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팩커를 이용한 공내재하 시험 방법 개발
Development of Packer-Dilatometer Method

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요약 / ABSTRACT

상업용 Packer를 이용하여 시추공내에서 암반의 변형율 측정 할 수 있는 Dilatometer방법을 개발하였다. 직경 0.5인치, AX, BX, NX 및 HX크기의 시추 공에서 사용 할 수 있는Packer-dilatometer를 개발하여 현장에서 암반 변형율을 측정하였다. 본 방법은 Packer에 의하여 시추 공 벽에 압력을 가하여 이때 발생된 암반의 변형을 Packer에 주입된 주입수의 양으로 측정하는 방법이다. 본 논문에서는 이방법의 이론적 해석, 장비, 시험방법 및 순서, Calibration 정수 산정을 위한 장비 및 방법, Contact pressure의 측정 및 이를 이용한 현장조사 결과에 대한 연구 내용을 기술 하였다

Packer-dilatometer techniques, which are borehole-dilatometer techniques using commercial rubber packer, were developed to measure the deformability of rocks. Packer-dilatometers for 0.5 inch, AX, BX, NX and HX size boreholes were developed and were used for rock deformability measurements in the field. In the packer-dilatometer method, the packer pressurizes the borehole-wall and the borehole deformation is determined by the amount of fluid injected into the packer. A detailed description of the theoretical development of quantitative interpretation of the packer-dilatometer method; apparatus, setup and procedures for the determining of calibration constants; contact pressure determination and field tests using the packer-dilatometer are provided.

Introduction

Rock deformability is an important parameter in the design of structures to be constructed on or within rock mass. The modulus value is necessary for numerical modeling, for bearing capacity and settlement calculations, and for stability analysis of underground and surface excavations.

The deformability, characterized by a modulus describing the relationship between the applied load and the resulting deformation, is determined by *in situ* testing and laboratory testing both statically and dynamically.

A number of borehole deformtion measurement devices has evolved during the last several decades to measure the deformability of rock in situ (Panek et al., 1964 ; Rocha, 1966 ; Goodman et al., 1968 ; Hustrulid and Hustrulid, 1972 ; de la Cruz, 1978 ; Yoon, 1986). These methods employ the application of a load to the walls of a borehole and the measurement of the response of the borehole wall. The devices are divided into three main categories : Borehole dilatometer, borehole jack and borehole penetrometer.

The most common borehole deformability testing methods are the borehole dilatometer and borehole jack tests. Borehole dilatometers are full circle radial expansion devices. Pressure is applied through an inflatable cylindrical probe placed down the borehole at the desired depth. The change in diameter is measured by either measuring the change in volume of the fluid and/or by using differential transformers.

The borehole packer-dilatometer techniques, which are borehole dilatometer techniques using commercial rubber packer, were developed to measure the deformability of rocks (Yoon, 1987). Packer-dilatometers for 0.5 inch, AX(1.88 inch), BX(2.38 inch), NX(3 inch) and HX(4.33 inch) boreholes were developed and were used for rock deformability in the field. The theoretical quantitative interpretation of the packer-dilatometer was developed on the basis the theory of the linear elasticity of a circular hole in an infinite plate under plane-strain conditions. In the packer-dilatometer method, the rubber packer pressurizes the borehole wall and the borehole deformation is determined by the amount of fluid injected into the packer. The volume of the fluid includes the deformation of the rock as well as the deformation of the instruments. The volume change due to expansion of the instrument was determined by the calibration constants using two calibration cylinders, in order to be able to determine the volume change due to the rock deformation alone. Also, the contact pressure of the packer between the borehole and packer-dilatometer was considered for the calculation of the modulus.

The borehole diameters of AX, BX, NX and HX used in this tests are common drillhole sizes. AX holes are used for exploration hole in mines. BX and NX holes are used for geological and civil site investigations. HX holes are used for petroleum exploration and hydrogeological investigations. Three inch boreholes are the type recommended by the American Society for Testing and Materials (1983) for site characterization. Further detailed information on the experiments and test results are in Yoons work(1987).

Theoretical Considerations of Borehole Packer-Dilatometer Deformability Measurement

The interpretation of borehole packer-dilatometer test results was developed from the Cylindrical Pressure Cell method of Panek et al (1965) who calculated the displacement of the borehole wall based on the linear elastic theory of a thick-wall cylinder without considering in-situ stress. In the packer-dilatometer method, the displacement of a borehole is considered a circular hole under the plane-strain condition in an infinite plate of elastic material, in order to express the borehole displacement under far-field stress conditions as the volume change.

Equation (1) is a fundamental relationship between the borehole radial displacement U and in-situ stresses(Jaeger and Cook, 1979, pp 253).

$$U = \frac{a(1-\nu^2)}{E}((S_1+S_2)+2(S_1-S_2)\cos 2\theta - \frac{P}{(1-\nu)} \tag{1}$$

Where : S1 : major principle stress
S2 : minor principle stress
a : radius of hole
r : radial distance
θ : Angle between the S1 direction
E : Young' s modulus
ν : Poissons ratio
P : Applied pressure

Since the principal far-field stresses are constant, the change in displacement (U) due to the pressure change (P) from P1 to P2, based on equation (1) is

$$\triangle U = \frac{a\triangle P(1+\nu)}{E} \tag{2}$$

This is the basic equation for determining the modulus with a circular hole, if Poisson's ratio is known. The packer-dilatometer method, however, measures volume changes resulting from pressure variations instead from the radial displacement. The change in the borehole volume ($\triangle V_r$) over the pressurized segment L when the pressure is varied from P1 to P2 is given by

$$\triangle V_r = \frac{2\pi La^2\triangle P}{E} \text{ or } \frac{\triangle V_r}{\triangle P} = \frac{\pi La^2}{G} \tag{3}$$

Thus, the modulus E and/or the modulus of rigidity G of the rock can be obtained directly from the borehole packer-dilatometer measurement if the pressure-volume relationship ($\triangle V_r$ / $\triangle P$) of rock is known ($E=2G(1+\nu)$).

The volume change in the borehole caused by expansion of the rock during internal pressurization, however, cannot be obtained directly from borehole-dilatometer measurements. Since the volume change measured includes the volume change of the rock and the expansion of portions of the apparatus-such as the dilatometer cell, pressure generator, high-pressure hoses and fittingsand the compression of the fluid. The correction factor that compensates for the volume change due to the apparatus is referred to as the "calibration constant." The volume changes in the packer-dilatometer test can be determined using

$$\frac{\triangle V_r}{\triangle P} = A\frac{\triangle V_d}{\triangle P} + B \tag{4}$$

Where,
$\triangle V_r$: volume change in the rock.
$\triangle V_d$: total volume change due to rock and apparatus.
A : constant coefficient-correct the volume change due to packer itself expansion.
B : the volume change due to compression of the fluid pressure generator, high-pressure hose, and auxiliary apparatus. B is a constant, since it does not depend on the type of rock tested.

A and B can be determined from the calibration tests run with two calibration cylinders. Thus, Young's modulus can be calculated by substituting equation (4) into equation (3),

$$E = \frac{2\pi a^2 L(1+\nu)}{A(\triangle V_d/\triangle P)+B} \tag{5}$$

Equation (5) is the basic relationship for the calculation of rock modulus.

Similarly, A and B can be determined using two calibration cylinders from following equation,

$$\frac{\Delta V_c}{\Delta P} = A(\frac{\Delta V_d}{\Delta P}) + B \qquad (6)$$

The volume change of the calibration cylinder (Vc) and the total volume change (Vd) can be determined experimentally. The material properties of the calibration cylinders are known.(Panek et al, 1965; Hustrulid and Hustrulid, 1972).

Based on the stress-displacement relationship of thick-wall cylinder, equation (7) gives the pressure-volume relation, in terms of the calibration cylinder's mechanical and geometric properties

$$\frac{\Delta V_c}{\Delta P} = \frac{2\pi aL}{E_c/R} \qquad (7)$$

Where,

$$R = a(\frac{1+a_2/b_2}{1-a_2/b_2} + v - \frac{2\nu^2}{b_2/a_2-1} - \frac{E_c\varepsilon_z}{P}) \qquad (8)$$

a=inner radius of the cylinder,

b=outer radius of the cylinder,

P=hydrostatic pressure, psi, against the inner wall of the cylinder.

ε_z=longitudinal strain,

E_c=Young's modulus of calibration cylinder,

ν =Poisson's ratio of calibration cylinder.

Substituting equation (7) into equation (6), gives :

$$\frac{2\pi aL}{E_c/R} = A(\frac{\Delta V_c}{\Delta P}) + B \qquad (9)$$

Equation (9) is a basic equation for the determination of calibration constants A and B. In the calibration tests, the E/R ratios are known. And equation (9) is solved for A and B. The calibration constants can be derived by substituting pressure, expressed in terms of turns (ΔT), into equation (9). Since this is a convenient method to measure the volume change-in terms of the number of turns of the pressure generator piston, rather than as an absolute volume. This gives :

$$\frac{2\pi aL}{E_c/R} = A(\frac{K}{m}) + B \qquad (10)$$

Where,

K=ΔV/T, volume change per turn. 0.00799 inch/turn for the 0.5 in. dilatometer and 0.1794 inch/turn for the AX, BX, NX and HX size dilatometers, and

m=slope of pressure-volume curve for the calibration cylinder.

Equation (10), from two calibration tests and calculation of the constant, can now be written as follows :

$$A = \frac{2\pi(a_1L_1R_1 - a_2L_2R_2)m_1m_2}{(M_b - M_a)K}$$

$$B = 2\pi a_1L_1R_1/E_1 - A(K/m_1)$$

Where,

a_1, a_2=radius of calibration cylinders 1 and 2.

R_1, R_2=R (see equation 8) of calibration cylinders 1 and 2.

L_1, L_2=effective lengths of calibration cylinder 1 and 2.

E_1, E_2=Young's moduli of calibration cylinders 1 and 2.

m_1, m_2=P/T-pressure-volume change relationship of calibration cylinders 1 and 2.

A and B, having been obtained from the calibration cylinders, are substituted in equation (9) to obtain the modulus of elasticity.

$$G=\frac{\pi arL_b}{B+A(K/M_r)}\ \text{or}\ E=\frac{2(1+\nu)ar^2L_b}{B+A(K/M_r)} \qquad (11)$$

Where,
M_b=slope of pressure-volume change of rock,
L_b=effective length in rock,
A_b=radius of rock.

Thus, this method requires following informations for the calibration and the calculation of Young's modulus of a rock;

A) From two calibration cylinders:
   1). Young's modulus and Poisson's ratio
   2). Inner and outer radii
   3). Pressure-volume relationship
   4). Axial strain
   5). Effective length of dilatometer cell
B) Pressure-volume relationship in the rock
C) Poisson's ratio of the rock.

Since the thickness of the packer-dilatometer cell is relatively large, the internal pressure of the packer-dilatometer has to be corrected to yield the contact pressure between the wall of the calibration cylinder.

The contact pressure can be determined from the axial and tangential strains of the outer surface of the cylinder, using the thick-wall cylinder solution under plane stress condition as follows.

$$Pi=\frac{E(b^2-a^2)(\varepsilon_\theta+\varepsilon_z)}{2a^2(1+\nu^2)} \qquad (12)$$

Where,
P_i=contact pressure,
a=inner radius of calibration cylinder,
b=outer radius of calibration cylinder,
ε_θ=tangential strain,
ε_z=axial strain, and

The contact pressure can be determined using equation (12) if the tangential- and axial-strains and the geometry of the cylinder are known. The tangential- and axial-strains for the contact pressure measurement is determined using strain gages. This has been described in the Section of contact pressure measurements.

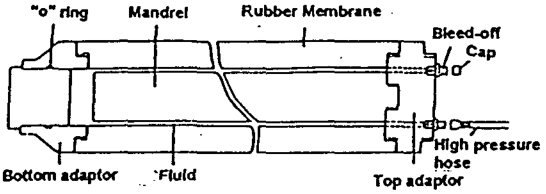

Fig. 1. A sketch of the modification of Packer elements.

Apparatus

The packer-dilatometer consists of a packer, a pressure generator, a pressure gage, a pressure transducer, a hand-pump and ancillary equipment. The commercial packers were used to contain the hydraulic fluid for pressurization of the borehole wall. A pressure generator and a hand pump are the pressurizing devices. The pressure generator piston is graduated allowing the estimation of the volume injected into the packer. A pressure gage and a pressure transducer sense the pressure. Followings are detailed descriptions of the apparatus used.

The commercial packer element is composed of a resilient rubber cover, braided-steel reinforcement, and an inner tube. Removable end adapters, a steel mandrel and proper fittings were attached to adapt the packer into a borehole-dilatometer (Figure 1).

1. Packer-dilatometers

Commercially available inflatable rubber packer elements (Lynes Co.) were used for field-testing.

Table 1 lists the packer sizes used in this study.

Table 1. Sizes of commercial rubber packers (Lynes Co).

Borehole	Packer	
Size	Outer dia.(inches)	Length(inches)
AX	1.375	48
BX	2.125	48
NX	2.75	48
HX	3.625	66

The top adapter threads into the packer element and provides both the mechanical connection to extension rods and the hydraulic connection to a high-pressure hydraulic hose. The bottom adapter is used only as a plug. The mandrel is a central solid steel shaft. The inflation line is the annulus between the dilatometer inner tube and the respective mandrel. The commercial packers can be pressurized up to 5000 psi(Lynes Co.). The ancillary equipment to complete the packer-dilatometer system consists of the following items :

1) A high pressure generator with vernier indicator, a pressure rating of 5000 psi, and a fluid capacity of 20 $inch^3$.
2) A pressure transducer rated at 0 to 5000 psi.
3) A bourdon pressure gage rated at 0 to 5000 psi.
4) A 15 feet flexible high-pressure hose rated at 12,000 psi burst pressure.
5) Short pieces of 1/4-inch outer diameter stainless steel high-pressure tubing.
6) A three-way, two stem high pressure valve.
7) High pressure fittings.
8) A hand pump.
9) An amplifier, power supply and digital multi-voltmeter.
10) A stopwatch

For tests conducted on laboratory sample, a miniature packer to fit 0.5-inch diameter holes was fabricated. It consists of a urethane tube molded to the specifications, a steel central shaft, and a steel ring. The ancillary equipment for the laboratory testing consisted of a low-volume pressure generator (0.67-$inch^3$ capacity). A 0.125 inch outer diameter tubing was used. Also, 1.5 feet long stainless tubing a small water hand-pump were used.

2. The 20-$inch^3$ Capacity Pressure Generator Development

The 20-$inch^3$ capacity pressure generator (Figure 2) was specially built for this research because the largest capacity of commercially available pressure generators is 3.7 $inch^3$, which is insufficient for field tests. The screw in this pressure generator is capable of 110 turns. It displaces 0.1794 $inch^3$ of fluid per turn.

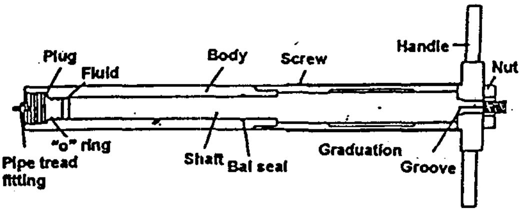

Fig. 2. A sketch of the pressure generator.

For the laboratory tests a small pressure generator of 0.67-$inch^3$ capacity (High Pressure Co.) was used and was 84 turns displacing 0.00799 $inch^3$ per turn.

3. Calibration Cylinders

Aluminum- and steel-hollow cylinders were used to calibrate the packer-dilatometers. The steel cylinders were ASTM 1040 for which

Young's modulus and Poisson's ratio are 30.3×10^6 psi and 0.29, respectively. The aluminum-cylinders were ASTM 2060 for which Young's modulus and Poisson's ratio are 10.3×10^6 psi and 0.33, respectively. The internal diameters of the steel-cylinders were approximately the same as the diameters of the drill boreholes. The outer- and inner-diameters, and length of the calibration cylinders used are given in Table 2.

Table 2. Size of the calibration cylinders.

Dilatometer	Calibration cylinder (inch)			
	Material	I.D	O.D	Length
0.5	aluminum	0.55	1.62	7
0.5	aluminum	0.565	0.75	7
0.5	aluminum	0.55	1.62	7
AX	steel	1.875	2	48
AX	steel	1.875	2	48
BX	aluminum	2.375	3.125	48
BX	steel	3	3	48
NX	steel	3	4	48
NX	aluminum	3	4	48
NX	aluminum	3	4	48
HX	steel	4	5.5	84
HX	aluminum	4.5	5.5	108

Experimental Setup for Calibration

1. Pressure vs. Volume Measurements

The calibration setup for the packer-dilatometer is shown in Figure 3. A hand-pump was used to fill the pressure generator. The dilatometer was inflated by turning the piston /screw mechanism in the pressure generator. The pressure was monitored by a transducer and a bourdon pressure gage. The displacement was monitored on the pressure generator in terms of volume per turn. The pressure transducer output was connected through an amplifier to a digital read-out. The experimental setup for the calibration of the miniature packer-dilatometer is similar to that of the larger packer-dilatometers, except that small size equipment was used.

2. Contact Pressure Measurements

The experimental setup for contact pressure measurements were the same as for the calibration setups described in previous section. The only difference was that strain gages were attached to the calibration cylinders. A 350 ohm rosette strain gage or two pairs of strain gages attached axially and laterally on the surface of the calibration cylinder and were used to determine the contact pressure of the dilatometer cell.

The deformation of the cylinder during the inflation of the dilatometer was recorded on an X-Y recorder in the form of pressure vs. strain. The contact pressure was calculated from the measured strains. Figure 3 shows the experimental setup for the determination of the contact pressure.

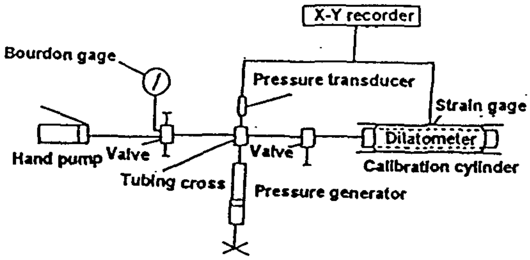

Fig. 3. Sketches of experimental setup for the calibration and contact pressure measurements.

Experimental Procedures

1. Dilatometers for the AX-, BX-, NX- and HX-holes.

Experimental procedure for the various size holes followed these steps :

1) The dilatometer was filled with oil, and the upper adapter was tightened.
2) The high-pressure flexible hose was connected and oil was pumped into the system with the hand-pump.
3) Oil was bled through the bleeding valve until the dilatometer was full.
4) Then the dilatometer was inserted into the calibration cylinder.
5) The whole system was pressurized up to approximately 1500 psi several times before the measurement started.
6) The system was pressurized to 900 psi and held for 20 minutes until the pressure was stabilized.
7) The pressure was increased using the pressure generator, and the pressure and number of turns were recorded. A 0.5 turn was added every 2 minutes for all the dilatometers except for the HX size dilatometer, for which a 1.5 turn adjustment was made eve 2 minutes, since it is a large packer.
8) The pressure was increased until around 1500 psi.
9) Then the pressure was released from the system.

2. Contact Pressure Measurements

Basically, the measurement of contact pressure is the same as the procedure for determining the pressure vs. volume relationship except that the pressurization was continuously increased in order to obtain a pressure-strain curve. The procedure for the measurement of contact pressures for the dilatometers was as follows :

1) Same as step 1) to step 6) in previous Section.
2) Pressure in the whole system was released.
3) Pressure-strain curves were recorded on the X-Y recorder as the pressure was increased from zero to approximately 2000 psi.
4) The contact pressures were calculated using equation (12).

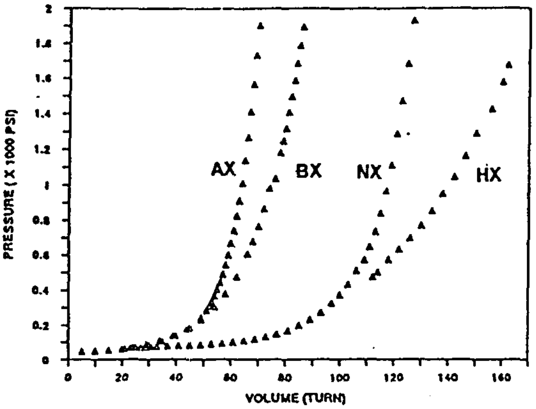

Fig. 4. The pressure-volume curves in the steel calibration cylinders.

Experiment Results and Discussion

1. Results of Pressure vs. Volume Measurements in Steel and Aluminum Calibration Cylinders

Pressure vs. volume curves in the steel cylinders were measured from approximately 40 psi to 2000 psi. Figure 4 shows typical pressure vs. volume curves for AX-, BX-, NX- and HX-dilatometers in the respective steel calibration cylinders. The curves show nonlinear relations at low pressures because of inflating of the system, e.g. the dilatometer, hoses and tubing, etc. The curves then become increasingly linear. The upper range of measurement was limited because of the capacity of the pressure generator, pressure limit of the 0.5-inch dilatometer, and the tensile strength of the rocks. And the most of the rocks used in this research have tensile strengths of less than 2000 psi. It was not necessary to withstand this high pressure.

Table 3. The linear pressure ranges for the various sizes of the packer-dilatometer in the steel cylinders.

Dilatometer	Linear pressure range(psi)	Coefficient of correlation(%)
0.5	300-1500	99.89
AX	530-1800	99.06
BX	531-1800	99.18
NX	610-1800	99.16
HX	600-1800	99.17

Table 3 shows the linear ranges of the pressure vs. volume curve in the steel calibration cylinder. The linear portion of the relationship was determined by linear regression. The span was shortened until the coefficient of correlation reached 99%. For most of the dilatometers, the range above 600 psi can be defined as linear. Pressure-volume calibrations were carried out for the every packer-dilatometer in the steel and aluminum calibration cylinders to determine the calibration constants A and B.

The results of pressure vs. volume measurements in the steel and aluminum calibration cylinders are shown in Table 4. The results show that the pressure change for the miniature packer-dilatometer is higher than that of the larger packer-dilatometer, since the ratio between the fluid volume injected by the pressure generator and the total volume of the fluid contained in the dilatometer is larger for the large dilatometer packers

The 0.5-inch-dilatometer shows 389.4 psi/turn for the steel cylinder and 403.45 psi/turn for the aluminum cylinder. The pressure change in the steel cylinder was lower than in the aluminum cylinder, since the steel cylinder diameter is thinner than that of the aluminum cylinder. The ratios between the inner and outer diameters are 1.16 for the steel cylinder and 2.95 for the aluminum cylinder.

Table 4. Pressure-volume measurements of calibration cylinders.

Dilato-meter (inch)	Material	Number of tests	Press.-vol. ratio(psi/turn*) average	corrected average
0.5	steel	5	389.31±5.44	
0.5	alum.	5	403.45±3.25	
0.5	alum.	5	363.24±5.85	
AX	steel	5	174.32±1.30	158.55±1.09
AX	alum.	4	144.26±5.30	134.17±2.02
BX	steel	5	137.24±2.59	129.28±2.18
BX	alum.	3	62.30±0.77	58.44±0.73
NX	steel	5	107.39±1.03	102.02±0.96
NX	alum.	4	96.01±2.15	90.92±2.04
NX	alum.	5	82.65±1.29	77.95±1.15
HX	steel	5	37.15±0.77	35.00±0.73
HX	alum	4	22.66±2.18	20.95±2.01

* 0.0079 in./turn for the 0.5 inch diameter dilatometer and 0.1794 in./turn for the AX, BX, NX and HX diameter hole dilatometer

The AX-hole packer-dilatometer increases 174.04 psi/turn and 142.25 psi/turn, in steel and aluminum calibration cylinders, respectively. The BX size packer-dilatometer increases 137.12 psi/turn and 61.92 psi/turn, in steel and aluminum calibration cylinders, respectively. The pressure vs. volume measurement in the aluminum cylinder is less than half of that in the steel cylinder, because the aluminum cylinder is thin and its inner diameter is much larger than that of steel cylinder. Consequently, such measurement yields a higher modulus value if the larger clearance calibration cylinder is used. For example, the results of modulus of BX-hole tests are higher than the other smaller hole test results

The NX-size dilatometer increases 107.73 psi/turn and 96.01 psi/turn for the steel and aluminum calibration cylinders, respectively. The HX size packer-dilatometer increases 37.16 psi/turn and 21.16 psi/turn for the steel and aluminum calibration cylinders, respectively. The larger fluid volume contained in the packer gives a smaller pressure increasing and a lower sensitivity.

The pressure measurements were repeated several times in order to determine whether the measured values were repeatable. In general, the test results, as shown in Table 4, were repeatable with a standard deviation of less than 6 psi/turn or 2% of the mean. There is a tendency that the first measurement values were lower than the subsequent values. They were not included in the calculations.

Additional pressure vs. volume measurements using the NX size dilatometer in the steel cylinder were performed about one month after the results in Table 4 were obtained. It was found that the mean pressure vs. volume was consistently 105.3 psi/turn, which is 2 psi/turn or about 2% lower than the earlier tests.

2. Contact-Pressure Measurements

The contact pressures were calculated by using Equation (14). The contact pressures were calculated from the tangential and axial strains at every 250 psi increment. The contact pressure of the 0.5-inch-diameter dilatometer shows no effect of the thickness of the dilatometer, since it is flexible and thin as compared with the packers.

In general, the contact-pressure were mainly influenced by the initial inflating pressure and size of the packer. Since the initial inflating pressure does affect the value of the pressure vs. volume ratio. The pressure-volume value should be determined by the ratio between the contact pressure and volume change, not the ratio between the gage pressure and volume change. The linear regression of the contact and gage pressures of the dilatometers are shown in Table 5, where Y is the contact pressure in psi and X is the gage pressure. Therefore, the values of pressure-volume measurements were corrected for the moduli calculated from the laboratory and field measurements.

Table 5. The linear regression of the contact pressures.

Dilatometer (inch)	Material	Linear regression Equation
0.5	aluminum	Y=X-95
0.5	steel	Y=X-83
AX	steel	Y=0.911X-112.6
BX	steel	Y=0.942X-117.2
BX	aluminum	Y=0.938X-132.5
NX	steel	Y=0.947X-126.6
NX	aluminum	Y=0.933X-127.9
HX	steel	Y=0.942X-128.7
HX	aluminum	Y=0.943X-138.0

2. Effective Length Measurements

Measurements of the effective length of the dilatometers were measured with different levels of internal pressure. Table 6 shows an example of the effective length measurement results. Most of the experimental results show that the effective lengths are larger than the original packer element length. But, when the ratio of the inner diameter of the calibration cylinder to the dilatometer diameter is larger than a certain value, the effective length becomes shorter than the original length. For example, the packer for the BX hole, which is 36 inches long, become 35.12 inches at 1000 psi inside the NX-inner-diameter aluminum cylinder, but becomes 37.11 inches at the same pressure inside the BX inner diameter.

Table 6. The effective lengths of NX hole Packers.

Steel(I.D 3 inch)		Aluminum(I.D 3.6 inch)	
Pressure (psi)	length (inches)	pressure (psi)	length (inches)
785	36.031	704.1	36.219
996	36.156	968.6	36.406
1119	36.156	1116.5	36.438
1390	36.172	1356.5	36.563
1503	36.375	1467.5	36.750
1742	36.406	1788.5	36.750

Table 7. Results of the calibration constants A and B, and calibration parameters.

Calibr. Cylinder	Axial strain (x 10^{-6})	Pressure-Volume (psi)	Effective length (inch)	Constant	
				A	B
0.5	-80	389.4	3.84	-3.983E-6	0.2150
0.5	-7.2	403.45	3.84		
0.5	-74	363.24	3.84		
AX	-8.7	158.55	36.98	-1.970E-4	0.1934
AX	-34.1	134.111	36.58		
BX	-11.8	129.28	37.11	-7.778E-5	0.8654
BX	-74.4	58.44	35.12		
NX	-11.7	102.02	36.49	-3.650E-2	0.2423
NX	-52.5	90.92	36.49		
NX	-104.4	77.95	36.16		
HX	-8.4	35.00	52.00	-8.7521E-2	0.1997
HX	-57.9	20.95	50.54		

The effective length changes less than 0.4 inches in the range of pressure from 900 psi to 1500 psi as shown in Table 6. The errors in the measurement of effective length do not significantly effect the results of rock modulus calculation.

4. Calibration Constants A and B of the Packer-Dilatometer

The calibration constants A and B for the packer dilatometers in Table 7 were calculated at a contact pressure of 1000 psi. The values of pressure vs. volume ratio are the slope of pressure vs. volume change with contact pressures between 750 and 1250 psi. The values of effective length and axial strain were calculated at a contact pressure of 1000 psi. The axial strains were determined during the measurement of contact pressure. An example of the moduli determination chart shown in Figure 5 is constructed using the constant A and B. Once the pressure vs. volume measurement is determined using the packer-dilatometer, the moduli of the rock can be obtained directly from the chart.

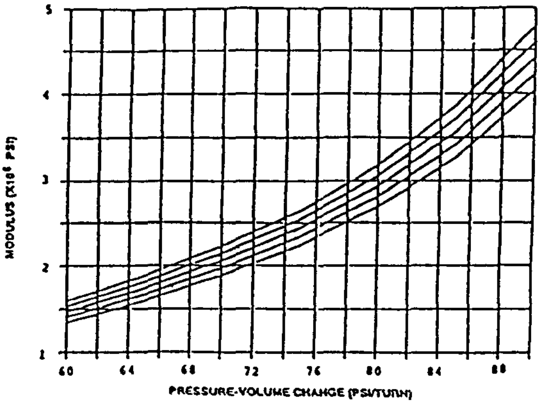

Fig. 5. Modulus determination chart with the NX dilatometer.

Field Measurements by the Packer-Dilatometer Techniques

Field tests were carried out using the developed packer-dilatometers in the Niagara dolomite at an abandoned quarry located in near Valders, Wisconsin, USA. Four boreholes for each of the AX, BX, NX and HX diameters holes, were determined the deformabilities within 8 feet from the surface.

1. Borehole Drilling

Vertical boreholes for the dilatometer tests were drilled using a Longyear 34 drilling machine and 4 different drilling bits (creating holes of AX, BX, NX and HX diameter). The locations of the test boreholes are shown in Figure 6. Sixteen boreholes, four holes for each size, were drilled in the floor of the quarry. The top two feet in the AX size holes (A-2, A-4) were drilled using a BX hole size bits. Thus, only the bottom part of the A-2 and A-4 holes were used for deformability tests. The locations of boreholes were selected based on the absence of jointing. The depth of boreholes was around 8 feet.

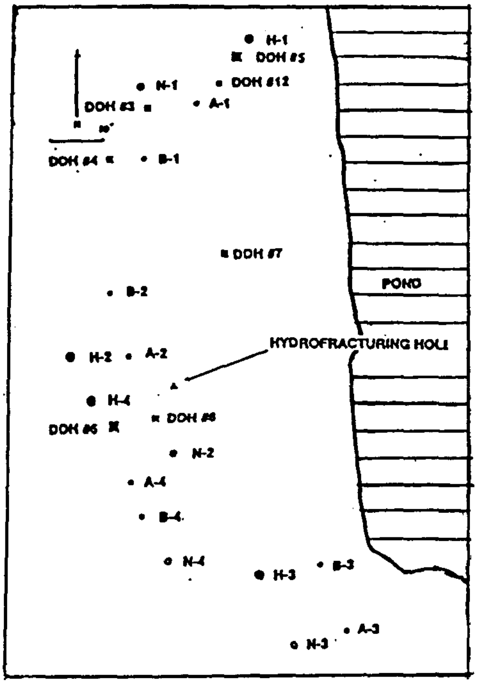

Fig. 6. Borehole locations.

2. Experimental Set-Up and Procedures

The experimental setup for the field tests is the same as shown in Figure 4. The apparatus consists of the packer-dilatometer gage, pressure generator (20-inch^3 capacity), a 15 feet long high-pressure· hose, hand pump, bourdon gage, pressure transducer and fittings. Dry batteries were used for the power supply for the pressure transducer.

The experimental procedures followed the same as the calibration tests. The system was initially pressurized to 900 psi using a hand pump. Then the pressure was increased in increments up to 1500 psi using the pressure generator. The rate maintained was 0.5 turns per 2 minutes for all dilatometer sizes Except the HX dilatometer for which increments of 1.5 turns were applied every 2 minutes. The pressure was monitored by a bourdon gage and pressure transducer (5000 psi). The pressure was calculated from the voltage output.

3. Field Test Results and Discussion

The pressure-volume relationship between contact pressures of 750 psi and 1250 psi (Gage pressure 900 to 1500 psi) was used to calculate the deformation modulus. The pressure range was limited because the strength of the dolomite is 2250 psi. The in-situ moduli measured by the packer-dilatometer were at around 50% of the tensile strength of the rock. Deformation moduli are summarized together with RQD information in Table 9.

The average modulus for the AX hole is 2.363

Table 9. Field test results of the moduli determination.

Hole No.	A-1	A-1	A-1	A-2	A-2	A-3	A-3	A-3	A-4	A-4		
Depth(inch)	6-43	30-76	50-87	40-77	40-77	10-47	40-95	58-95	40-77	40-77		
Press./Turn(psi/turn)	124.722	110.790	121.950	131.650	130.630	96.474	123.844	117.114	120.312	126.480		
Modulus(x10 psi)	2.537	1.863	2.381	2.990	2.917	1.377	2.486	2.137	2.295	2.643		
R.Q.D(%)	85.810	70.850	71.220	100.000	-	77.030	100.000	100.000	79.050	-		
Hole No.	B-1	B-1	B-2	B-2	B-2	B-3	B-3	B-3	B-4	B-4	B-4	
Depth(inch)	8-45	8-45	4-45	20-37	42-79	5-42	30-47	42-79	4-41	25-62	50-87	
Press./Turn(psi/turn)	90.895	90.549	97.947	80.482	90.868	69.130	72.800	93.340	72.805	81.920	90.800	
Modulus(x10 psi)	3.481	3.458	3.977	2.843	3.479	2.252	2.433	3.647	2.433	2.926	3.475	
R.Q.D(%)	87.840	-	91.890	95.950	100.000	85.810	85.810	100.000	73.650	74.320	82.430	
Hole No.	N-1	N-1	N-1	N-2	N-2	N-2	N-3	N-3	N-3	N-4	N-4	N-4
Depth(inch)	6-43	30-67	50-87	6-67	25-65	50-87	6-43	30-67	43-80	3-40	24-61	44-81
Press./Turn(psi/turn)	82.962	78.183	74.139	68.340	74.274	72.980	72.938	76.191	81.381	66.162	57.402	75.924
Modulus(x10 psi)	2.555	2.171	1.892	1.577	1.908	1.830	1.827	2.030	2.419	1.472	1.105	2.014
R.Q.D(%)	100.000	86.500	91.900	78.400	86.500	91.900	100.000	100.000	83.700	85.100	93.900	100.000
Hole No.	H-1	H-1	H-2	H-2	H-3	H-3	H-4	H-4				
Depth(inch)	16-67	16-67	20-71	20-71	17-68	17-68	21-72	21-72				
Press./Turn(psi/turn)	21.937	22.640	18.245	18.720	22.940	22.590	21.558	21.937				
Modulus(x10 psi)	1.930	2.060	1.367	1.430	2.118	2.051	1.863	1.930				
R.Q.D(%)	94.230	-	-	-	100.000	-	-	-				

x 106 psi with a maximum of 2.990 x 106 psi (A-2, 31 to 68 inch) and a minimum of 1.377 x 106 psi (A-3, 6 to 43 inch). The average modulus for the NX hole is 1.904 x 106 psi with a maximum of 2.55 x 106 psi (N-1, 6 to 43 inch) and a minimum of 1.105 x 106 psi (N-4, 18 to 55 inch). The average modulus for the HX diameter hole is 1.844 x 106 with a maximum 2.118 x 106 psi (H-1) and a minimum 1.317 x 106 psi (H-2).

The measurements were repeated twice in the A-1, B-1, H-1 to H-4 holes. The moduli differences were obtained with 9.96 % (A-1), 1.62 % (B-1), 3.4 % (H-1), 2.35 % (H-2), 2.59 % (H-3) and 1.85% (H-4).

The variation of the standard deviation indicates that the borehole packer-dilatometer techniques give consistent results in the field as well as the laboratory.

Advantage and Disadvantage of the Packer-Dilatometer over Other Dilatometer Techniques

The borehole packer-dilatometer technique has an advantage of simplicity, availability, and inexpensiveness in making the packer-dilatometer. Various sizes of packer element are available commercially. Thus, one can make the device easily. One need not build a mold for the dilatometer cell as in the Colorado School of Mine cell method (Hustrulid and Hustrulid, 1972) nor build an attachment for the L.V.D.T and wire line channel as in the L.N.E.C method (Roch et al, 1970).

Since the contact pressure at the borehole wall and calibration constants from two calibration cylinders are considered, this method is probably more accurate than other dilatometer techniques. None of the other dilatometers consider contact pressure between the device and the borehole wall. Ignoring contact pressure, which can give higher rock deformation values since the internal pressure, is taken into account as being the same as the pressure at the borehole.

The rock volume involved in the packer-dilatometer· test is larger than that in the C.S.M cell, C.P.C method or L.N.E.C dilatometer method so that the modulus determined using this device can be more representative. The length of the packer-dilatometer (for NX diameter hole) is 36 inches, which is twice as long as the others are. Thus, this method can represent the deformability of twice as much volume of rock mass. Also, This method can be used at a great depth if it is required, since a flexible high pressure is used. The C.S.M cell method has a limitation of 50 feet in depth because stiff stainless steel tubing is used. This method can be used in the field in conjunction with hydrofracturing stress measurements, since the equipment and borehole size for the both measurements are very similar. The packer-dilatometer method is good for the low deformation modulus rocks which gives a larger volume change than the high modulus rocks. Also, this method may be less sensitive than the C.S.M cell or the L.E.N.C method, since a large volume of fluid is involved in this method. It takes longer to measure, since the time interval between the measurement is longer. The strength of rock higher than 5000 psi cannot be measured in this method, since the packer-dilatometer can only sustains 5000 psi.

Conclusion

1. The borehole packer-dilatometer techniques can be used for the determination of rock modulus economically using a commercial packer with a simple modification. The pressure-volume ratios of the steel and aluminum calibration cylinder were determined with less than a 5% of differences by the developed packer-dilatometers. Also, Young's moduli for the steel- and aluminum-calibration cylinders were determined by the packer-dilatometers as part of a verification of the calibration constants A and B with less than a 5% error Therefore, the borehole packer-dilatometer techniques using calibration constant A and B from the two calibration cylinder, is reliable. However, the determination of linear range and contact pressure of the packer-dilatometers indicates that the modulus of rocks can be determined in the range of above 500 psi, since the initial inflating pressure is required to be the linear pressure-volume increase of the devices. Further, larger sizes of borehole-dilatometers can be developed with a large capacity of a pressure generator.

2. The borehole packer-dilatometer devices are simple to use and to build, easily available commercially and inexpensive to build and test. Also, the tested volume by this method is twice as large as the conventional dilatometers; it represents more rock mass. This method is good for the low modulus rocks since the volume

change due to the rock displacement is large and takes about one hour to measure one test.

3. The in-situ moduli of Niagara dolomite, in Valders, Wisconsin with the packer-dilatometer techniques for the AX, NX and HX diameter holes vary from 1.105 to 2.990 x 106 psi with an average of 2.132 x 106 psi. The high modulus values were obtained in the region where R.Q.D and joint spacing are high while low values are obtained in the region where the long vertical cracks and large horizontal joint are present.

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