The Effect of Stress on Borehole Deformability
응력이 공내 변형률에 미치는 영향

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요 지

초기수평 응력상태를 모사하여 응력이 변형계수에 미치는 영향을 검토 하기 위하여 암석 시료에 대하여 공내재하 변형 실내시험을 했다. 실험은 수평 응력의 크기, 응력비, 측정지점을 변화 시켜서 변형계수를 측정하였다. 측정결과 응력의 크기가 증가함에 따라 변형계수가 증가하며 최대:최소응력비가 커짐에 따라 변형계수는 최소응력 방향에서는 증가하고, 최대응력 방향에서는 감소하는 경향을 보였다. 이는 측정 위치에서 접선응력의 크기 변화에 따른 것으로 초기응력의 크기, 방향 및 내압의 크기에 따라 응력이 압축, 인장 또는 압축-인장상태로 바뀌기 때문이다. 따라서 변형 계수 측정 시 이들의 영향을 분석한 후 결과치를 해석하여야 한다. 이와 같은 해석은 공내재하 변형 측정 결과 뿐만 아니라 내압이 있는 가스 저장 또는 압축터널 설계 및 터널 계측 결과 해석에도 적용되어야 한다.

Abstract

Modulus measurements in vertical boreholes under simulated horizontal in-situ stress conditions were performed on laboratory rock specimens. The experimental program was focused on the examination of modulus change with the variation of the orientation, magnitude and ratios of horizontal biaxial stresses. The experiment results show that the modulus increases when the magnitude of the horizontal stresses increases. The modulus measured in the minimum principal direction increased when the ratio between the horizontal principal stresses increased, while the modulus measured in the maximum principal direction decreased when the ratio of the horizontal principal stresses increased. These were caused by the tangential stresses that vary depending upon the magnitude of horizontal stresses, the applied pressure and the orientation of measurement. Also, the measured moduli were determined under tensile stress, compressive stress, or both stresses. Thus, the stress effect on deformation modulus should be considered, not only for the interpretation of the results of borehole deformability measurement, but also for the design of underground gas storage and pressure tunnel, and for the interpretation of tunnel monitoring.

Keywords : Stress effect, Modulus, Rock deformation, In-situ stress, Borehole test

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1. Introduction

The purpose of this laboratory experiments was an examination of varying in situ (far-field) stress levels on the magnitude of deformation moduli. A number of modulus measurements in vertical holes under simulated non-equal and equal horizontal principal stress conditions were performed on laboratory specimens of five rock types. Both the strain gage and the borehole packer dilatometer techniques were used.

The deformation moduli under a variety of horizontal stress conditions were examined since current interpretation of rock modulus from borehole tests ignores the effect of in-situ stress. (Panek et al., 1964, Goodman et al., 1968; Rocha et al., 1970; Hustrulid and Hustrulid, 1972; Yow,1993). Modulus calculations for borehole deformability tests have been obtained by using the theory of linear elasticity for thick wall rock cylinders under internal pressure, without considering the in-situ stresses. This is a fair approximation as long as in-situ stresses are zero, but this is rarely the case in practical situations. Thus in-situ stress condition should be considered in borehole deformability results because the stress affects the modulus in rock as induced by the typical non-linear stress-strain curve obtained under uniaxial compression and by the over steepening stress-strain curves in triaxial tests as the confining pressure increases. It is known from various sources that modulus of rock increases under compressive stress (Uniaxial test :Adams and Williamson, 1923; Walsh, 1965; Brace, 1969; Haimson, 1978, Triaxial test : Koopman, 1986, Biaxial test : Yoon, 1987). Adams and Williamson suggested that the modulus variation was due to cracks or pores in the intact rock, formed before the rock was stressed; this suggestion is now widely accepted (Brace, 1974). These cracks increase the compliance of the rock. As the confining pressure in a triaxial test is raised, the cracks begin to close, the modulus increases, and the stress-strain curve becomes steeper. When the pressure has closed all the cracks, the curve becomes linear because the behavior of the rock is nearly perfectly elastic. Walsh reported that one or more kilobars were required to close the microcrack in intact rock. Brace (1974) and Haimson (1978) reported modulus variation, in uniaxial tests, for Westerly granite: the modulus increased gradually as the stress level is raised from tension into compression (Figure 1). The interpretation of a calculated modulus in a borehole test should therefore take account of in-situ stress conditions. The stress in a borehole varies from $3S_1-S_2-P$ at S_2 to $3S_2-S_1-P$ at S_1, where S_1 and S_2 are the maximum and minimum horizontal principal stresses, and P is the applied borehole pressure of the test device. The stresses will typically increase when the depth of a borehole increases. Recently, Koopman et al., (1986) determined the stress effect on the modulus of granite, sandstone, and limestone in a borehole. The moduli were determined, under triaxial stress conditions in the laboratory, for 3.8 cm(5-inch) boreholes in 30.5 cm(12-inch) cubic block. The results show that the modulus increases as the confining pressures increase. They concluded that the moduli are affected by the stress. The stress condition in the field, however, is rarely one of hydrostatic stress condition

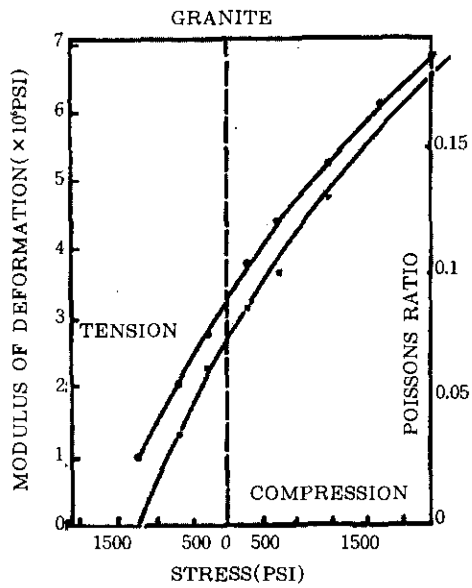


Figure 1. Modulus of Westerly Granite in uniaxial test (After Brace, 1969)

In this investigation, therefore, the moduli were determined under various magnitudes and ratios of the far-field stress. The experiment was limited to intact rocks and rock with one vertical joint. If the results of this experiment could indicate the effect of in situ stress on the modulus, it could also help to interpret borehole deformability measurements of rock masses. The moduli of rock masses can be affected more by the in situ stress, since they are more deformable than intact rocks. The experimental program was focused on the examination of modulus change with the variation of the orientation, magnitude and ratio of horizontal stresses.

2. Specimens

2.1 Rock Types

A brief description of the rock types tested is as follows. Berea sandstone is a light gray, loosely cemented, medium grained sandstone. It is a permeable, porous rock of low compressive strength. It is composed of quartz and feldspar with chert matrix. The grains are anhedral to subhedral. Indiana limestone is a whitish gray, medium grained, fossiliferous limestone containing oolite and shells of carbonate materials in calcite matrix. Valders dolomite is whitish light gray, compact, and laminated. The minerals are predominantly dolomite, with accessory chert, calcite and clay. Montello granite is coarse grained and brownish red. It is composed of orthoclase, plagioclase, quartz, and a few mafic minerals. The grains are anhedral and subhedral. Dresser basalt is dark grayish green. The minerals are plagioclase and pyroxene, with chlorite, magnetite and sericite. The grains are subhedral to anhedral. The uniaxial compressive modulus and Poisson's ratios of five rock types are given in Table 1.

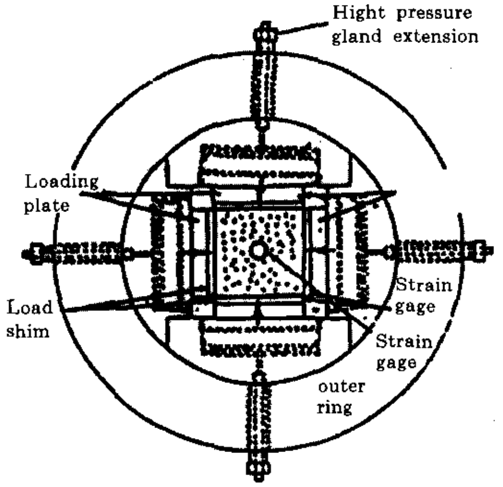
Table 1. The properties of compressive modulus and Poisson's ratio

Rock type	No. of specimen	Compressive Modulus($\times 10^5$kg/cm^2)	Poisson's Ratio
Dresser basalt	3	4.429 (0.065*)	0.19 (0.04*)
Valders dolomite	5	4.157 (0.108)	0.23 (0.06)
Montello Granite	3	5.032(0.100)	0.17 (0.05)
Indiana Limestone	3	2.437 (0.093)	0.14 (0.06)
Berea sandstone	3	1.311 (0.053)	0.19 (0.12)

*: Standard deviation

2.2 Specimen Preparation

A 1.2cm(0.5 inch) diameter borehole in a 12.7(5 inch)×12.7(5 inch)×17.8(7 inch) cm cubic rock was considered to be large enough to simulate a field test borehole. The ratio between the 1.2-cm-diameter borehole and the width of the 12.7×12.7×17.8 cm specimen was assumed sufficient to simulate a hole in the infinite medium. The stress distribution around a borehole was considered with the external stress of zero: the radial and tangential stresses decrease by $1/r^2$, where r is the radial distance from the center. The specimens were prepared from rough surface cubic blocks by trimming with a diamond saw. The sides were ground to yield faces parallel, within 0.005cm. A 1.2-cm diameter borehole was drilled axially through the center of each block with a diamond bit. For the strain gage method a 350-ohm strain gage was bonded to the borehole wall at mid-depth. Some artificially jointed specimens for the packer dilatometer tests were prepared by fracturing the rock in the polyaxial chamber.



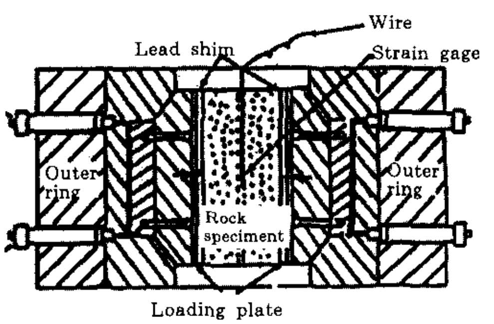


Figure 2. Experimental apparatus and setup

3. Experimental setup

The borehole dilatometer setup shown in Figure 2 was used with a servo-controlled polyaxial chamber. Figure 2 shows plane and vertical cross sections of the polyaxial cell. The polyaxial cell can accommodate rock specimens of sizes up to 13.3(5.25 inch)×13.3(5.25 inch)×17.8(7 inch)cm. It has four independently actuated pistons for the application of two unequal lateral loads to a prismatic specimen. The pistons are round inside of the cell housing to facilitate proper fitting and "O"-ring sealing, but are rectangular outside. Different platens can be used to accommodate specimens of various sizes. Pressures up to 2,100 kg/cm^2 can be applied to each of the four pressure chambers inside the cell. This translates to pressures up to 1,400 kg/cm^2 on the specimen. The pressures in the polyaxial cell were controlled by the servo-control unit (MTS machine).

4. Experimental Procedures

The specimens were placed in the polyaxial cell in positions equidistant from the retracted loading platens. Aluminum and lead shims were inserted between the platen and the specimen sides in order to reduce friction and uneven loading. The cell rested on a loading machine. External horizontal loads were applied by the polyaxial cell, simultaneously pressurizing opposite pairs of loading platens, through a servo-controlled unit. After the specimen had been positioned and secured by the shims, two horizontal, mutually perpendicular loads were applied simultaneously and gradually raised until the predetermined value of the minimum principal horizontal stress was reached. The predetermined maximum horizontal pressure was applied. The two horizontal loads, simulating the two principal stresses in the rock, were kept constant during the test. Then, by inserting a packer dilatometer into the borehole started the borehole deformation test. The borehole pressure was raised to 52.5 kg/cm^2 for the sandstone and limestone and to 70 kg/cm^2 for the granite, basalt, and dolomite, by inflating the packer dilatometer using a pressure generator (11 cm3 capacity). All pressures were monitored by pressure transducers, and were recorded. The pressure, tangential strain and number of turns of the pressure generator were recorded depending on the method used. Table 2 gives the ranges of horizontal stresses, applied pressures, and strain gage positions for the rock types tested by the strain gage method. The most common horizontal stresses ratios in the field (Wontokin et al, 1967; Haimson, 1983; 윤건신, 1992) were selected. The pressure applied by the packer-dilatometer method was limited by the tensile strength of each rock. The orientation of the strain gage was selected at the maximum, minimum, and average stress-concentration positions, i.e., in the direction of the minimum horizontal principal stress (S_2), in the direction of the maximum horizontal principal stress (S_1) and at 45° from S_1. Most measurements were carried out from high horizontal pressure to low horizontal pressure, in order to prevent the breaking of the rock by the pressure applied in inflating the packer dilatometer.

Table 2. Applied pressure, ratios of horizontal principal orientations of strain gage of the strain gage method

Rock Type	Applied Presure(kg/cm^2)	Ratios of S_1/S_2	Strain gage orientation
Montello granite	70	1, 2, 3	S_1 and S_2
Dresser basalt(#1)	70	1, 2, 3	S_1 and S_2
Dresser basalt(#2)	70	1, 2, 3, 5, 10	S_1
Valders Dolomite(#1)	70	1, 2, 3	S_1
Valders Dolomite(#1)	70	1, 2, 3, 5, 10	45°
Berea Sandstone(#1)	52.5	1, 2, 3	S_1
Berea Sandstone(#2)	52.5	1, 2, 3	S_1 and S_2
Indiana Limestone(#1)	52.5	1, 2, 3	S_1
Indiana Limestone(#1)	52.5	1, 2, 3	S_1

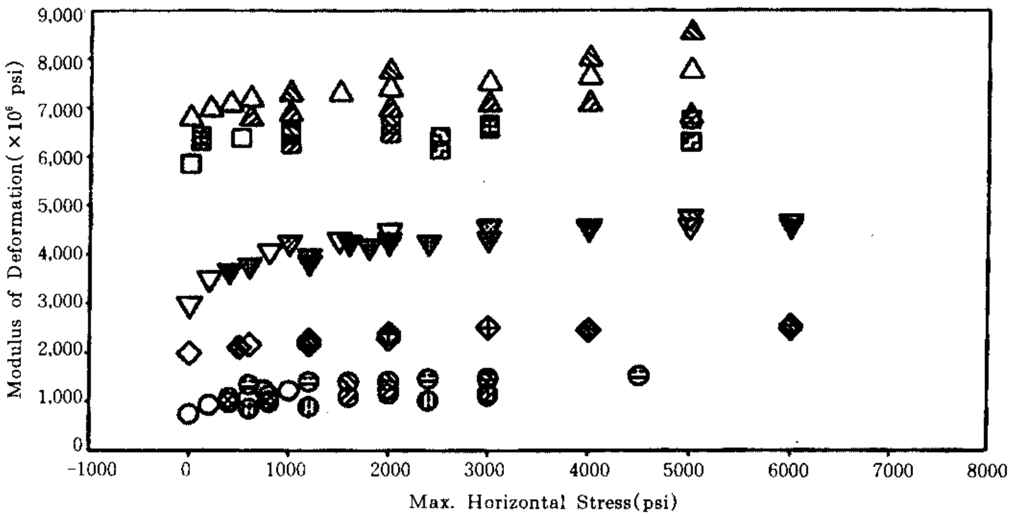
5. Experimental Results and Discussion

Moduli were determined for 1.2-cm diameter boreholes in the rectangular specimen, using 5 rock types under various biaxial stress conditions. Two techniques were used: the packer dilatometer method and the strain gage method. The former method provides an average modulus around the borehole wall, like that provided by the Colorado School of Mine cell (Hustrulid and Hustrulid, 1972). While the latter method provides moduli reflecting various orientations of horizontal principal stresses, like those provided by borehole-jack methods (Goodman et al, 1965; de la Cruz, 1976).

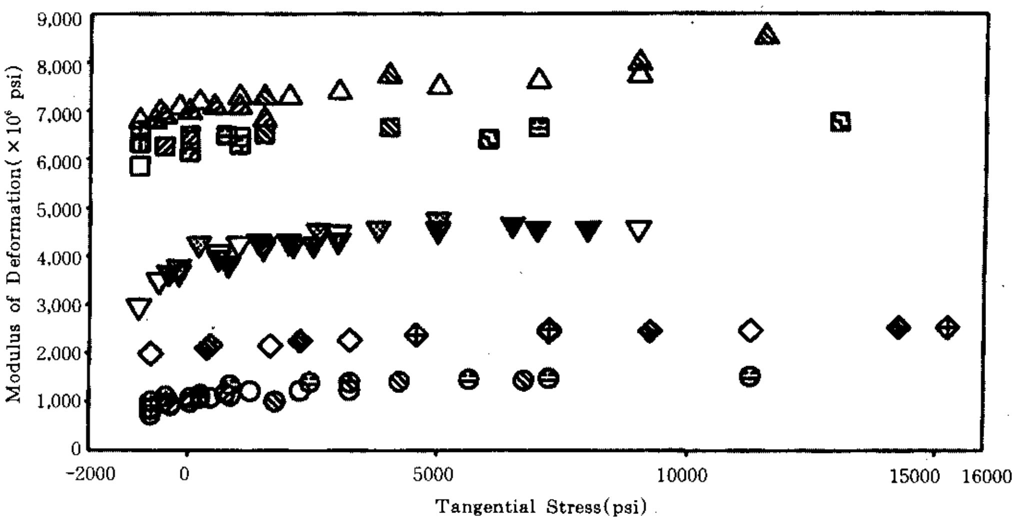
5.1 Intact rock tests by strain gage method

The results of the modulus determined by the strain gage method are shown in Figure 3. The results have been interpreted using Equation (1) and the Poisson's ratio as determined from the uniaxial testing (Table 1). Examples of pressure-strain curves of rocks are shown in Figure 4. They show qusi-linear curves. These pressure-strain curves maintained the same shape under various horizontal stress conditions throughout the tests.

The results from all the tested specimens show that the modulus of deformation increases as the magnitude of horizontal stress increases. For example, the moduli of deformation of basalt, granite and sandstone at S_1 increase when the magnitude of the horizontal stresses increase. Also the moduli of basalt, dolomite, sandstone and limestone at S_2 increase when horizontal stresses increase. The modulus of dolomite at 45° from the principal stress also increases when the horizontal stresses increase. When the moduli were measured at the S_1, the magnitude of the modulus decreases when the ratio of horizontal principal stresses increases. When the moduli were measured at the S_2 direction, the modulus increases when the ratio of horizontal principal stresses increases. Also, the modulus of the dolomite at 45o decreases when the horizontal principal stress ratio increases as shown in Figure 3. The moduli of granite, basalt and sandstone show that the modulus gives higher value at the S_2 than at the S_1 under the same horizontal stress ratio and magnitude.



(a) The modulus change with the maximum horizontal stress change



(b) The modulus change with the tangential stress change

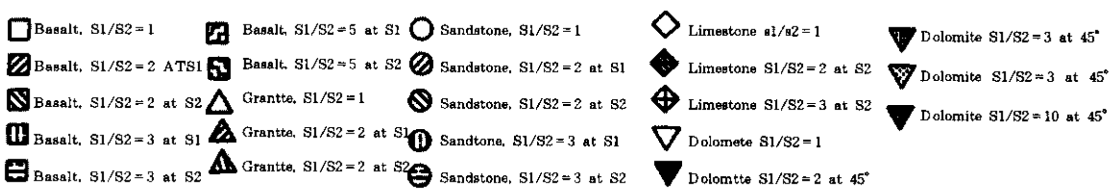


Fig.3 The results of moduli of intact rock under biaxial stresses with various magnitudes and orientation

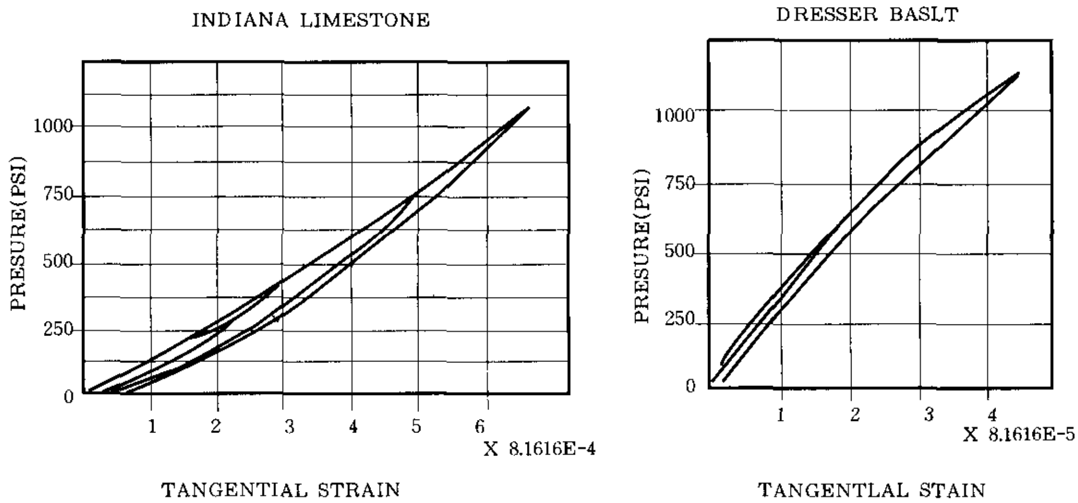


Fig.4 Typical stress-strain curves of the tested rocks

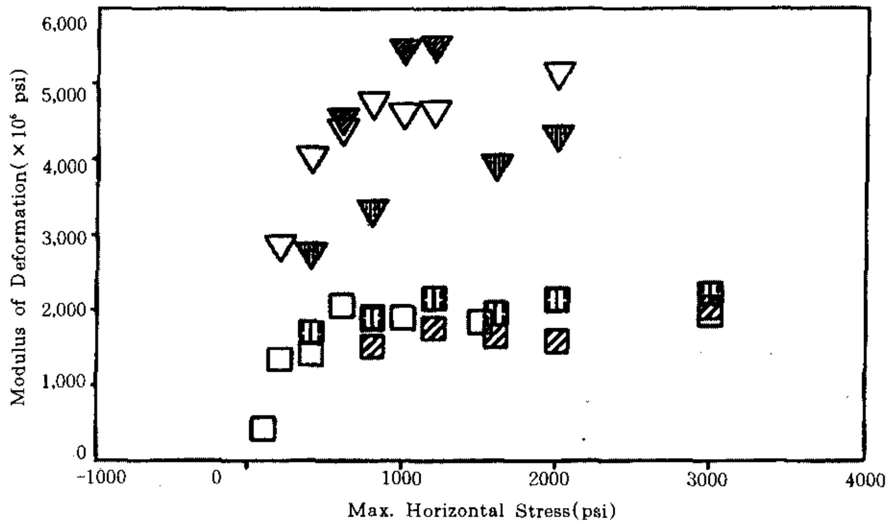
5.2 Jointed rock test by packer dilatometer method

Modulus for the vertically and artificially jointed rocks of Valders dolomite and Dresser basalt was determined by using the packer dilatometer. Fig. 5 is plots of the moduli of deformation for the jointed rocks when S_1 and S_2 are parallel to the vertical joint direction with horizontal stress ratios of 2. The moduli results are scattered but show the increasing of the moduli when the magnitude of the horizontal stresses increase. The moduli determined when the joint plane is parallel to the S1 are lower value than the value obtained when the joint plane is parallel to the S_2. The modulus of the joint basalt which was determined under the horizontal stress of $7kg/cm^2$, is $2.95 \times 10^4 kg/cm^2$ which is three times lower than that of $14kg/cm^2$ as shown in Figure 5. This indicates that the moduli can be much lower at the surface where the in-situ stresses are small.

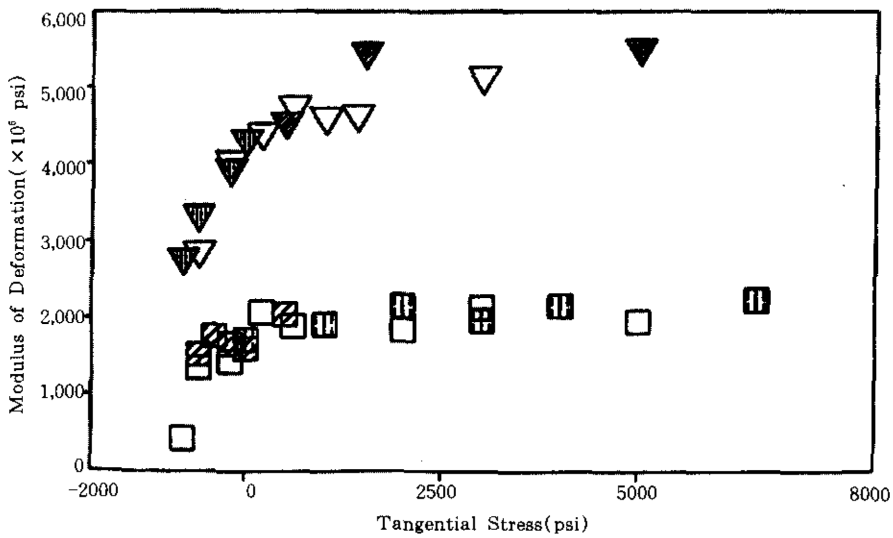
5.3 Discussion

The moduli results of the Montello granite, Dresser basalt, Valders dolomite, Indiana limestone and Berea sandstone increase when the tangential stress increases, and decrease when the tangential stress decreases as shown in the lower part of Figure 3. The tangential stresses were calculated at the applied pressure of $70kg/cm^2$ for the granite, basalt and dolomite, and 52.5 kg/cm^2 for the sandstone and limestone. Followings are the further explanation of the tangential stress and modulus relationships. The following equation is the basic calculation equation of modulus from the borehole strain gage tests,

$$E = \frac{P(1+v)}{\varepsilon_\theta} \qquad (1)$$



(a) The modulus change with the maximum horizontal stress change



(b) The modulus change with the tangential stress change

Fig. 5 The results of moduli of jointed rock under biaxial stresses with various magnitudes and orientations

Where: E is the modulus, ε_θ is the tangential strain, P is the applied stress, and ν is Poisson's ratio.

The above equation does not include the principal stresses since they are constant in the natural condition, but the state of stress changes around the borehole due to the applied pressure as shown in the following equations. According to the stress-strain relationship in cylindrical coordinates:

$$\varepsilon_\theta = \frac{\sigma_\theta - \nu\sigma_\gamma}{E} \tag{2}$$

Where: σ_θ is the tangential stress, $S_1+S_2-2(S_1-S_2)\mathrm{Cos}2\theta-P$, σ_γ is the radial stress and P is the applied pressure.

Equation (2) shows that the modulus and tangential strain are dependent. The strain variation is related to the principal horizontal stresses. The tangential stress increases the tangential strain proportionally, but the tangential strain varies nonlinearly because of the presence of the defects in rocks. The nonlinearly is influenced by the stress, which causes the modulus variation. For example, the tangential stress at S_1 is $3S_2-S_1$ before the borehole test. But when the pressure (P) is applied by the borehole test device such as platen or dilatometer, the tangential stress becomes $3S_2-S_1-P$. The tangential stress at S_2 is $3S_1-S_2$ before the test and becomes $3\ S_1-S_2-P$ during the test. The stress difference is the applied stress due to the borehole expanding pressure. The stresses can change from compressive into tensile depending upon the magnitude of in-situ stress and applied pressure. The calculation of modulus for the borehole test is a simple calculation equation but the results should consider the stress path due to the borehole tests. Equation (2) shows that the modulus is mainly affected by the tangential stress, which varies in a hole from $3S_2-S_1-P$ when θ is 0° or 180° to $3S_1-S_2-P$ when $\theta=90°$ or 270°.

The following cases can be considered:

1). Compressive stress only occurs when $P < 3S_2-S_1$.

2). Tensile stress only occurs when $P > 3S_1-S_2$.

3). Both compressive and tensile stress occur when between $3S_1-S_2 < P < 3S_2-S_1$.

Table 3. Tangential stresses at 0°, 45° and 90° from the maximum horizontal principal stress direction under various ratios of horizontal principal stresses.

S_1/S_2 Ratio	Orientation		
	0° (S_1)	45°	90° (S_2)
$S_1/S_2=1$	2 S_1	2 S_1	2 S_1
$S_1/S_2=2$	0.5 S_1	1.5 S_1	2.5 S_1
$S_1/S_2=3$	0	4/3 S_1	8/3 S_1
$S_1/S_2=5$	−0.4 S_1	1.2 S_1	2.8 S_1
$S_1/S_2=10$	−0.7 S_1	1.1 S_1	2.9 S_1

Table 3 gives the variation of tangential stress at the borehole wall in the direction of S_1, S_2 and 45° between S_1 and S_2 when the ratio of horizontal principal stress is 1, 2, 3, 5 and 10. The table shows that the tangential stress at a borehole wall increases when the orientation changes from the S_1 to S_2 directions. Also tangential stress at the S_2 always increases when the ratio of horizontal principal stress increases, while the tangential stress decreases at S_1 and 45° directions when the ratio of the horizontal stress increases. The tangential stress at 45° and 135° are always an average tangential stress around the borehole as shown in Table 3. Since the stress in a borehole varies from $3S_2-S_1$ to $3S_1-S_2$, the modulus varies with the orientation of the maximum principal stress direction accordingly. The modulus is lowest in the S_1 and highest in the S_2 direction. And the modulus at 45° is always the average of the moduli at S_1 and S_2 direction, which is the value obtained by the packer dilatometer measurement. And the modulus increases when the magnitude of the horizontal principal stresses is increasing. Also, as the ratio between the horizontal stresses increases, the modulus at S_1 decreases since the stress at S_1 decreases at the borehole wall. According to de la Cruz and Karfakias (1980), in their statistical analysis of the field test by the borehole jack tests in Washington, the orientation has more significant effect than the depth and hole location.

Table 4 gives the ranges of tangential stress for the compressive only (Ec), tensile only (Et) and both the compressive and tensile moduli. This table indicates that most of the borehole deformability tests in the field measure both the compressive and tensile moduli since a differential in-situ stress usually exists. But the tensile modulus is always measured at S1 direction, when the S_1/S_2 ratio is over three. These variations of modulus under various horizontal stresses can be explained by the closing of microcracks and/or pores in the rocks. Adams and Williamson (1923) reported that the elastic moduli of rocks increase when the hydrostatic pressure applied to the specimen is increased. The closing of cracks in the rock sample causes their explanation for this phenomenon of the increase in moduli. Further investigations, made by Brace (1965) and Simons and Richter (1976), show the same effect. Batzle and Simmons(1980) observed the microcrack

Table 4. Ranges of tangential compressive, tensile and both stress with various ratios and orientations.

S1/S2 Ratio	Modulus	Orientation		
		0° (S_1)	45°	90° (S_2)
S_1/S_2 = 1	Ec	$2S_1 < P$	$2S_1 < P$	$2S_1 < P$
	Et	None	None	None
	Ec & Et	$2S_1 < P$	$2S_1 < P$	$2S_1 < P$
S_1/S_2 = 2	Ec	$0.5S_1 > P$	$1.5S_1 > P$	$2.5S_1 > P$
	Et	None	None	None
	Ec & Et	$0.5S_1 < P$	$1.5S_1 < P$	$2.5S_1 > P$
S_1/S_2 = 3	Ec	None	$4/3\,S_1 > P$	$8/3\,S_1 > P$
	Et	All	None	None
	Ec & Et	None	$4/3\,S_1 < P$	$8/3\,S_1 < P$

Ec: compressive modulus, Et: tensile modulus, Ec & Et: Compressive and tensile modulus closure under hydrostatic stress condition under a Scanning electron microscopy. They observed that microcracks are closing and opening depending on the orientation to the applied load direction. When the microcrack is parallel to the loading direction, it opened; when the microcrack is perpendicular to the loading direction, it closed. Therefore, the microcracks, pores, or joints will depend on the magnitude and orientation of and ratio of horizontal stresses.

6. Conclusion

1. The modulus increases when the magnitude of the horizontal stresses increases. The modulus measured in the minimum principal direction increased when the ratio between the horizontal principal stresses increased, while the modulus measured in the maximum horizontal direction decreased when the ratio of the horizontal principal stresses increased.
2. The moduli determined by direct borehole deformability methods using L.V.D.T techniques such as borehole jack methods and Rocha's dilatometer should be interpreted with the in-situ stress information, the internal pressure, the orientation of the measurement, and the depth of borehole. Also, whether the measured moduli were determined under tensile stress, compressive stress, or both stresses should be considered, since the moduli vary depending upon the tangential stress. The moduli, however, in a borehole under the same biaxial stress condition vary less than 10 % between the maximum and minimum principal directions in the intact rock. The moduli of rock mass may vary wider between the maximum and minimum principal directions, since the rock mass contains more discontinuities than the intact rock.
3. The moduli determined in the artificially jointed rock show that moduli vary with the stress change as the results shown from the strain gage tests. The modulus increases with the horizontal principal stress increase and decreases with horizontal stress ratio increases. When the jointed direction is parallel to the maximum horizontal stress direction, the moduli are lower than the moduli obtained at the opposite direction. Also, the modulus become very low when the horizontal stresses of the applied borehole pressure upon the joint are low. Therefore, the directions of discontinuities and maximum horizontal principal stress are important for evaluating the moduli result in rock masses.

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