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LABORATORY HYDRAULIC-FRACTURING EXPERIMENTS

Summary. The technique of hydro-fracturing has recently developed into a method for measuring stresses of rock bodies. As a method for this purpose, it has the advantage of saving the trouble of overcoring, and does not measure strain at a point through the use of sophisticated instrumentation. In order to investigate the mechanism of rock being hydraulically fractured and to verify the theory of hydraulic fracturing, the author of this paper carried out a series of hydro-fracturing experiments on rock specimens and models. Presented in this paper are the devices used in the experiments, as well as the results of the experiments and their analyses.

I. Experimental Set-up and Loading Methods

The devices and instruments required for hydrofracturing simulation are as follows: modelled loading frames, plane jacks, manual pressure pumps of Model SY, manual oil pumps, X-Y function loggers, pressure gauges, 100-t all-purpose experimenters, and some others.

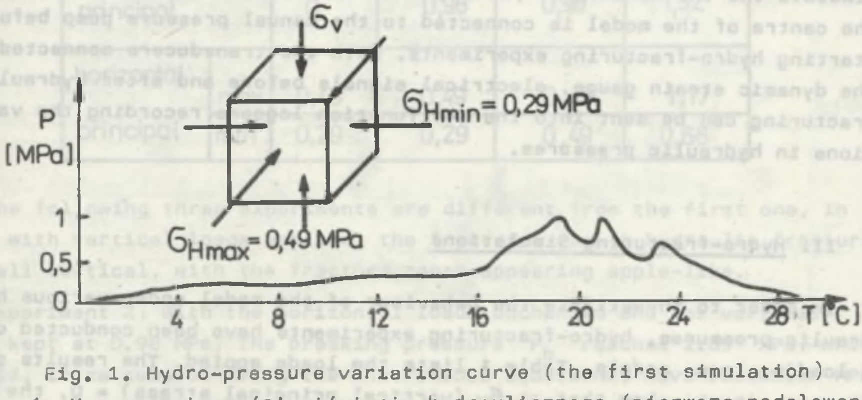


Fig. 1. Hydro-pressure variation curve (the first simulation)

Rys. 1. Krzywa zmienności ciśnienia hydraulicznego (pierwsze modelowanie)

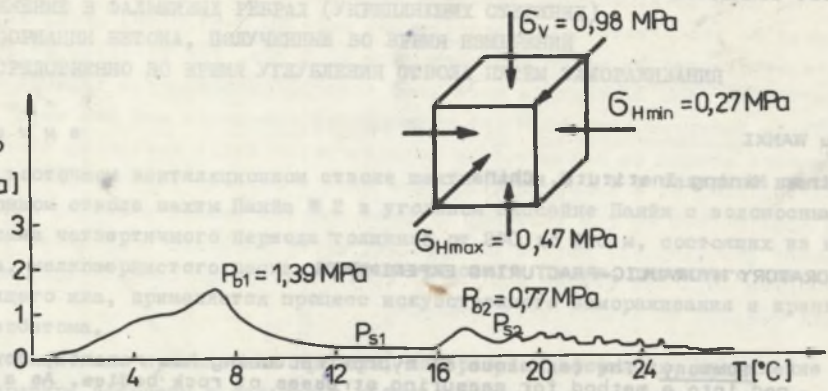


Fig. 2. Hydro-pressure variation curve (the second simulation)
Rys. 2. Krzywa zmienności ciśnienia hydraulicznego (drugie modelowanie)

The modelling material used is solid-state paraffin, which is easy to cast, repeatedly usable, and non-infiltrating, with a compressive strength of 1.17 MPa and a tensile strength of 2.5 MPa.

Models are cast in the following steps: lay a steel sheet on the ground; set on it the loading frame whose inner dimensions are 215 x 215 x x 215 mm; close to the internal surface of the frame, erect 2 plane jacks made up of copper plates through welding; and rinally cast the pre-melt paraffin into the frame at the centre of which a steel pipe is planted, with an iron bar inserted. After the paraffin has become solid, the iron bar is pulled out, leaving the modelled boring hole.

24 hours after the casting, the model is placed on the all-purpose experimenter, and then loads are applied along the axis of the borehole, to simulate the vertical principal stress of the rock body. Pre-settled loads are applied through the two oil pumps on to the two plane jacks, to simulate the two horizontal principal stresses. Then the steel pipe at the centre of the model is connected to the manual pressure pump before starting hydro-fracturing experiments. With the transducers connected to the dynamic strain gauge, electrical signals before and after hydraulic fracturing can be sent into the X-Y function loggers recording the variations in hydraulic pressures.

II. Hydro-fracturing Simulations

In order to investigate the behaviour of the model under various hydraulic pressures, hydro-fracturing experiments have been conducted on 4 loading frame models. Table 1 lists the loads appied. The results of the experiments show that at σ_v (vertical principal stress) = 0, the artificial fractures due to the hydraulic fracturing appear horizontal; and when it is the maximum principal stress or equal to the maximum horizontal one, the artificial fractures appear vertical.

Experiment 1: Breaking pressure reaches 0.98 MPa, a little bit lower than the tensile strength of paraffin. The fractures produced appear horizontal. The breaking pressure, according to the theory of hydraulic fracturing, should have been 1.17 MPa, with a difference of 0.19 MPa, which can be accounted for by the different methods in determining the tensile strength of paraffin which should be 1.17 MPa if determined by the Brazilian method and by the hydro-fracturing experiments on cylindrical specimens). The behaviour of P_b in this experiment is shown in fig. 1. In the figure there appear 3 peaks on the pressure-time curve. The first two peaks are equally high, indicating that the horizontal fractures are still very small at the first peak, but have been expanded considerably after the second peak. Extra pressure provided by a second pumping necessary to re-open the fractures is somewhat smaller than either or the first two peaks, being about 0.58 MPa, which is used mainly to balance the bond between the modelling material and the internal surface of the loading frame. When breaking pressure P_b reaches a third peak, no more pressures are pumped to the central hole, where hydraulic pressures diminish, until zero. This shows that shutdown pressure P_s is close to zero, which shoul, theoretically, have been equal to the minimum principal stress, that is $P_s = \sigma_v = 0$.

Table 1

loading sequence / stresses		No.1	No.2	No.3	No.4
vertical principal		0	0,98	0,98	1,32
horizontal principal	max	0,49	0,49	0,49	1,17
	min	0,29	0,29	0,49	0,68

The following three experiments are different from the first one, in that with vertical loads applied, the fractures due to hydraulic fracturing are all vertical, with the fracture zones appearing apple-like.

Experiment 2: With the horizontal loads unchanged and the vertical ones kept at 0.98 MPa, the breaking pressure P_b reaches 1.89 MPa, which should, if calculated using the theoretical equations, have been 1.56 MPa.

The difference is obviously caused by T, the tensile strength of paraffin. According to the hydraulic pressure (P)-time curve in fig. 2, shutdown pressure P_s = 0.29 MPa, which is just the minimum horizontal principal stress P_{Hmin}, conforming with the theoretical equations. As shown by the curve of hydraulic pressure variations in fig. 4, P_{b1} (the first peak) is 1.89 MPa and P_{b2} 0.77 MPa, with a difference of 1.11 MPa. Theoretically, the tensile strength of paraffin $T = P_b - P_{b2}$ = 1.11 MPa; while by the Brazilian method and by the hydro-fracturing method on cylindrical specimens, it should be 1.17 MPa. This shows that different methods have lead to practically the same result, and also shows that the theory is correct.

Experiment 3: The maximum principal stresses, both vertical and horizontal, are 0.98 MPa. The minimum horizontal principal stress is still 0.49 MPa. The fractures produced are vertical, to σ_{Hmin}, the minimum horizontal principal stress. Fig. 3 shows the curve of variations in the hydraulic pressures in this experiment. Form the figure, it is known that P_b (breaking pressure in the first experiment) is 1.47 MPa, and P_{b2} and P_{b3} are both 1.11 MPa. P_{b1} should, theoretically calculated, have been 1.66 MPa, with a difference of 0.19 MPa as compared with that obtained in the experiment. In addition, the tensile strength of paraffin as calculated by the theoretical equation $T = P_{b1} - P_{b2}$ is only 0.35 MPa, far lower than the value otherwise obtained (1.17 MPa). Analysis has indicated that this is probably due to an improper casting of paraffin, in the process of which bedding planes were formed to lower the tensile strength. However, P_s as shown in the figure is still lower than σ_{Hmin}, minimum horizontal principal stress (0.49 MPa), conforming with the theory.

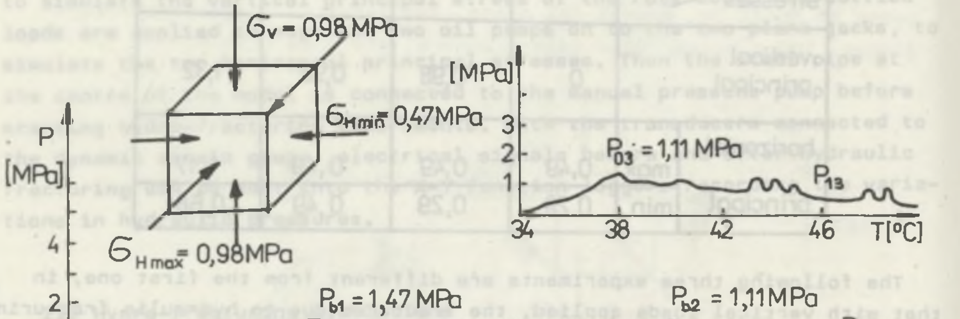


Fig. 3. Hydro-pressure variation curve (the third simulation)

Rys. 3. Krzywa zmienności ciśnienia hydraulicznego (trzecie modelowanie)

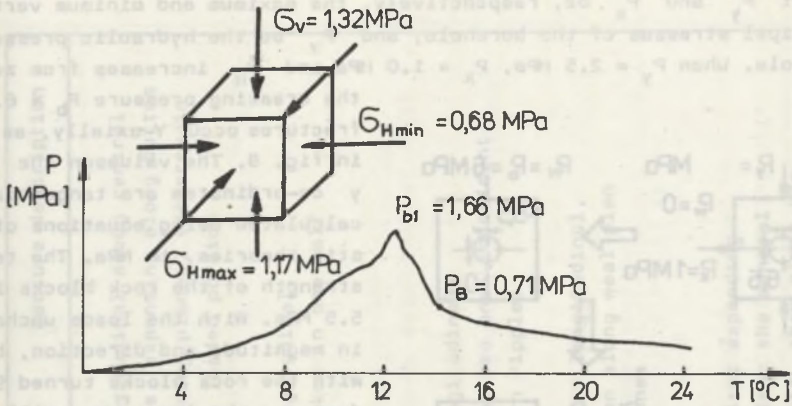


Fig. 4. Hydro-pressure variation curve (the fourth simulation)

Rys. 4. Krzywa zmienności ciśnienia hydraulicznego (czwarto modelowanie)

Experiment 4: When the horizontal principal stress is kept at 1.17 MPa, the minimum at 0.68 MPa and the vertical one between 1.27 and 2.45 MPa (not easy to control at the moment), the fractures produced are still vertical, to $б_{Hmin}$, the **minimum** horizontal principal stress. P_{b1}, which should theoretically have been 2.05 MPa, is actually 1.66 MPa. It can be seen from the pressure variation curve in fig. 4 that the pressure at the turning point B is 0.71 MPa, fairly close to $б_{Hmin}$ (the minimum horizontal principal stress) and so can be taken as the shutdown pressure at the point. It can be easily seen from the above that. The fractures due to hydraulic fracturing are always vertical to the minimum principal stress; If the vertical principal stress happens tobe the minimum, the fractures appear horizontal;

If the vertical principal stress is greater than either of the two horizontal principal stresses or is equal to the maximum horizontal principal stress, the fractures appear vertical;

The difference between the two breaking pressure can represent the tensile strength of the medium;

The shutdown pressure P_s is equal to the minimum principal stress.

III. Hydro-fracturing Experiments on Granite Blocks

The simulated experiments as described above are all on paraffin models. The same applies when rock blocks are used. Associate Professor Yashiaki Mitzta of the Engineering Faculty of Yamaguchi University, Japan, conducted some experiments of this kind in the University of Minnesota, the U.S.A. He subjected 200 x 200 x 200 mm granite cubics under different loads. The following is a brief summary of his experiments.

Let P_y and P_x be, respencively, the maximum and minimum vertical principal stresses of the borehole, and P_w be the hydraulic pressure in the hole. When P_y = 2.5 MPa, P_x = 1.0 MPa and P_w increases from zero to the breaking pressure P_b = 6.0 MPa, fractures occur Y-axially, as shown in fig. 8. The valueson the x and y co-ordinates are tangential as calculated using equations of elastic theories, in MPa. The tensile strength of the rock blocks in 5.5 MPa. With the loads unchanged, in magnitude and direction, but with the rock blocks turned 90 degrees, the fractures still expand y-axially at P_w = 6 MPa, as shown in fig. 5. With the blocks unmoved after the first failure, but by providing P_w as little as 0.5 MPa, the artificial fractures will re-open. The facts indicate the the stress field is not disturbed after the artificial fractures are shut, for the fractures re-open in the same direction as before at a second pressure pumping. It is obvious that the tensile strength of the rock blocks is determined by the difference between the two breaking pressures, to be exact, the tensile strength of the rock blocks T = P_{b1}-P_{b2} = 6-0.5 = = 5.5 MPa.

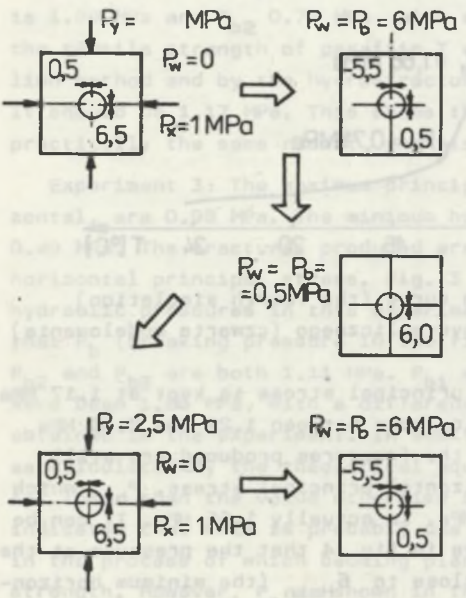


Fig. 5. Fracture expanding patterns of granite after hydrofracturing

Rys. 5. Modele rozprzestrzeniania się pęknięcia w granicie po pęknięciu w wyniku działania wody

IV. Hydro-fracturing Experiments on Sandstone Specimens

The tensile strength of the rock is a very important parameter in the measurement of stresses in rock bodies being hydro-fractured. There are various ways to determine the tensile strength: splitting method (also known as the Brazilian method), direct method, and hydro-fracturing/field-measuring method (determined by the difference between the first two breaking pressures). The accuracy of the tensile strength will have direct effects on the reliability of the stress measurements of rock bodies. This experiment is to discover a correct method for determining the

Table 2

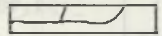
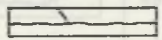
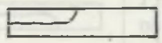
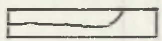
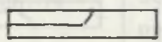
Specimen No.	Pb (MPa)	T (MPa)	Facture shape	Lithology	Facture description
1	8.82	8.82		medium-grained, visible surface bedding	longitudinal along central axis, expanding along bottom bedding planes, traverse in the loaded portion
2	9.31	9.31		medium-grained, dense-textured, undeveloped bedding	longitudinal, brokon in one half
3	9.8	9.8		medium-grained, dense-textured, clear ripples	longitudinal; traverse ones coincident with ripples
4	9.31	9.31		medium-coarse grained, unini-form, unclear ripples	first longitudinal, then along weal plan planes
5	8.82	8.82		medium-grained, obvious bedding, with concretions	first expanding along the central axis, then along the bedding

Table 2

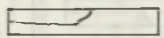
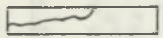
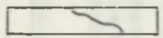
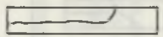
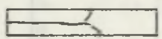
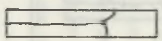
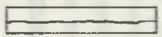
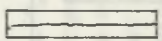
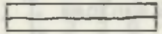
Specimen No.	Pb (MPa)	T (MPa)	Facture shape	Lithology	Facture description
6	9.11	9.11		medium-fine grained, dense-textured, uniform	longitudinal along central hole, traverse ones at bottom
7	8.82	8.82		medium-grained	longitudinal; traverse in the upper loaded portion
8	8.82	8.82		relatively coarse-grained	as with No. 5
9	4.9	4.9		upper fine, lower coarse	first longitudinal, then spreading along bedding
10	19.6	19.6		fine-grained dense-textured uniform	longitudinal along central hole; traverse at bottom
11	8.82	8.82		as above	as above
12	5.88	5.88		relatively fine-grained; weak planes throughout	longitudinal
13	14.7	14.7		as above	as above
14	14.7	14.7		fine-grained uniform	as above

Table 3

Specimen No.	Lithology	Comp. strength MPa	Elastic modulus 10^5 MPa	Tens. strenght MPa *	Poisson ratio
1	red sandstone	87.22	0.15	4.70	0.33
2	as above	85.75	0.12	2.14	0.2
3	as above	47.13	0.47	1.67	0.8
4	as above	27.34	0.13	2.67	0.12
5	as above	37.92	0.16	2.55	0.16
6	as above		0.14	2.45	
7	as above		0.14	2.68	
8	as above		0.14	1.82	
9	sandstone		0.14	2.48	
10	as above		0.14	2.68	
11	as above		0.14		
12	as above	86.53	0.35	2.42	
13	as above	86.53	0.35	2.42	
14	siltstone	65.95	0.35	1.84	

* The tensile strength is callculated by the Brazilian method.

tensile strength of rocks, with hydro-fracturing method as an attempt. However, the results of our experiments are not satisfactory, for the tensile strength values obtained are usually greater than those obtained by using the Brazilian method and by using the hadrofracturing/field-measuring method. The deffirence is yet to be accounted for. Here is the brief summary of our experiments:

The rock specimens used are cylindres out of rock cores, with the height between 10 and 12 cm and the diameter of 5.5 cm and 8.8 m. A hole 8-15 cm deep and 8 cm across is bored along the central axis of the specimen. And then a copper pipe welded with couplings is inserted into the hole. The hole opening is sealed with epoxy resin, for as long as 2 cm. The central pipe in the hole is connected through a highpressure rubber hose to the manual cilpump. The hydraulic pressures for facturing are read off the pressure gauge.

14 specimens are prepared for the experiments, of which No. 1 to No. 9 are red sandstone, cored from the boreholes specially for this purpose on the campus of Huainan Mining Institute, and No. 12 to No. 14 are grey sandstone, from the underground roadways of Kongji Coalimen of Husinan. Table 2 lists the breaking pressures of the specimens due to hydraulic fracturing (according to elastic theories, those values should be equal to those of tensile strength). Table 3 tabulized the values of tensile strength, compressive strength and elastic modulus, obtained through the Brazilian methoc, a conventional one. As shown in the above two tables, the values of tensile strength obtained through hydraulic frecturing are, quite out of expectation, times greater than those obtained through the Brazilian method or through the hydro-fracturing/field-measuring method. As far as the failure shape due to hydraulic fracturing is concerned, not only tensile fractures out also shear fractures occur. And there may be some resustances involed which are yet to be considered.

Recenzent: Prof. dr hab. inż. Mirosław Chudek

Wpłynęło do Redakcji w czerwcu 1988 r.

LABORATORYJNE DOŚWIADCZENIA HYDRAULICZNEGO PĘKANIA

S t r e s z c z e n i e

Technika hydro-łamania została ostatnio rozwinięta w metodę do mierzenia napięć skał. Jako taka ma ona tę zaletę, że pozwala uniknąć kłopotu z przerdzeniowaniem i nie mierzy odkształcenia w punkcie poprzez zastosowanie skomplikowanego oprzyrządowania. W celu zbadania mechanizmu hydraulicznego pękania (kruszenia) skał i dla potwierdzenia teroii hydraulicznego pękania, autor artykułu przeprowadził wiele doświadczeń hydro-łamania na próbkach skał i modelach.

Przedstawione są urządzenia użyte w tych doświadczeniach, jak i wyniki badań oraz ich analizy.

I. Urządzenie doświadczalne i metody obciążania (ładowania).
II. Symulacje hydro-łamania.
III. Doświadczenia hydro-łamania na blokach granitu.
IV. Doświadczenia hydro-łamania na próbkach piaskowca.

ЛАБОРАТОРНЫЕ ИССЛЕДОВАНИЯ ГИДРАВЛИЧЕСКОГО РАСТРЕСКИВАНИЯ

Р е з ю м е

Техника гидро-ломки за последнее время развилась в метод измерения напряжения горных пород. Она позволяет избежать хлопоты связанные с прорыванием и измерением деформации в точке с применением сложного оборудования. Для исследования механизма гидравлического растрескивания (крошения) горных пород и для подтверждения теории гидравлического растрескивания автор статьи произвёл ряд экспериментов по гидро-ломке на образцах горных пород и на модели.

В статье представлены устройства, которые были использованн в экспериментах, а также результаты исследования и их анализ.

I. Экспериментальное оборудование и методы нагрузки.
II. Симуляция гидро-ломки.
III. Опыт гидро-ломки на гранитных блоках.
IV. Опыт гидро-ломки на образцах песчаника.