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Laboratory Studies on the Stability of Vertical and Deviated Boreholes

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ABSTRACT

Polyaxial or true triaxial tests have been performed on weak and strong sandstones in order to investigate the stability of model boreholes. Both vertical and deviated boreholes in anisotropic stress systems have been studied. The results indicate the decrease in stability of the deviated boreholes with increasing inclination. Boreholes oriented parallel to the maximum horizontal stress direction also produces less stable boreholes compared to those drilled parallel to the minimum horizontal stress. Comparisons of the laboratory test results with simple predictions using linear elasticity, and a Mohr Coulomb failure criterion, show that the boreholes in the strong sandstones are approximately 4 times stronger than predicted; while the weak sandstones are approximately 8 times stronger than predicted.

1.0 INTRODUCTION

Increasing use of highly deviated, extended reach and horizontal drilling, has focussed attention on many aspects of drilling, not least on the ability of highly deviated holes to remain open. Associated with this issue, is the potential for hole cleaning problems or the drill packing off, both of which are aggravated by excessive spalling of the wellbore wall. The challenge of minimising such problems, has resulted in the need for more analytical tools, with which to plan the drilling of the boreholes, and assess their feasibility.

References and illustrations at end of paper

The analytical and numerical prediction of borehole stability predominantly considers the stresses developed in a plane perpendicular to the borehole axis, and the comparison of these stresses with the strength of the surrounding material. The comparison of such analyses with laboratory tests, shows an under estimation of the strength of the boreholes by factors of two to four times for competent rocks (Guenot and Santarelli [1]). These conservative predictions are generally attributed to the use of linear elasticity in the analyses and models. Analytical solutions and numerical models incorporating pressure dependent elastic moduli and elasto-plasticity show less conservatism associated with their predictions of mud weights required to ensure wellbore stability.

The validation, and the assessment of the accuracy of numerical models and analytical solutions, is of prime importance if these techniques are to be used as predictive tools. Validation of the predictions of these tools would most satisfactorily be performed by comparison with the behaviour and response of drilling a monitored borehole. However, such field validations would not only be expensive, but possibly inconclusive due to difficulties in accurately determining the three in-situ stresses and the in-situ strength and behaviour of the rock, Fleming et al. [2]. These latter parameters are of fundamental importance in the input to current analytical and numerical methods. These limitations restrict our present day validation of predictive tools to comparisons with laboratory test results.

2.0 BACKGROUND TO WELLBORE STABILITY TESTS

Validation of wellbore stability models requires the comparison of theoretical models with experimental simulations of wellbore behaviour. Laboratory simulations are necessary in order to eliminate the uncertainties in material behaviour and boundary conditions, which occur with field comparisons. Hollow cylinder testing (Santarelli and Brown [3], Fjaer et al. [4]) is commonly used as a method of simulating wellbore stability. However, such tests are restricted to reproducing simple stress systems, and are not appropriate for the study of deviated wellbores. Therefore, in this study true triaxial, or polyaxial tests are used.

2.1 Mechanical Behaviour of the Rocks

Two types of rock were tested in this study. One was an artificial weak rock, and the second a more competent natural rock, Gres des Vosges sandstone. Both were sandstones, as most predictive tools can only model isotropic materials, such as sandstones; the choice of a permeable material also avoided induced pore pressures during loading. Anisotropic or transversely isotropic materials such as shales are therefore not represented in these tests.

The weak sandstone was prepared using a mixture of cement and uniformly graded sand, which was compacted in layers into a mold to obtain an optimum and uniform density throughout the manufactured block. Raining of the mixture was not used, as initial tests showed differential compaction resulting in considerable density variations through the block occurred with this method. The blocks were submerged in water for 14 days to enable the cement to form bonds between the sand grains. The procedures were carefully repeated to ensure reproducibility of the blocks.

Standard triaxial classification tests were performed on the two sandstones, ensuring representative mechanical data was available as input in to numerical codes. The stress-strain data, the variation in modulus with minimum principal stress and the failure envelopes for the sandstones are shown in Figures 1-3. More detailed information concerning the mechanical and physical properties of the sandstones is given in Table 1.

The peak strength envelope for the strong sandstone, is curved, as such the linear assumption for the failure envelope over estimates the unconfined strength of the material. The peak strength friction angles and cohesion quoted for the sandstone are valid for effective confining stresses above 0.5 MPa. The peak strength for the unconfined sample is underestimated by approximately 10% by the yield criteria given in Table 1.

Considering only the unconfined sample and the sample at 0.5 MPa confinement, the appropriate peak strength criteria is

$$\tau = 1.0 + \sigma_n \tan(75.3)$$

2.2 Polyaxial Test Equipment

The in-situ stress field consists of three mutually perpendicular independent stresses. This is reproduced in the laboratory by applying three independent stresses to opposing faces of a cubic sample. This enables any ratio of stresses to be modelled, so long as the failure condition for the sandstone is not violated. Two polyaxial rigs were used during this study, a piston based system at the University of Lille for the strong sandstone, and a flatjack system applying the stresses to the weak sandstones which were tested at NGI in Oslo. The capacity of the low pressure rig is 30 MPa (4,350 psi) and the rig used to test the strong sandstone has a maximum capacity of 70 MPa (10,152 psi). Both of these values relate to loads applied to cubic samples of 0.125 m^3. It was suspected that the stress capacity of the high pressure rig was insufficient to induce failure in the wellbores of the strong sandstone, as such the block size was reduced to 0.064 m^3. In both series of borehole tests, the model boreholes were 5.08 cm (2") in diameter. Friction between the sandstone blocks and the loading plates will induce shear stresses which are transfered to the blocks. In order to minimise this low friction interfaces were used.

The onset of wellbore instability, was evaluated by using calipers measuring the change in diameter of the borehole wall with the buildup of externally applied stress. Also, implanted sensors and acoustic emission devices were used as backup systems with which to detect the onset of failure in the wellbores, for the weak and strong sandstone samples, respectively.

2.3 Polyaxial Test Procedure

The whole purpose of these tests, was to determine what magnitude of externally applied stress would be required in order to cause yielding at the borehole wall.

The boreholes were formed under two different conditions, in the weak sandstone tests, a small stress was applied to the block samples inside the polyaxial cell, whereupon the boreholes were drilled. In the strong sandstone tests, holes were pre-drilled under atmospheric conditions before inserting the drilled block into the polyaxial test rig. The test procedure simply consisted of gradually increasing the magnitude of the three stresses exerted on the faces of the block in pre-determined ratios, until borehole failure had been

attained. In the weak sandstone tests, the external stresses were increased incrementally, whilst a ramped increase was used for the strong sandstone samples. In the tests, the pore pressure in the blocks was kept at atmospheric pressure.

3.0 METHODOLOGY OF THE BOREHOLE STABILITY TESTS

The objective of this study was to investigate the influence of, stress anisotropy, well deviation (inclination) and the orientation of deviated wells, on the stabilities of the boreholes. Of particular interest, was the determination of the role of the intermediate principal stress on borehole stability. Secondary aspects include the comparison of strong sandstones with weaker analogues.

3.1 Test Programme

In order to investigate the factors outlined above, two series of tests were performed. The first, performed on the weak sandstone, investigated the behaviour of the deviated wellbores. The second series, performed on the strong sandstone, concentrated on the influence of stress anisotopy. Two tests were replicated on both sandstones, allowing not only a comparison of the results to a 'standard' test, but also enabling a comparison of the effect of the material properties on the relative borehole stabilities.

The details of the test programme are shown in Table 2. The tests performed on the weak sandstones are refered to as Series 2 and on the strong sandstone, Series 3.

The deviation of the model boreholes refers to the inclination of the borehole with respect to the maximum stress, σ_v, which is considered to be equivalent to the vertical overburden stress in-situ. The orientation is given in terms of azimuth of the deviated hole relative to the maximum horizontal stress, σ_H.

4.0 BOREHOLE STABILITY TEST RESULTS

The failure stresses recorded for the block tests were deduced from the borehole radial displacement measurements. Failure in the context of this paper is described by the abrupt change in slope of the radial displacement vs external stress curve. This point is equivalent to the tangential stress at the borehole wall reaching the peak strength of the material. The wellbore was observed in order to evaluate the onset of fracture of the borehole walls.

In the initial tests on the weak sandstone blocks, the signals from the borehole diameter caliper were erratic and unreliable. This was later seen as a result of the 'bedding in' of the borehole caliper arms into the borehole wall. In these earlier tests (Blocks 2.1 - 2.4), the response of implanted sensors are used to determine the failure point of the boreholes.

The external boundary stresses applied to the blocks at the instances of borehole failure are detailed in Table 3.

4.1 Effect of Stress Anisotropy

The effect of the ratio of vertical to horizontal stress on the stability of the model borehole can be seen by comparing two sets of vertical boreholes, in tests 2.1 and 2.2 for the weak sandstone, and 3.1 and 3.2 for the strong sandstone.

Both sandstones show that the stress acting parallel to the wellbore has little if any influence on the stability of the well. This stress is normally considered to be the intermediate principal stress. For the strong sandstone, an increase of 7.5% in the strength of the wellbore is observed. It is rather difficult to translate this in to field terms because of the difference in the depth represented by the two different vertical stresses. This 7.5% value assumes no variation in strength between the blocks.

The boundary stresses at failure for the weak sandstone test with a $\sigma_H/\sigma_v = 0.6$ appears to be lower than those for failure in the isotropic block. A range for the boundary stresses at failure is quoted due to experimental difficulties described earlier. However, the significant fact is the apparent lack of any increase in strength of the borehole in the presence of the larger axial stress.

4.2 Effect of Wellbore Deviation

Well deviation will be an influential factor on the stability of the well, in areas where the vertical and horizontal stresses are unequal. Block tests 2.2 to 2.4 were used to study this effect. The wells were drilled vertically, and at 30° and 60° deviation. The boundary stresses at which failure was deduced, decrease with increasing deviation, as a result of the increasing influence of the vertical stress.

The failure stresses recorded in Table 3 for these block tests, are consistently higher than the linear elastic predictions. Linear elasticity predicts horizontal boundary stresses of 0.25, 0.18 and 0.13 MPa for the maximum tangential stress at the wellbore wall to equal the unconfined compressive strength of the sandstone. A comparison of the horizontal stress level required to fail the sandstone block with the predicted boundary stresses are shown in Figure 4.

4.3 Effect of Wellbore Orientation

The stability of deviated wells has been shown above to be dependent on the inclination. This is due to the anisotropic stresses acting in the plane perpendicular to the borehole axis. In the field where three independent stresses exist at depth, the transformed stresses influencing wellbore failure will be a function of the orientation of the wellbore, with respect to the in-situ horizontal stresses. As such, borehole stability should in theory be a function of orientation in a true triaxial stress field, where $\sigma_v \neq \sigma_H \neq \sigma_h$.

Tests 2.5 to 2.7 were performed to evaluate this aspect of borehole stability. The boreholes in these tests were drilled at an angle of 45°, and the 'far field' stress anisotropy applied to the blocks were maintained in a ratio of 1, 0.8 and 0.4. The orientation of the wells are referenced relative to the maximum horizontal stress direction, and shown in Table 2.

Table 3 shows that the least stable borehole was that drilled parallel to the maximum horizontal stress direction, the stronger well being the one bisecting the maximum and minimum horizontal stress directions. The well which was drilled parallel to the minimum horizontal stress direction was significantly stronger than the well drilled parallel to the maximum horizontal stress direction. The former more stable well, required boundary stresses 7.4% higher than those to induce failure in the well drilled parallel to σ_H.

The comparison of the maximum horizontal stress applied to the blocks at failure and those stresses which would be required to predict failure, if a simple linear elastic model and a Mohr Coulomb failure criterion was used, are shown in Figure 4. Again the difference between the block test results and the predictions are consistently at odds.

4.4 Effect of Horizontal Stress Anisotropy

The influence of anisotropic horizontal stresses on the stability of vertical wells was studied on the strong sandstone. The boundary stress data at the point of wellbore failure (Table 3) are not conclusive as the borehole with the most anisotropic stresses, appears to have a similar maximum horizontal stress to the two tests with isotropic horizontal stresses. However, Test 3.3 did show a considerable decrease in the magnitude of stresses at failure, with σ_h/σ_H of 0.85.

4.5 Failure Mode

The existence of spalling or wellbore cracking in wellbore walls, will be the determining factor for hole problems. The failure zones developed around the boreholes tested in this study were maintained intact in order to examine whether extensional or 'traditional' spalling occurred, as observed by Ewy et al. [5], or whether shearing was the mechanism of instability in the two sandstones tested.

Previous model borehole tests conducted under isotropic stress fields have resulted in non-uniform failure zones around the boreholes. This observation has been attributed to material anisotropy in terms of modulus and/or strength variation, as well as a stress concentration effect on the opposite diameter to which the wellbore failure initiates. In the weak sandstones tested in this study uniform failure zones were observed while in the strong sandstones a more complex failure was observed but generally would be thought to be relatively uniform, as the failure zone was not restricted to one diameter of the borehole. In the weak sandstone shearing was the mechanism of failure zone growth. This is seen in the failure zone developed in Test 2.6 where earlier shear bands are seen to be displaced by later features, Figure 5. The growth mechanism of the failure zones developed around the boreholes in the strong sandstone was indeterminate.

5.0 DISCUSSION

The tests described in the last sections have been designed to enable validations and quantification of numerical codes. The advantages of laboratory tests being the relatively well defined strength and material properties of the materials studied, as well as the known boundary stresses applied to the blocks. The tests were not designed to enable direct comparisons for field behaviour. Such tests would preferably maintain the boundary stresses constant and decrease the wellbore pressures.

Failure of the wellbores in the block tests refers to the stress at which an abrupt change in slope of external stress vs radial displacement is observed, and represents the point at which the material at the wall of the borehole reaches the peak strength. Wellbore cracking in the weak sandstone tests was seen to occur at boundary stresses up to 30% higher than those equated with the failure point. Similar observations have been made by Santarelli and Brown [3] for natural sandstones. This increase may be material dependent, and a function of the strain required for the material to move from peak strength to residual.

A comparison of the weak and strong sandstones can be performed by comparing the calculated tangential stress based on linear elasticity at wellbore failure, relative to the unconfined compressive strength of the sandstones measured in standard triaxial tests; such values are shown in Table 4. Two cases are presented, for the isotropic and anisotropic ($\sigma_H=\sigma_h=0.6x\sigma_v$) stress tests. In

In both cases the ratios are approximately the same, again showing the limited influence of the axial stress on the strength of the boreholes. Guenot and Santarelli [1] quote ratios generally up to 4 for different materials tested and modelled by previous workers. The ratios for the strong sandstone are similar to those quoted by Guenot and Santarelli [1], while the weak sandstone is twice the 'normal' range. This higher ratio is probably due to the strong dependence of the modulus on the confining pressure, Figure 2a, and the relative shear stresses at which the yield and peak strength occur, i.e the increase in strength in the post-yield to pre-peak work hardening region. The accurate modelling and comparison of the results presented here are beyond the scope of this paper.

The size of the borehole also appears to have an influence on the stress at failure, Herrick and Haimson [6]. However, no concensus has yet been reached concerning this aspect.

6.0 CONCLUSIONS

The conclusions obtained from this limited series of tests are as follows;

1. The axial stress appears to have little if any influence on the strength of boreholes.

2. The stability of deviated wells decreases with increasing deviation, when the horizontal stresses are smaller than the vertical stress.

3. Where three unequal stresses exist, wells drilled parallel to the minimum horizontal stress will be more stable than those drilled parallel the maximum horizontal stress.

4. The vertical boreholes in the weak and strong sandstones are 8 and 4 times stronger than linear elasticity would predict.

5. The strength of the inclined wells is approximately 9 times the linear elastic predictions.

NOMENCLATURE

(Compression assumed positive throughout)

q	Deviatoric stress (σ_1-σ_3)
σ_v	Vertical/Overburden stress
σ_H	Maximum horizontal in-situ stress
σ_h	Minimum horizontal in-situ stress
σ'	Effective stress.
τ	Shear stress acting parallel to the failure plane, (σ_1-σ_2)/2.
σ_n	Normal stress acting perpendicular to the failure plane.
φ	Angle of internal friction.
UCS	Unconfined Compressive Strength.

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TABLE 1 Physical and Mechanical Properties of the Sandstones.

		Weak Sandstone	Strong Sandstone
Median Grain Size (mm)		0.15	-
Porosity (%)		39.5	15.3
Unconfined Compressive Strength (MPa)		0.5	24.4
Young's Modulus (GPa)		0.19	0.99
Average Initial Modulus (GPa)		0.31	2.44
Average Poisson's Ratio		0.24	0.18
Friction Angle	Yield	35.8°	51.2°
Cohesion (MPa)	Strength	0.08	4.0
Friction Angle	Peak	36.2°	38.5°
Cohesion (MPa)	Strength	0.14	16.5

TABLE 2 Borehole Stability Test Programme.

Test	Stress Anisotropy		Borehole Trajectory		
Block	σ_v/σ_H	σ_H/σ_h	Deviation	Orientation	Sandstone
2.1	1.0	1.0	0°	-	Weak
2.2	1.6	1.0	0°	-	Weak
2.3	1.6	1.0	30°	-	Weak
2.4	1.6	1.0	60°	-	Weak
2.5	1.25	2.0	45°	0°	Weak
2.6	1.25	2.0	45°	90°	Weak
2.7	1.25	2.0	45°	45°	Weak
3.1	1.0	1.0	0°	-	Strong
3.2	1.6	1.0	0°	-	Strong
3.3	1.54	1.18	0°	-	Strong
3.4	1.25	2.0	0°	-	Strong

TABLE 3 External Stresses Required to Induce Borehole Failure

	External Boundary Stresses (MPa)		
Test Block	σ_v	σ_H	σ_h
2.1	2.1	2.1	2.1
2.2	2.00-3.30	1.62-1.98	1.62-1.98
2.3	2.90-3.10	1.74-1.86	1.74-1.86
2.4	2.20	1.32	1.32
2.5	2.70	2.16	1.08
2.6	2.90	2.32	1.16
2.7	3.00	2.40	1.20
3.1	48.00	48.00	48.00
3.2	86.00	51.60	51.60
3.3	62.00	40.30	34.20
3.4	64.00	51.20	25.60

TABLE 4 Ratios of Tangential Stresses to Unconfined Compressive Strength Required to Induce Borehole Failure.

	Tangential Stress† / UCS	
Stress ratios	Weak	Strong
Isotropic	8.4	4.0
Anisotropic	8.0	4.2

Where: † The tangential stress calculated using linear elastic theory.

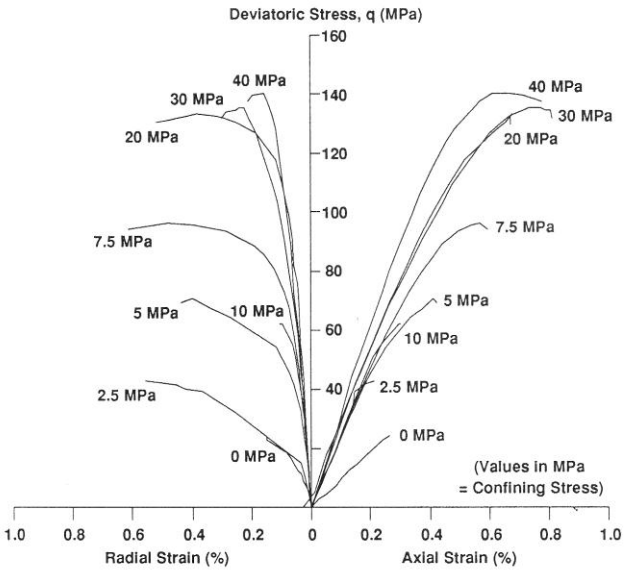

Figure 1a. Stress Strain Curves For The Strong Sandstone.

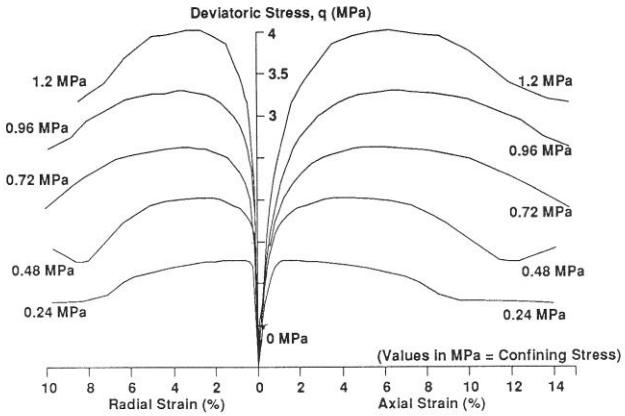

Figure 1b. Stress Strain Curves For The Weak Sandstone.

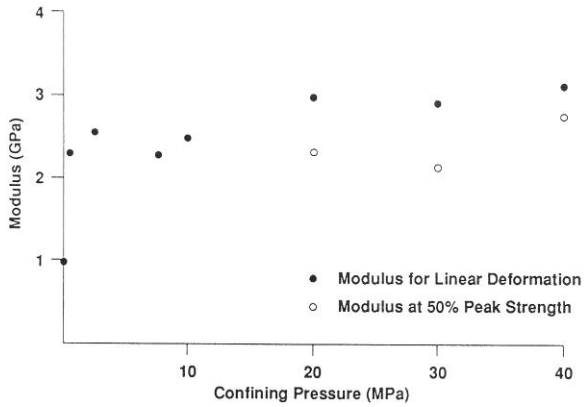

Figure 2a. Modulus Variation With Confining Stress For The Strong Sandstone.

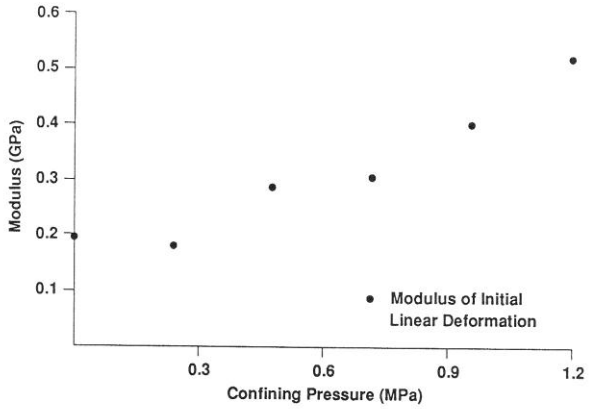

Figure 2b. Modulus Variation With Confining Stress For The Weak Sandstone.

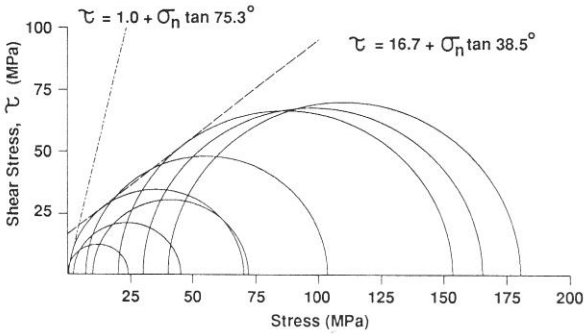

Figure 3a. Mohr-Coulomb Envelope For The Strong Sandstone.

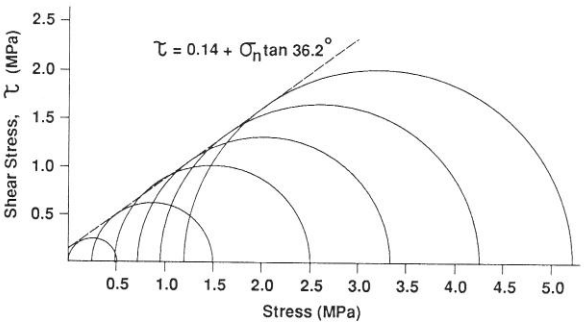

Figure 3b. Mohr-Coulomb Envelope For The Weak Sandstone.

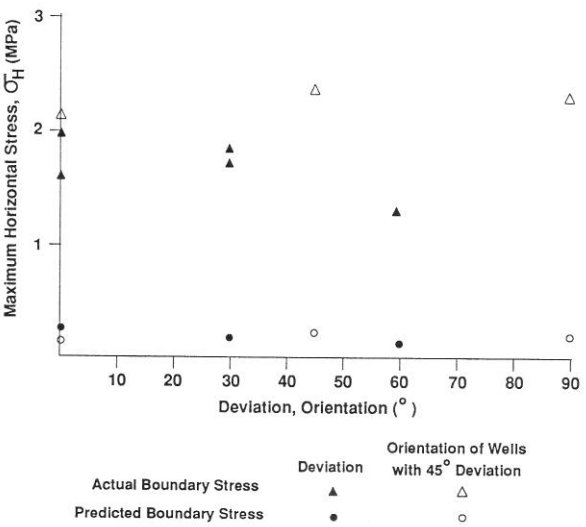

Figure 4. Comparison of Linear Elastic Predictions With Some Block Test Results.

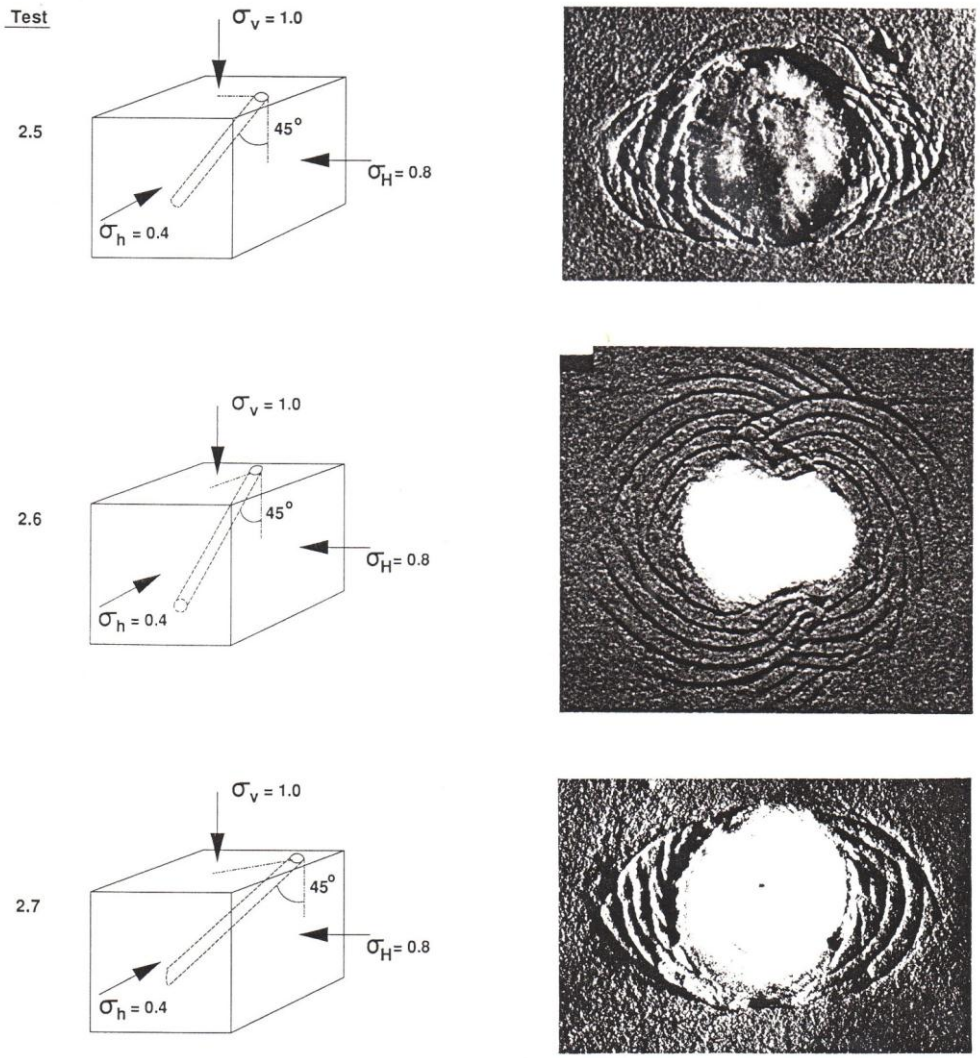

Figure 5b. Failure Zones Formed Around The Boreholes In The Weak Sandstone
- Tests To Investigate The Influence Of Orientation On The Stability Of Deviated Wells.

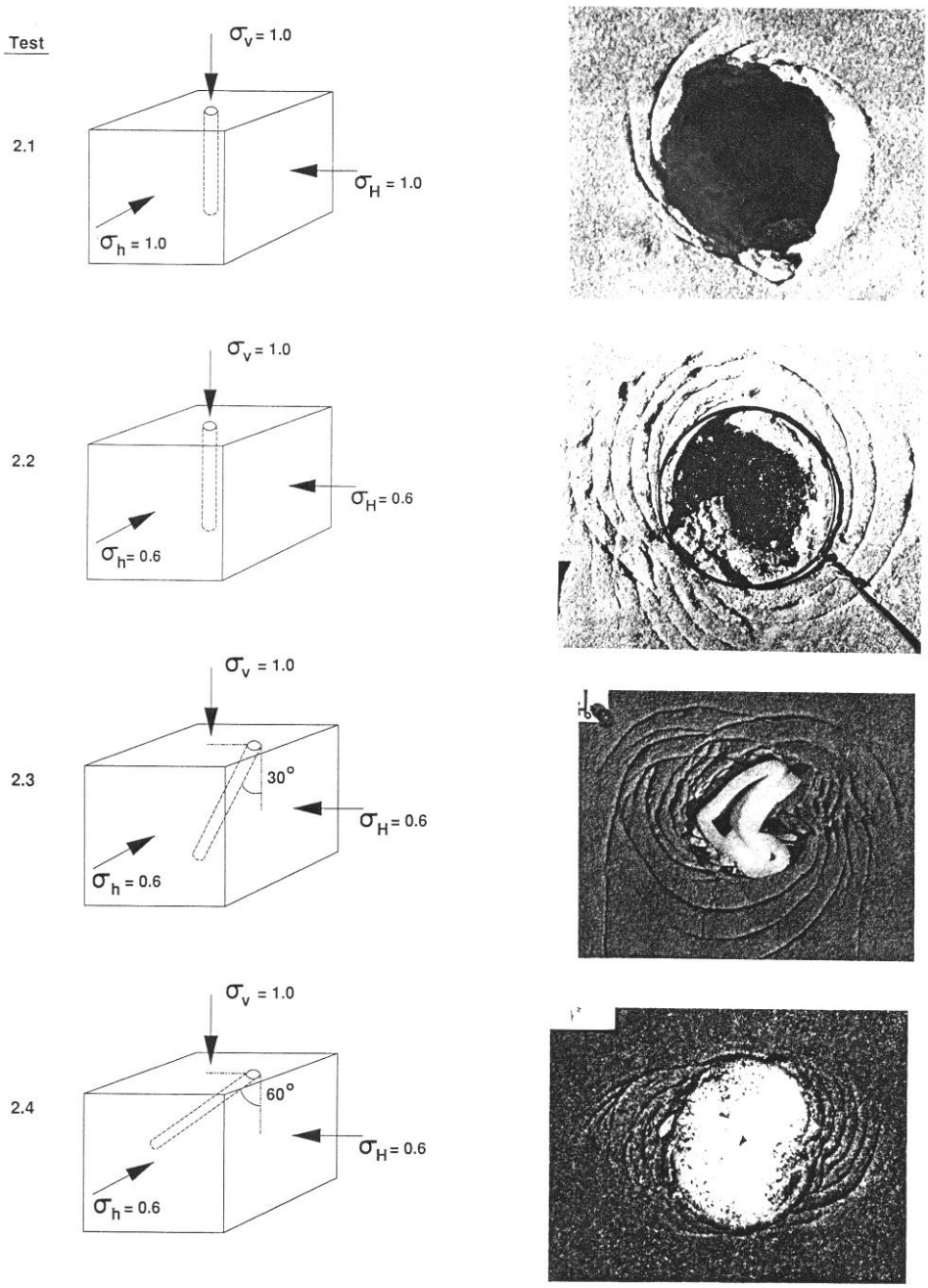

Figure 5a. Failure Zones Formed Around The Boreholes In The Weak Sandstone - Tests To Investigate The Influence Of Deviation On Stability.