburden pressure without tensile fracturing. In this case, σ_h/σ_v was ~ 0,6. The multiple shear fracture in the failure zone presumeably dissipated the stresses by shear reversals, whereas part of the radial pressure was probably taken up uniformly by the strain-hardened circumferential zone. It should be noted that unsuccessful minifrac stress measurements occur sometimes in practice due to the inability to breakdown the formation when compressible shale formations are involved.

The lack of fluid penetration in our present tests should however be noted. The possibility of local reduction in effective stress through fluid penetration in initial cracks is absent in these membrane simulations of mud pressure acting through an assumed impermeable mud cake.

Conclusions

1. Polyaxially loaded physical model boreholes drilled in simulated weak, deformable rocks demonstrate improved mechancial stability, compared to that predicted by 2-D conceptual models.

2. The progressive formation and extension of a failure zone around the hole may be a key factor in the mechanical performance. The failure zone may take the form of a few well-defined shear fractures, or that of multiple shear-planes resembling a logarithmic spiral, depending on the stress anisotropy and the matrix strength.

3. The failure zone may dissipate high stresses away from the hole circumference both during compressive and tensile loading. The extent of the zone seems to depend on the frictional properties of the matrix. Complete collapse of the hole occurs when the failure zone reaches a size such that matrix continuity cannot be preserved.

4. The principal stress parallel to the hole axis has a stabilizing effect due to the lateral support it provides to the failure zone, and due to the biaxial state of stress created at the hole boundary. The latter may explain the apparent ability of the borehole walls to support compressive stresses considerably higher than σ_c.

5. Preliminary comparisons between experiments and numerical solutions appear promising. Better understanding of the failure mechanisms and stress redistributions will allow improvement of analytical solutions and choice or development of appropriate criteria for the matrix strength.

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