Natural stress field evaluation using borehole ovalisation analysis and its comparison with hydrofract measurements

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ABSTRACT: This paper shows the results of borehole ovalisation analysis, developed to predict the natural stress field by means of the study of the deformation in vertical boreholes.
The methodology has been tested in several boreholes, in a soft argillaceous formations concluding:

- Reasonable results, in agreement with hydrofract measurements.
- Ratio σ_H/σ_h depends on the selected value of θ (breakout angle).
- The rock mass cohesion adopted has a major influence in the estimation of σ_H magnitude.

In this paper it is presented the methodology developed and the comparison between the results obtained with it and the measurements of three hydrofract profiles done in three boreholes.

1 INTRODUCTION

First of all an intensive literature review was done in order to analyze the previous jobs done using ovalisation-breakout of boreholes as method to estimate rock stresses.

This approach has been included by ISRM as a suggested method for stress measurement (Ljunggren *et al.*, 2003).

1.1 *Fundamentals of Borehole Ovalisation Analysis*

Borehole breakouts are failures of the borehole wall due to concentration of stresses, giving as a result elongation intervals with non-circular cross-section in the perpendicular direction to the maximum horizontal stress.

The breakouts are compressive failure structures that take place if the tangential stress exceeds the compressive rock strength, as it is shown in Figure 1.

The developed studies before now appeal to the breakout of the borehole to calculate the orientation of the principal horizontal stress and even more, the most recent studies use this method to estimate the magnitude of one of the principal horizontal stress, since it has been found that they influence directly in the form of a breakout.

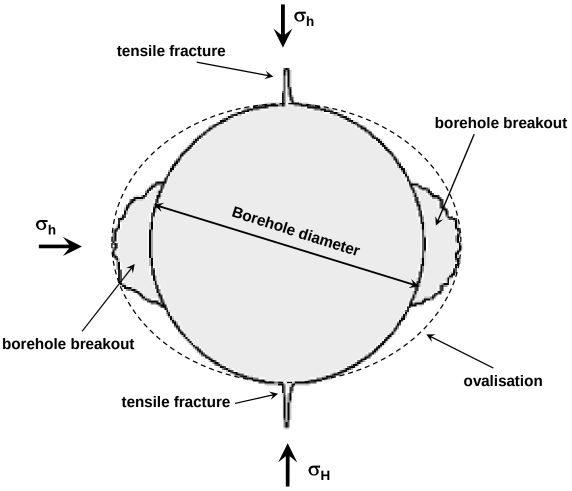


Figure 1.- Cross-section of the borehole with the effect of natural stress in it..

<u>The main observations in situ are:</u>

- *Babcok, 1978 and Cox, 1970:* the zones with elongated cross-sections show a constant preferential elongation direction, which is independent of the stratigraphy.
- *Bell and Gough 1982:* the shear fracturing could initially extend the hole by 8-10% of its original diameter.
- *Plumb and Hickman, 1985:* 1) borehole elongations were symmetrical and aligned with the minimum horizontal stress, and 2) were not associated with natural fractures intersecting the well.
- *Dart and Zoback*, *1987*: 1) breakouts are elliptical in cross-section along an axis which is parallel to the least horizontal *in situ* stress, 2) these

breakouts are found in all rock types and tectonic environments, 3) they form structural region that have essentially the same azimuth, and 4) orientation stresses inferred by breakouts are coherent to estimations made by other methods.

- *Leeman, 1964*: 1) borehole spalling is the result of excessive compressive stress, 2) fracture degree in the sidewall of a borehole gives quantitative information about the variation in rock stress along the length of the borehole, and 3) the broken-out segments are perpendicular to the maximum principal stress in the plane perpendicular to the borehole axis.

The main observations of the laboratory are:

- *Haimson* and *Edl, 1972*: the breakouts get extended throughout the circumference of the borehole and its depth shows a clear increase respect to the increase in confining pressure.
- *Mastin*, *1984*: width of the breakouts remains basically unchanged regardless of the final depth of spalling.
- *Haimson* and *Herrick*, *1985-1986:* 1) major breakout mechanism is the tensile rupture along surfaces, parallel to the borehole wall, and 2) breakout depth and width were directly proportional to the magnitude of the least principal stress.
- *Santarelli* and *Brown*, *1989*: elastic behaviour of the rock around cylindrical openings is important for fracture and failure development and for borehole wall.
- *Ewy and Cook, 1990*: the deformation process starts with a process of plastic pore and crack closure followed by a phase of micro-crack development, as it is shown in Figure 2.

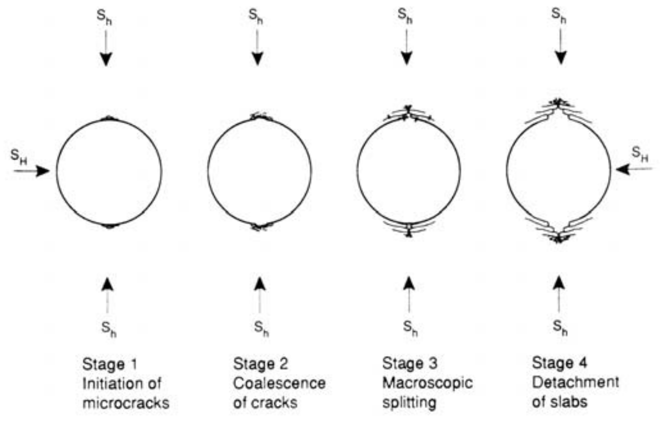


Figure 2.- Development of ovalisation process (*Ewy y Cook, 1990*).

- *Lee and Haimson, 1993:* 1) in crystalline rock, breakouts are aligned to the minimum horizontal stress, extensile cracking are a basic mechanism of breakout initiation, followed by a progressive detachment of rock flakes bounded by cracks, leading to V-shape cross-sections, 2) the value of the maximum horizontal stress, at which breakouts initiate, increase linearly within the magnitude of minimum horizontal stress, 3) and breakout depth and angular width increase linearly within the value of the maximum horizontal stress for fixed values of the vertical and minimum horizontal stress.
- *Lee and Haimson, 1995:* 1) V-shaped breakouts developed in granite are smaller than those in sedimentary rocks, 2) and depth and angular width of breakouts could be used as constraining factors, determining the orientation and magnitude of in situ stresses, since they both depend on the applied stress level.

Over the last decade, the analysis of borehole wall breakouts has become a promising technique for estimating in situ stress orientation at all depths and in all geological conditions, and particularly at great depths where direct in situ stress measurements are difficult to obtain. The breakout analysis is carried out together with other stress measurement methods such as hydraulic fracturing.

In most borehole breakouts studies, it has been found that their origin and orientation are ascribed only to large-scale tectonics and stress fields. The probable influence of local geological structures on the orientation and magnitude of borehole breakouts has been discussed by several authors.

Finally, the breakout borehole is an accurate precise method for the estimate of the orientation of the principal stresses. Regarding the calculation of principal stresses magnitudes there is a relatively short experience and the factors to consider have not been specified yet. The most generic study is the one carried out by Zoback (1985).

1.2 *Development of an ovalisation analysis*

Many authors use the breakout borehole method for their investigations but the main difference among each is taking the data in situ, which depends on the application tools, and in the parameters affecting the breakout when it develops, these are the factors to keep in mind when choosing the most appropriate methodology. On the other hand, the calculation of magnitudes of the principals stresses does not use to the generic method of breakout borehole breakoutut an adaptation and combination of other procedures.

The main theory for Borehole Ovalisation Analysis comes from the study of a cylindrical hole in a thick, homogeneous, isotropic and elastic plate subjected to effective minimum and maximum principal stresses. In this case the following equations apply (Kirsch, 1898; Jaeger, 1961):

$$\sigma_r = \frac{(S_H + S_h)}{2}\left(1 - \frac{R^2}{r^2}\right) + \frac{(S_H - S_h)}{2}\left(1 + 3\frac{R^4}{r^4} - 4\frac{R^2}{r^2}\right)\cos 2\theta + \Delta P\frac{R^2}{r^2} \qquad (1)$$

$$\sigma_\theta = \frac{(S_H + S_h)}{2}\left(1+\frac{R^2}{r^2}\right) - \frac{(S_H - S_h)}{2}\left(1+3\frac{R^4}{r^4}\right)\cos 2\theta - \Delta P\frac{R^2}{r^2} \tag{2}$$

$$\tau_{r\theta} = -\frac{(S_H + S_h)}{2}\left(1-3\frac{R^4}{r^4}-2\frac{R^2}{r^2}\right)\sin 2\theta \tag{3}$$

The magnitude of the shear and normal stresses along these potential failure surfaces varies as a function of the radius *r* and the angle θ.

Assumed:

- At each point (r,θ) the maximum and minimum principal stresses are in the horizontal plane and the failure surfaces are parallel to the borehole vertical axis.
- The rock have a coefficient of internal friction $\mu = \tan\phi$ and internal cohesive strength *C*.
- $S_H \le 3S_h$ and $\Delta P = 0$

According to the Mohr- Coulomb criterion:

$$|\tau| = C + \mu\sigma \tag{4}$$

The maximum value of cohesive strength at which the material will fail is given by:

$$C = (1+\mu^2)^{1/2}\left(\left(\frac{\sigma_\theta - \sigma_r}{2}\right)^2 + \tau^2{}_{r\theta}\right)^{1/2} - \mu\left(\frac{\sigma_\theta + \sigma_r}{2}\right) \tag{5}$$

Whereas the third and fourth supposition, we would obtain in the following equations:

$$C\ (R, \theta b) = 0{,}5(a\cdot\sigma_H + b\cdot\sigma_h) \tag{6}$$

$$C\ (rb, \pi/2) = 0{,}5(c\cdot\sigma_H + d\cdot\sigma_h) \tag{7}$$

$$a = \left[(1+\mu^2)^{1/2} - \mu\right][1-2\cos 2\theta_b] \tag{8}$$

$$c = -\mu + (1+\mu^2)^{1/2} - \frac{R^2}{r^2{}_b}\left[(1+\mu^2)^{1/2} + 2\mu\right] + 3\frac{R^4}{r^4{}_b}(1+\mu^2)^{1/2} \tag{9}$$

$$b = \left[(1+\mu^2)^{1/2} - \mu\right][1+2\cos 2\theta_b] \tag{10}$$

$$d = -\mu - (1+\mu^2)^{1/2} + \frac{R^2}{r^2{}_b}\left[3(1+\mu^2)^{1/2} + 2\mu\right] + 3\frac{R^4}{r^4{}_b}(1+\mu^2)^{1/2} \tag{11}$$

Consider now a breakout which follows a trajectory for a given value of the cohesive strength C such that C (R, θb) = C (rb, π/2) = C;

$$\sigma_H = 2C\frac{d-b}{ad-bc} \qquad \sigma_h = 2C\frac{a-c}{ad-bc} \tag{12}$$

$$\frac{\sigma_H}{\sigma_h} = \frac{d-b}{a-c} \tag{13}$$

2 PROCEDURE FOR A BOREHOLE OVALISATION ANALYSIS

The following procedure is used:

1 Geometrical analysis of the section

Drawing the nominal diameter of the borehole and the three aims caliper information.

Calculation of the ellipse containing the minor radius (nominal or measured by the caliper) and the maximum radius measured.

Calculation of the intersection of the ellipse and the circle with the minor radius. This intersection determines θ (Breakout Angle).

As a result of this first stage the orientation of σ_H is established as well as the breakout angle is defined.

2 Analytical analysis of σ_H and σ_h

Once the orientation analysis is finished and the breakout angle is estimated, the analytical calculation of σ_H and σ_h, according with the expressions included in the previous item, is done.

The value adopted for the cohesion of the ground has a large influence in the magnitude of σ_H, while ratio σ_H/σ_h highly depends on the selected value of the breakout angle θ.

Finally the friction angle of the ground has a minor influence in the results.

According with this, it is highly recommended to make this analytical analysis with reasonable pairs of values of cohesion and breakout angle.

3 CASE STUDIES

To check the effectiveness of this method several measures of deformation, were made with a caliper of 6 arms.

The analysis was done using several values of θ, as well as changing the values of cohesion and friction angle between the rate measured in the laboratory test.

1 First application

An argillaceous formation from the South of Spain was chosen, as in this site both:

- hydrofract tests and
- caliper measurement,

were available.

In Figure 3 it is shown the results of the hydrofract measurements carried out in this site.

As it can be observed a very good knowledge of the natural stress field is assure. This stress field can be resumed as:

$$\sigma_h\ (\text{MPa}) = 5{,}9 + (0{,}02 \pm 0{,}006)\ (z\ (\text{m}) - 374) \tag{14}$$

$$\sigma_H\ (\text{MPa}) = 13{,}9 + (0{,}02 \pm 0{,}011)\ (z\ (\text{m}) - 374) \tag{15}$$

$$\sigma_V\ (\text{MPa}) = 0{,}0245 \cdot z\ (\text{m}) \tag{16}$$

where z is the depth in meters.

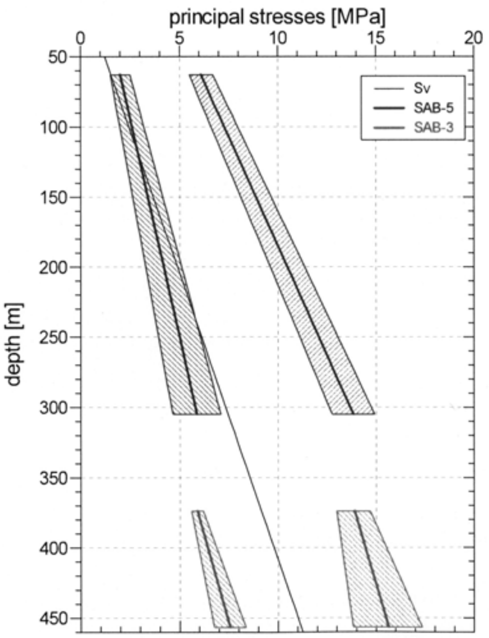


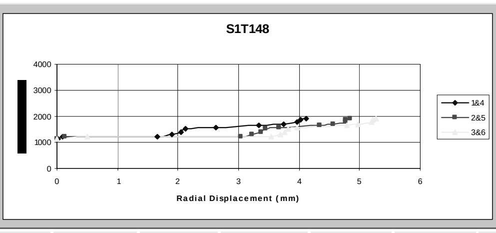
Figure 3.- Stress profile of boreholes SAB-3 and SAB-5.

The orientation of the maximum horizontal stress is N-104º-E (± 2º).

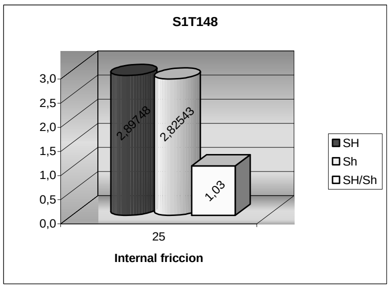
In the vicinity of these two boreholes we have the borehole number 1 (S1) in which a very good quality of calliper was available. Therefore ovalisation analysis was carried out in this hole.

In Figure 4, it is shown the analysis done at a depth of 148 m (S1T148).

CALIBRATED DATA	**S1T148**	DEPTH (m)	**148.00**



C (MPa)	**ϕ**	**μ**	**$\phi_{Perf.}$ (mm)**	**ϕ_{sonda} (mm)**	**1-4 (mm)**	**2-5 (mm)**	**3-6 (mm)**
1.8	25	0.47	101.0	95.0	1.6590	3.0329	3.5385
1.0	20	0.36	101.0	95.0	1.6590	3.0329	3.5385
1.8	20	0.36	101.0	95.0	1.6590	3.0329	3.5385
1.0	25	0.47	101.0	95.0	1.6590	3.0329	3.5385
θ_b	**a**	**b**	**c**	**D**	**S_H**	**S_h**	**S_H/S_h**
30	0.00	1.274	1.816	-0.589	2.89748	2.82543	1.02550
30	0.00	1.400	1.805	-0.650	1.45996	1.42815	1.02227
30	0.00	1.400	1.816	-0.549	2.62793	2.57067	1.02227
30	0.00	1.274	1.805	-0.650	1.60971	1.56969	1.02550



This graph shows, the value obtain from S_H/S_h, for a depth of 148m, with using this method

Figure 4.- Analysis of test at S1T148.

According with the hydrofract measurements the following values are expected:

σ_V = 3,6 MPa

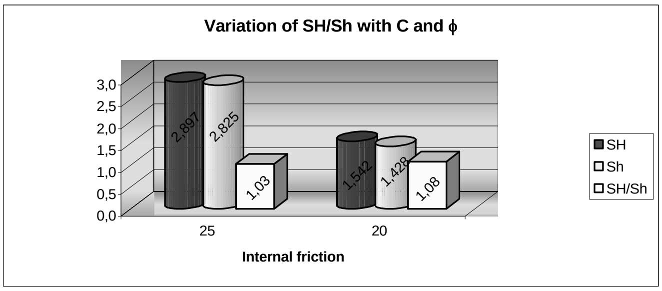
σ_H = 8,9 MPa

σ_h = 3,3 MPa

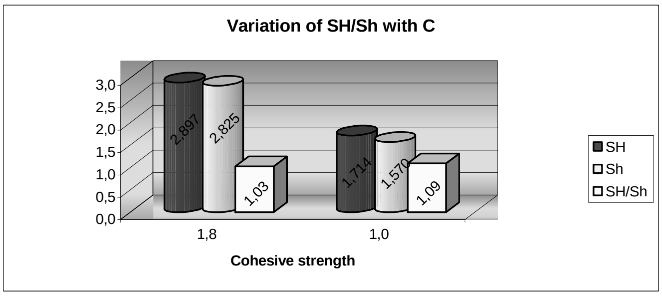
that give a ratio σ_H / σ_h = 26.

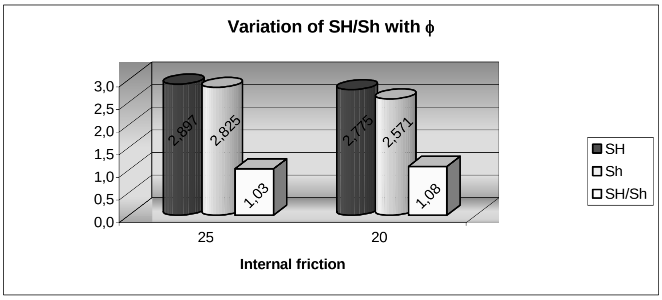
The range of cohesion goes from 1 to 1,8 MPa, while the friction angle goes from 20 to 25º.

In Figure 5 it is shown a parametric study of the obtained results. It can be concluded that the ratio σ_H / σ_h can be easily derived as well as orientation, while some problems exist to obtain the predicted magnitude of σ_H, that depends mainly on the adopted value of cohesion.



A reduction of S_h and S_H and an increase of the ratio S_H/S_h is caused by the variation of C and ϕ





The variation of C decrease S_H and S_h,, remaining constant the ratio S_H/S_h. On the other hand, the variation of ϕ causes a small reduction in S_H, S_h and the ratio S_H/S_h.

Figure 5.- Parametric study of the obtained results.

2 Second application

The second application was done in the Northwest of Spain, in Ciñera, Matallana Coal Field (León).

Several tests were done in three boreholes (S74, S84 and S88). Following the test done in 574 at 194 m depth is described.

According with hydrofract measurement the following natural stress field was expected:

- σ_V = 4,8 MPa
- σ_H = 10,7 MPa
- σ_h = 5,9 MPa

with a strike of N-40º-E for σ_H.

In Figure 6, the geometrical analysis described in 4 is shown.

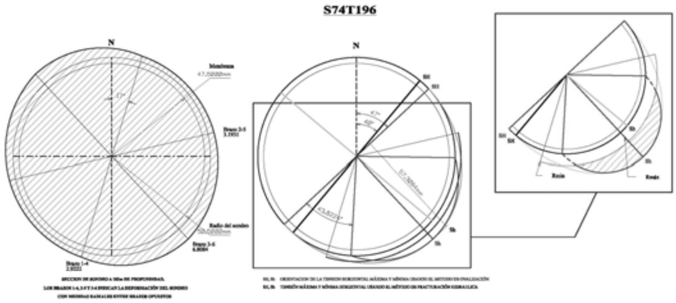
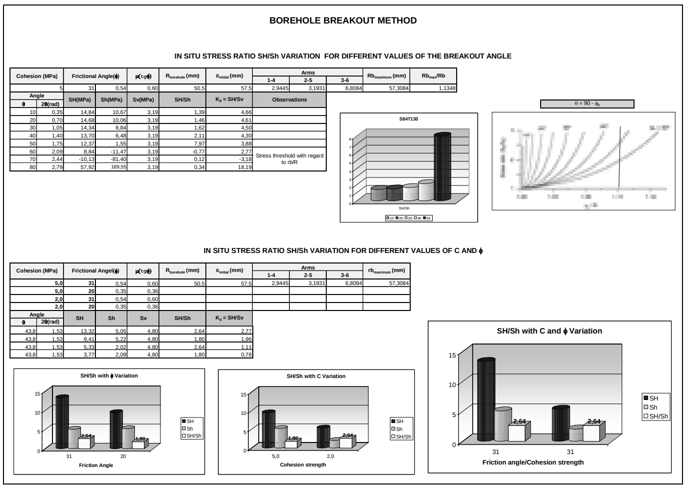


Figure 6.- Example of ovalisation analysis (S74T196).

The results obtained are shown in Figure 7 with the following results:

- σ_H = 9,4 MPa
- σ_h = 5,2 MPa

with a strike of σ_H N-47º-E.



BOREHOLE BREAKOUT METHOD

IN SITU STRESS RATIO SH/Sh VARIATION FOR DIFFERENT VALUES OF THE BREAKOUT ANGLE

Cohesion (MPa)	Frictional Angle(ϕ)		μ(tgϕ)	$R_{borehole}$ (mm)	$R_{initial}$ (mm)	Arms 1-4	Arms 2-5	Arms 3-6	$Rb_{maximum}$ (mm)	Rb_{max}/Rb
5	31	0,54	0,60	50,5	57,5	2,9445	3,1931	6,8084	57,3084	1,1348

Angle θ	Angle 2θ(rad)	SH(MPa)	Sh(MPa)	Sv(MPa)	SH/Sh	K_0 = SH/Sv	Observations
10	0,35	14,84	10,67	3,19	1,39	4,66	
20	0,70	14,68	10,06	3,19	1,46	4,61	
30	1,05	14,34	8,84	3,19	1,62	4,50	
40	1,40	13,70	6,48	3,19	2,11	4,30	
50	1,75	12,37	1,55	3,19	7,97	3,88	
60	2,09	8,84	-11,47	3,19	-0,77	2,77	Stress threshold with regard to rb/R
70	2,44	-10,13	-81,40	3,19	0,12	-3,18	
80	2,79	57,92	169,55	3,19	0,34	18,19	

IN SITU STRESS RATIO SH/Sh VARIATION FOR DIFFERENT VALUES OF C AND ϕ

Cohesion (MPa)	Frictional Angel(ϕ)		μ(tgϕ)	$R_{borehole}$ (mm)	$R_{initial}$ (mm)	Arms 1-4	Arms 2-5	Arms 3-6	$rb_{maximum}$ (mm)
5,0	31	0,54	0,60	50,5	57,5	2,9445	3,1931	6,8084	57,3084
5,0	20	0,35	0,36						
2,0	31	0,54	0,60						
2,0	20	0,35	0,36						

Angle θ	Angle 2θ(rad)	SH	Sh	Sv	SH/Sh	K_0 = SH/Sv
43,8	1,53	13,32	5,05	4,80	2,64	2,77
43,8	1,53	9,41	5,22	4,80	1,80	1,96
43,8	1,53	5,33	2,02	4,80	2,64	1,11
43,8	1,53	3,77	2,09	4,80	1,80	0,78

Figure 7.- Analytical evaluation of the test done at S74T196.

Table 1 shows the comparison of results between the estimation done with ovalisation analysis and the result of hydrofract measurements in the three boreholes. A good agreement between both estimations can be observed.

Table 1.- Comparison between the hydrofrac and ovalisation estimations.

Borehole	Depth (m)	σ_V (MPa)	Hydrofrac			Ovalisation		
			Strike	σ_H (MPa)	σ_h (MPa)	Strike	σ_H (MPa)	σ_h (MPa)
S-78	196	4,8	N-40º±4º	10,72	5,96	N-47º	9,41	5,22
S-84	143	3,5	N-139º±16º	12,86	7,26	N-117º	12,9	7,3
S-88	210	5,1	N-93º±17º	6,70	4,41	N-76º	6,7	4,4

So a very good agreement between both systems was achieved, with the following conclusions:

- The developed method provides a reasonable estimation of natural stress field.
- It is necessary to make a previous tectonic analysis of the site investigated.
- This prediction only works at deep boreholes. (Depending of the ground geotechnical quality).
- Several sections at different depths are necessary to choose the strike of σ_H. (Valid sections).
- The value of C and ∅ that fits the results are the obtained from lab tests.

4 NUMERICAL ANALYSIS OF OVALISATION

Further investigations are suggested. They consist in the interpretation of borehole data using stress-strain analysis with FLAC-2D.

As an example it is shown the type of results obtained until now, with same S74T196.

In Tables 2 and 3 it is included the rock mass properties considered in three different cases analysed as well as the results obtained.

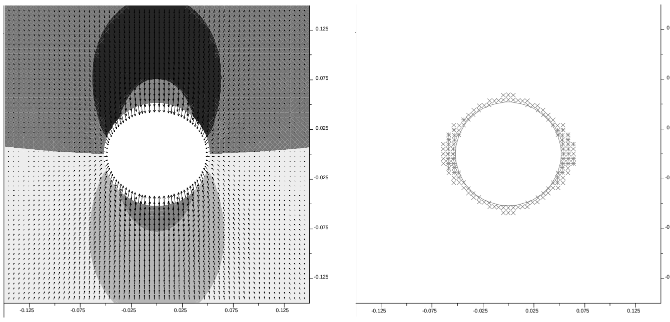
Table 2.- Rock Mass parameters.

	E (MPa)	ν	ϕ (º)	C (MPa)
Case 1	13233	0.25	20	5
Case 2	1466	0.25	30	0.24
Case 3	1466	0.25	20	5

Table 3.- Results obtained in FLAC analysis.

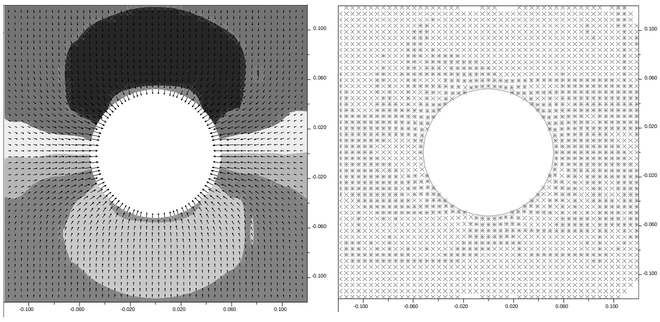
	Radial deformation		Yield radius	
	Axis σ_H (mm)	Axis σ_h (mm)	Axis σ_H (mm)	Axis σ_h (mm)
Case 1	0.07126	0.02626	0	12
Case 2	3.3	5.56	30	120
Case 3	0.6409	0.2361	0	13

These results are graphically showed in Figures 8, 9 and 10.



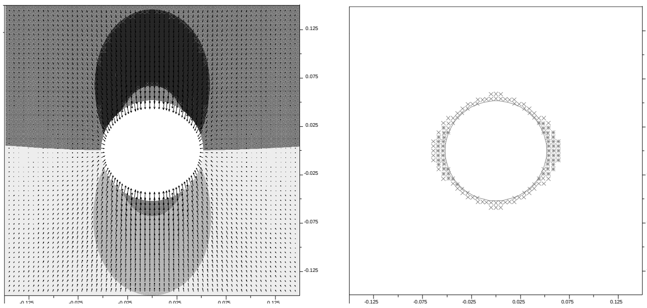
Displacement on σ_H Axis Plastified elements

Figure 8.- Results of Case no. 1.



Displacement on σ_H Axis Plastified elements

Figure 9.- Results of Case no. 2.



Displacement on σ_H Axis Plastified elements

Figure 10.- Results of Case no. 3.

5 CONCLUSIONS

The following main conclusions have been obtained:

- It is a promising cost-effective method for the estimation of the natural stress field.
- Several sections are needed for making a reliable estimation.
- Those sections must be at enough depth, so ovalisation break-out phenomena can occur.
- Reliable values of cohesion are needed.
- Reliable calliper tool must be used.

Also the following improvements for the future are suggested:

- The use of a televiewer tool.
- The use of numerical codes for the interpretation of the ovalised sections.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

Babcok, E.A. 1978. Measurement of subsurface fractures from dipmeter logs. Amer. Ass. Petrol. Geol. Bull., 62, 7:111-1126.

Bell, J.S. & Gough, D. I. 1982. The use of borehole breakouts in the study of crustal stress. In M. D. Zoback and B.C. Haimson, eds., Workshop on hydraulic fracturing stress measurements [December 2-5], proceedings: U.S. Geological Survey Open-file Report 82-1075: 539-557.

Cox, J.W. 1970. The high resolution dipmeter reveals dip-related borehole and formation characteristics. Trans. SPWLA, 11th Annual Logging Symp. Los Angeles, CA.

Dart, R.L. and Zoback, M.L. 1987. Well-bore breakout-stress analysis within the continental United States. In Proc. 2nd Int. Symp. on Borehole Geophysics for Minerals, Geotechnical, and Ground-water Applications, Golden, Soc. Of Prof. Well Log Analysts Publ., pp.1-11.

Ewy, R.T. & Cook, N.G.W. 1990. Deformation and fracture around cylindrical openings in rock – I. Observatiosn and analysis of deformation, II. Initiation, growth and iteraction of fractures. Int. J. Rock Mech. Min. Sci. & Geomech. Abstr. 27, I: 387-407, II: 409-427.

Haimson, B.C. & Edl, J.N. 1972. Hydraulic fracturing of deep wells. SPE Paper No. SPE 4061.

Haimson, B. C. and C. Herrick. 1985. In-situ stress evaluation from borehole breakouts: experimental studies, in Proc. 26th US Symp. Rock Mech., Rapid City, Balkema, Rotterdam, 1207-1218

Haimson, B.C. and Lee, M.Y. 1995. Estimating in situ stress conditions from borehole breakouts and core disking-experimental results in granite. In Proc. Int. Workshop on Rock Stress Measurement at Great Depth, Tokyo, Japan, 8th ISRM Congress, pp. 19-24.

Jaeger, J. (1961). Elasticity, Fracture and Flow, 212 pp., Methuen, London, 1961.

Kirsch, G. (1898). Die Theorie der Elastizitat und die Beaurforisse der Festigkeitslehre, V DI Z 1857 1968, 42 707 1898.

Leeman, E. R. 1964. The measurement of stress in rock – Part I. J. S. Afr. Inst. Min. Metall,. 65: 45-114.

Ljunggren, C., Yanting Chang, J. T. & Christiansson, R. 2003. An overview of rock stress measurement methods Special Issue on Rock Stress Estimation. Int. J. Rock. Mech. Min.Sci., 40, 7/8.

Mastin, L.G. 1984. Development of borehole break-outs in sandstone, unpublished MSc Thesis, Stanford University, Palo Alto.

Plum, R.A. and Hickman, S.H. 1985. Stress induced borehole elongation-a comparison between four-arm dipmeter tool and the borehole televiewer**,** in the Auburn geothermal well. Journal Geophysical Research, 90(B7): 5513-5521.

Santarelli, F.J. & Brown, E.T. 1989. Failure of three sedimentary rocks in triaxial and hollow cylinder compression tests. Int. J. Rock Mech. Min.Sci. & Geomech. Abstr., 26: 401-413.

Zoback, M.D., D. Moos, L. Mastin, and R.N. Anderson (1985). Wellbore breakouts and in situ stress, In: Journal of Geophysical Research, v.90, no. B7, p.5523-5530. Discussion and reply, Journal of Geophysical Research, v.91, no. B14, p. 14, 161-14, 164.