# 4.4 Rock mechanical investigations

# 4.4.1 Overview

# 4.4.1.1 Objectives

The objectives of the rock mechanical investigations, based on the goals set for the entire MIU Project and its Phases, are as follows <sup>(7)</sup>.

- Acquisition of data on the mechanical properties of the rock mass between the surface and depth at the Shobasama Site
- Determination of the in situ stress state, construction of the rock mechanical model and confirmation of its appropriateness
- Prediction of changes in the mechanical stability of the rock mass adjacent to the shaft during shaft excavation
- Development of methodologies for systematic investigation and analyses of rock mechanical properties of the rock mass

# 4.4.1.2 Performance of the study

This investigation targets the granite. In general, properties of structural discontinuities and their distribution patterns exert a great influence on in-situ mechanical properties of the rock mass. For example, it is assumed that the Tsukiyoshi Fault has a great effect on the stress state of the rock mass distributed in the Shobasama Site. In these investigations, construction and revision of rock mechanics conceptual models were done for the Shobasama Site following analysis of the survey results from AN-1 and MIU-1, 2 and 3. The rock mechanics conceptual model refers to a model in which the rock mass can be divided into several zones according to physical/mechanical properties and in situ stresses. A numerical rock mechanical model. With this model, a predictive simulation was carried out to assess the mechanical effects of drift excavation.

The information on rock mechanical data was obtained by a variety of methods, including borehole geophysics, in situ borehole testing such as hydraulic fracturing to determine in situ stress state and a variety of laboratory tests on core to determine rock mass properties and estimates of in situ stress. Based on the results, a rock mechanics conceptual model for the Shobasama Site was constructed. In practice, as each new borehole was drilled to obtain rock mechanical data, the conceptual model would be compared with the new information and revised as necessary. As a result, the conceptual model was revised based on results of the comparative study.

In this report, concepts, contents, results and evaluation of investigations in the AN-1, MIU-1, 2 and 3 are described and the rock mechanics conceptual model is shown.

# 4.4.1.3 Overview of the investigations

The investigations were divided into two components, determination of physical properties of the rock mass and determination of in situ stress distributions in terms of magnitude and direction.

#### Physical properties of the rock mass

The distribution of rock mass properties between the surface and a depth of 1,000 m was determined by physical and mechanical property tests of core samples. The physical property tests measure apparent specific gravity, water content, effective porosity and elastic wave (P-wave, S-wave) velocity. The mechanical tests consist of uniaxial compression tests, Brazilian tests and triaxial compression tests. All of the tests were carried out based on ISRM guidelines or JIS standards.

# In situ stress

The distribution of in situ stresses between the ground surface and a depth of 1,000 m was investigated by AE/DRA tests on core samples and hydraulic fracturing tests in boreholes. The AE/DRA testing was intended to obtain data on the vertical distribution of in situ stress. The hydraulic fracturing tests were aimed at obtaining data on the distribution of principal stress magnitudes and directions. The hydraulic fracturing tests were employed not only because it was an accepted and best available test at the time to measure the in situ stress state from the ground surface to a depth of 1,000 m, but also because vertical stresses could be one of the principal stresses in this area according to the previous work <sup>(73,74)</sup>.

To ensure the investigation results are comparable, the same types of studies were done in all boreholes. However, the number and depths of testing vary according to the individual boreholes. The tests items carried out in the individual boreholes are shown in Table 4.26. Physical property tests, mechanical property tests, AE/DRA tests and hydraulic fracturing tests number some 20 to 180, 20 to 90, 10 and 10 to 20, in each borehole respectively. As was stated in the geology section, the Shobasama Site is underlain by fractured granite; therefore, results of BTV investigations were used to choose the depths for hydraulic fracturing tests.

	Item	AN-1	MIU-1	MIU-2	MIU-3
Physical property	Apparent density		180	20	40
	Effective porosity	20	180	20	40
	Water content	20	180	20	40
	Seismic wave velocity (P-wave and S-wave)	20	180	20	40
Mechanical property	Uniaxial compressive test	20	90	20	10
	Brazilian test	40	30	40	10
	Triaxial compressive test	-	90	-	30
In situ stress	AE/DRA	-	10	10	10
determination	Hydraulic fracturing	20	-	20	10

 Table 4.26
 Number of rock mechanical investigations

# 4.4.2 Construction of the rock mechanics conceptual model

# 4.4.2.1 Overview of the investigations in the AN-1 and the MIU-1 $^{(39, 75 \sim 77)}$

#### **Concept of the investigations**

Investigations were carried out in the two 1,000 m-deep boreholes in the early stages of investigations at the Shobasama Site. These are the first investigations carried out using 1,000 m-deep boreholes. Their main aim was to obtain comprehensive data on physical properties and the in situ stresses of the rock mass between the ground surface and 1,000 m in depth.

#### Scope of the investigations

Based on the objectives and concepts discussed in the above Overview, Section 4.4.1, physical and mechanical property tests and in situ stress measurements were carried out at intervals of about 100 m and 50 to 100 m, respectively. The specifications and quantity of physical/mechanical property tests performed in AN-1 and MIU-1 are shown in Table 4.27. Depths of the in situ stress measurements are shown in Table 4.28.

	Item	Specification	AN-1	MIU-1
Physical	Apparent density	ISRM method	20	180
property	Effective porosity	ISRM method	20	180
	Water ratio	ISRM method	20	180
	Seismic wave velocity (P wave and S wave)	Receiver and transmitter : 200kHz	20	180
Mechanical	Uniaxial compression test	Loading rate ( 3kgf/cm <sup>2</sup> /s )	20	90
property	Brazilian test	Loading rate ( 3kgf/cm <sup>2</sup> /s )	40	30
	Triaxial compression test	ISRM method	-	90

Table 4.27 Details of physical/mechanical property tests in AN-1 and MIU-1

Table 4.28	Measurement	depth	of in	situ	stress	measurements	at	the AN-	1 an	d MIU	í <b>-</b> 1
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Test	Borehole	Measurement point	Measurement depth (m)
AE/DRA *	MIU-1	10	196.13-196.32; 297.77-298.21; 409.64-409.56; 504.04-504.43; 590.64-592.39; 674.70-674.96; 799.62-799.67; 896.52-896.78; 932.63-932.76; 990.04-990.36
Hydraulic fracturing **	AN-1	20	49.0; 97.0; 156.0; 199.0; 249.0; 309.0; 351.0; 404.0; 439.0; 498.5; 564.0; 600.0; 651.0; 700.0; 749.0; 790.0; 850.0; 900.0; 941.0; 991.0

\*: Sampling depth for AE/DRA

\*\*: Mid-point of test interval depth for hydraulic fracturing

# **Results of the investigations**

Results of the physical/mechanical property tests in AN-1 and MIU-1 are shown in Table 4.29 and Figure 4.61. The data varied so widely that results approximated by quartic polynomial expression are also shown in Figure 4.61 to show the relationship between the individual physical property values and depths. Vertical

in situ stress values obtained by AE/DRA tests in the MIU-1 are shown in Figure 4.62. Horizontal in situ stress states obtained by hydraulic fracturing tests in the AN-1 are shown in Figure 4.63. Hydraulic fracturing tests carried out at four depths, 97.0 m, 156.0 m, 439.0 m and 749.0 m, in AN-1 did not produce any longitudinal fracturing needed to satisfy the theoretical assumption. Therefore, the tests at these depths are not used for assessment of stress states and are not shown in the Figure. Also, pore water pressures of the rock mass at depth exert a great influence on values of calculated maximum principal stress. Therefore, both values of maximum principal stress with pore pressures ( $H_{min}$ ) taken into consideration and without pore pressure (total stress;  $H_{max}$ ) taken into consideration are shown in Figure 4.63. Concerning azimuths of maximum principal stress, the error ranges obtained by a linear approximation using the least squares method for the longitudinal fractures produced by hydraulic fracturing are also shown in Figure 4.63 (b).

	Item	Unit	AN-1	MIU-1
	Apparent density	-	2.59 to 2.62	2.61 to 2.64
	Effective porosity	%	1.0 to 1.8	1.0 to 1.8
Physical	Water content	%	0.15 to 0.30	0.30 to 0.70
property	Seismic wave velocity (V <sub>p</sub> )	km/s	4.0 to 4.5	5.0 ~ 5.8
	Seismic wave velocity (V <sub>s</sub> )	km/s	2.2 ~ 2.7	2.8 ~ 3.0
	Uniaxial compression test	MPa	120 ~ 240	130 ~ 250
	Young's modulus (E <sub>50</sub> )	GPa	34 ~ 60	45 ~ 65
Mechanical property	Poisson's ratio	-	0.30 ~ 0.37	0.30 ~ 0.37
	Tensile strength (by Brazilian test)	MPa	3 ~ 11	4 ~ 11
	Cohesion	MPa	-	20 ~ 26
	Internal friction angle	Degree	-	50 ~ 60

Table 4.29 Results of physical/mechanical property tests in AN-1 and MIU-1

# **Evaluation of the results**

Both physical and mechanical properties of the rock mass in AN-1 show an uneven distribution. The relationships between these properties and depth show different tendencies in the following sections:

- Surface to 300 m in depth
- 300 to 700 m depth
- More than 700 m depth

These relationships in MIU-1 are similar to those in AN-1. Characteristically, values of specific gravity and tensile strength change periodically.

The values of vertical stress obtained by AE tests on core from MIU-1 are thought to be equal to overburden pressure approximated by unit weight and overburden. However, the measured values at 590.64 to 592.39 m, 896.52 to 896.78 m and 990.04 to 990.36 m in depth actually range from a half to a fifth the estimated overburdens. At these depths, fractures are abundant and fracture surfaces are softened. Also, stress discontinuities are found in these depths in the hydraulic fracturing tests. These facts suggest that stresses change locally at these depths. On the other hand, no clear critical point appears in any stress-strain difference curve produced by one to five- repeat loadings. Also, the DRA tests show wide

strain differences in the calculation of vertical stress. These facts suggest that the reliability of the estimated stresses may be low.

Regarding the in situ stress state in horizontal planes determined by hydraulic fracturing tests in AN-1, the maximum principal stress decreases at 300 m and 700 m depth. Furthermore the maximum principal stress does not increase in a uniform linear pattern with depth. Given that vertical stress is equal to calculated overburden pressure, 3-D stress states expected are as follows:

- 0 to 300 m depth Reverse-fault-type ( $_{\rm H}$ >  $_{\rm h}$ >  $_{\rm v}$ ),
- 300 to 700 m depth Transitional-type ( $_{\rm H}$ >  $_{\rm h}$  v), and
- 700 to 1,000 m depth Strike-slip-fault-type  $(_{H} > _{v} > _{h})$

The maximum principal stress orientation changes as follows:

- 0 to 250 m depth N-S
- 300 to 1,000 m depth NW to WNW

Thus, the horizontal in situ stresses around AN-1 are divided into three sections: 0 to 300 m, 300 to 700 m and 700 to 1,000 m depth.

Referring to the results of BTV investigations in AN-1 and MIU-1, the characteristics of the fracture distribution in the Shobasama Site were examined. Histograms of fracture frequency distributions observed by BTV investigations in 50 m intervals in these boreholes between the ground surface and 1,000 m in depth are shown in Figure 4.64. These histograms indicate that the degree of fracturing changes at depths of about 300 m and 700 m in AN-1 and 350 m and 750 m in MIU-1, respectively. The results of the BTV investigations affirm the division into three sections based on the results of in situ stress measurement.

# 4.4.2.2 Construction of rock mechanics conceptual model (78)

As previously stated, the physical and mechanical properties, in situ stress state and fracture distributions change at about 300 m and 700 m in depth. Consequently, a rock mechanics conceptual model can be constructed in which rock mass is divided into three zones with different physical/mechanical properties and stress states at the above depths.

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# (a) Physical properties

Figure 4.61 Physical and mechanical properties of the Toki Granite



# (b) Mechanical properties

Figure 4.61 Physical and mechanical properties of the Toki Granite



Figure 4.62 Distribution of the vertical stresses vs depth

# (a)Magnitude of stress (MPa)



# (b) Direction of maximum principal stress



Figure 4.63 Distribution of the horizontal principal stress

# 4.4.3 Revision of the model based on the results of the MIU-2 investigations

# 4.4.3.1 Overview of the MIU-2 investigations <sup>(40,79)</sup>

#### Concept of the investigations

The main aim is assess and confirm and then build on the above rock mechanics conceptual model.

# Scope of the investigations

Tests for physical/mechanical properties, AE/DRA tests and hydraulic fracturing tests were carried out at intervals of 100 m, 100 m and 50 m, respectively, in MIU-2. The intent was to investigate if the distribution of physical properties and in situ stresses are the same or similar in the three depth ranges in MIU-2 and thus confirm the investigation results obtained from AN-1 and MIU-1. However, MIU-2 intersects a major fault, the Tsukiyoshi Fault, in which the footwall has too many fractures for the performance of hydraulic fracturing tests. Thus, the hydraulic fracturing tests were only carried out in the hanging wall of the fault. Details of tests for physical/mechanical properties are shown in Table 4.30. The depths for in situ stress measurements are shown in Table 4.31.

	Item	Specification	Point
	Apparent density	ISRM method	20
Physical	Effective porosity	ISRM method	20
property	Water ratio	ISRM method	20
	Seismic wave velocity (P and S wave)	Receiver and transmitter: 200kHz	20
Maahaniaal	Uniaxial compression test	Loading rate ( 3kgf/cm <sup>2</sup> /s )	20
property	Brazilian test	Loading rate ( 3kgf/cm <sup>2</sup> /s )	40
property	Triaxial compression test	ISRM method	-

Table 4.30 Details of physical/mechanical property tests for MIU-2

Table 4.31 Measurement depth of in situ stress measurements at the MIU-2

Test	Measurement point	Measurement depth (m)*
AE/DRA*	10	106.68-107.88; 196.49-199.45; 296.30-296.66; 402.00-402.36; 505.52-565.58; 603.00-603.35; 698.34-698.70; 800.59-801.39; 963.29-964.77; 1002.20-1011.37
Hydraulic fracturing**	20	138.2; 158.0; 187.3; 254.0; 294.7; 301.5; 356.4; 413.4; 452.0; 491.0; 555.0; 604.0; 651.0; 682.0; 698.5; 733.7; 761.3; 811.3; 837.7; 878.1

\*: Sampling depth for AE/DRA

\*\*: Mid-point depth of test interval for hydraulic fracturing

#### **Results of the investigations**

Results of physical/mechanical property tests in MIU-2 are shown in Table 4.32 and Figure 4.61. Vertical in situ stresses obtained by AE/DRA tests on cores from the MIU-2 and in situ stress states on horizontal planes obtained by hydraulic fracturing tests are shown in Figures 4.62, 4.63, respectively. The hydraulic fracturing tests produced echelon-type fractures at depths of 604.0 m, 651.0 m, 682.0 m and 698.5 m<sup>(80)</sup>, where it is probable that none of the principal stresses is vertical.

	Item	Unit	Result
Physical	Apparent density	-	2.51 ~ 2.65
property	Effective porosity	%	0.7 ~ 2.0
	Water content	%	0.24 ~ 0.50
	Seismic wave velocity (V <sub>p</sub> )	km/s	4.0 ~ 6.0
	Seismic wave velocity (V <sub>s</sub> )	km/s	2.0 ~ 3.0
Mechanical	Uniaxial compression test	MPa	130 ~ 240
property	Young's modulus (E <sub>50</sub> )	GPa	32 ~ 63
	Poisson's ratio	-	0.30 ~ 0.46
	Tensile strength (by Brazilian test)	MPa	4 ~ 10
	Cohesion	MPa	13 ~ 25
	Internal friction angle	Degree	55 ~ 63

Table 4.32 Results of physical/mechanical property tests in MIU-2

# **Evaluation of the results**

Both the physical and mechanical properties of the rock mass intersected by MIU-2 are unevenly distributed, as in AN-1 and MIU-1. Comprehensive examination of the distribution of physical/mechanical properties in MIU-2 indicate that the rock mass can be divided into four zones based on the different trends of the properties: 0 to 400 m, 400 to 600 m, 600 to 900 m depth (the depth of the Tsukiyoshi Fault) and deeper than 900 m. These four zones have the following characteristics.

# Zone 1: ground surface to 400 m depth

Apparent density is small, but water content and effective porosity are large. Physical properties tend to vary a little with depth. Young's modulus, uniaxial compressive strength and tensile strength (Brazilian tests) increase slightly with increase in depth.

# **Zone 2**: 400 m to 600 m depth

Variations in average physical properties within this depth range are relatively small. Physical properties abruptly change around the upper and lower boundaries of this zone. All the physical properties but for Poisson's ratio are considerably lower than those in the rock above and below the Zones.

# Zone 3: 600 m to 900 m depth (the Tsukiyoshi Fault)

Physical properties tend to change with increased depth. Apparent density and seismic wave velocity, Young's modulus and Poisson's ratio increase with depth, whereas water content and effective porosity decrease.

# Zone 4: deeper than 900 m (footwall of the Tsukiyoshi Fault)

Physical properties at this depth and structural position change somewhat from those in the hanging wall; Young's modulus and tensile strength drop abruptly, all the other properties do not change.

The MIU-2 intersects the Tsukiyoshi Fault at 890 to 915m depths. It is known that the hanging wall and

footwall differ in lithofacies from each other (hanging wall: Biotite granite, footwall: Felsic granite). Nevertheless, no meaningful correlation between the facies change and the difference in physical properties has been found yet. Consequently, it is presumed that the discontinuous change in physical/mechanical properties deeper than 900 m is due to damage associated with formation of the fault.

Results of AE tests on the MIU-2 core vary more widely than results from the DRA tests. While sensors for AE tests are usually set in the central part of a test specimen, the sensors are set at both ends of the specimen in this measurement. Presumable this could result in differences in the AE values. Therefore, the distribution of vertical in situ stresses is assessed mainly by the results of DRA tests. The values of vertical stress obtained by DRA tests are approximately equal to the estimated overburden pressure based on unit weight and overburden between the surface and 800 m depth. However, they are a little smaller than the estimated overburden pressures below 900 m in depth.

The in situ stress states in horizontal planes were assessed only in the hanging wall of the fault by hydraulic fracturing tests because these tests could not be carried out below 900 m depth due to the degree of fracturing. The results indicate that stress magnitudes overall tend to increase with depth, but the maximum principal stress magnitude drops at about 300 m and 600 m depth.

Assuming that vertical stress is equal to overburden pressure, the 3-D stress states expected were:

- 0 to 300 m: Reverse-fault-type  $( H^{>} h^{>} v)$ ,
- 300 to 600 m : Transitional-type ( $_{\rm H}$ >  $_{\rm h}$  v),
- 600 to 900 m: Strike slip-fault-type ( $_{\text{H}}$ >  $_{\text{v}}$ >  $_{\text{h}}$ )..

The direction of the maximum principal stress tends to rotate as follows:

- 0 to 400 m: N-S to WNW-ESE,
- 400 to 700 m: N-S to WNW-ESE,
- 700 to 900 m: NNW to WNW and returns to NNW.

Specifically, the azimuth of the maximum principal stress rotates about  $60^{\circ}$  in the two sections ranging in depth from 0 to 400 m and 400 to 700 m. Furthermore, it rotates from NNW to WNW and back to NNW in the section between 700 and 900 m in depth.

Accordingly, the in situ stress states in the hanging wall of the Tsukiyoshi Fault around MIU-2 are divided into three sections ranging in depth from 0 to 300/400 m, 300/400 m to 600/700 m and 600/700 m to 900 m.

Histograms of fractures distributions sampled by BTV investigations in MIU-2 are shown in Figure 4.64. These histograms indicate that not only do the fracture numbers in MIU-2 change abruptly at 400 m and 700 m depth but also the trend in distributions of the fracture numbers is nearly identical with that of MIU-1.

Thus, physical/mechanical properties, in situ stress states, and fracture distributions abruptly change at 300

to 400 m, 600 to 700 m and about 900 m depth. It indicates that the hanging wall of the Tsukiyoshi Fault is composed of three Zones with different physical/mechanical properties and in situ stress states. Also, it is probable that the footwall of the Tsukiyoshi Fault has different properties from the hanging wall.

# 4.4.3.2 Comparison between the results of the MIU-2 investigations and the rock mechanics conceptual model based on AN-1 and MIU-1 data. (See Section 4.4.2)

The mean values of the results obtained by physical/mechanical property tests carried out in the AN-1 and MIU-1 and 2 are shown in Table 4.33.

1 2	1 1 2	,		
		AN-1	MIU-1	MIU-2
Physical properties				
Apparent density	Average	2.61	2.62	2.61
( )	Standard deviation	0.01	0.01	0.03
Effective porosity	Average	1.40	1.33	1.19
(%)	Standard deviation	0.26	0.25	0.27
Water ratio	Average	0.23	0.44	0.36
(%)	Standard deviation	0.05	0.08	0.07
Seismic wave velocity (P wave)	Average	4.51	5.48	5.12
( km/s )	Standard deviation	0.37	0.27	0.52
Mechanical properties				
Young's modulus (E50)	Average	47.28	55.95	49.97
( GPa )	Standard deviation	8.05	5.94	7.45
Uniaxial compressive strength	Average	197.16	180.11	165.92
(MPa)	Standard deviation	44.70	38.30	34.53
Poisson's ratio	Average	0.34	0.32	0.37
( )	Standard deviation	0.03	0.04	0.04
Tensile strength (by Brazilian test)	Average	8.47	7.18	7.92
( MPa )	Standard deviation	1.82	1.83	1.42
Cohesion	Average		39.04	22.79
( MPa )	Standard deviation		8.91	4.89
Angle of Internal friction	Average		52.60	57.72
( degree )	Standard deviation		4.58	2.50

Table 4.33 Results of physical/mechanical property tests in the AN-1, MIU-1 and MIU-2

Average values of physical properties in MIU-2 are on average, comparable with the results obtained by the previous investigations. They are close to the values obtained in AN-1 but tend to be slightly lower than those obtained in MIU-1, as a whole. With the exception of values for cohesion, the averages for each of the MIU-2 properties ranges up to 15 % from the averages in other boreholes but most are within 10%. Specifically, values of physical properties, such as unit weight, effective porosity, water cotent and seismic wave velocity are smaller than those of MIU-1. With respect to mechanical properties, all but for angle of internal friction and Poisson's ratio of MIU-2 are less than those same properties in MIU-1. The variation of physical properties with depth tends to increase from AN-1 to MIU-2; that is, from south to north the range in values increases. Though the vertical distribution of Young's modulus shows a similar tendency, none of the other properties shows a clear tendency. Based on these facts, it is presumed that greater mechanical damage has been induced during fault formation in the hanging wall of the Tsukiyoshi Fault, as proximity to the fault increases.

It is presumed that the values of vertical in situ stress in the hanging wall of the Tsukiyoshi Fault are nearly equal to the estimated overburden pressures. The values of principal stresses in horizontal planes tend to increase with depth in the sections between 0 to 300 m and deeper than 600/700 m in AN-1. However, in MIU-2 only slight variation in the principal stress values occurs with depth. Though AN-1 and the MIU-2 are similar to each other in distribution of stresses in the section 300 to 600/700 m depth, stresses in the MIU-2 are larger than those in the AN-1. The azimuth of principal stress shows rotation of as much as 45° at the 300 m depth in AN-1. On the other hand, it rotates from N-S to WNW-ESE with an increase in depth in the sections 0 to 400 m and 400 to 700 m in depth in the MIU-2. However, it changes erratically below 700 m depth in MIU-2. These facts suggest that the existence of the fault might exert a great influence on the present day in-situ stress field.

# 4.4.3.3 Revision of the rock mechanics conceptual model<sup>(81)</sup>

Based on the investigation results from the three 1,000 m-deep boreholes (AN-1, MIU-1 and 2), it was shown that the rock mass on the hanging wall side of the fault can be divided into three zones having different geological and mechanical properties down to 1,000 m in depth. Specifically, the ranges of the first, second and third zones are changed slightly from the earlier model with the inclusion of observations from MIU-2. The new ranges are, in themselves, indicative of the heterogeneity of rock mass properties and in situ stress at the site. The new ranges are

- 0 to 300/400 m
- 300/400 to 600/700 m
- Deeper than 600/700 m

Based on the investigation results for the three boreholes, the rock mechanics conceptual model of the rock mass on the hanging wall side of the fault in the Shobasama Site was constructed as shown in Figure 4.65. The rock mechanics conceptual model was constructed on the following assumptions.

- The vertical distribution of in situ stress values in the MIU-2 is complicated due to proximity to and effects of the fault. Thus, attention was paid mainly to the variation in azimuth of principal stresses, which correspond well with the variation in the vertical frequency distribution of fractures.
- The maximum principal stresses in AN-1, which is located farthest from the fault, show a consistent NW-SE trend below 300 m depth. This is coincident with the regional compressive axis <sup>(82)</sup>. Consequently, it is assumed that the influence of the fault on the stress axes at this location is minimal.
- The results of BTV investigations in AN-1 show almost the same trend of fracture frequency distribution as those in MIU-1 and 2. Therefore, the structural zone divisions of the rock mass are extended nearly horizontally from MIU-2 to AN-1. However, it is assumed for simplification that stress values at locations distant from the fault increase linearly with depth in each structural zone or domain.

This rock mechanics conceptual model leads to the following interpretation. The current tectonic stress in

the rock mass on the hanging wall side of the Tsukiyoshi Fault is NW oriented, producing oblique compression against the fault. This would be an explanation for the observation that vertical stress in the footwall of the fault is smaller than the estimated overburden pressure and less than horizontal stresses in the hanging wall. Also, a reason for the rotation in azimuths of principal stresses in the individual structural zones could be explained. It is thought that the validity of this hypothesis may be indirectly verified by determining the in situ stress state on the footwall side of the fault in MIU-3.



Figure 4.64 Fracture frequency detected by BTV investigations



	Zone 1	Zone 2	Zone 3
Fracture frequency	High (subhorizontal - horizontal)	Low	High (subvertical)
Deformability of matrix	Relatively small	Relatively large	Relatively small
Anisotropy of mechanical	Relatively small	Relatively large	Relatively small
properties of rock matrix			

# Figure 4.65 Rock mechanics conceptual model of hanging wall of Tsukiyoshi Fault

# 4.4.4 Revision of the model based on the results of the MIU-3 investigations

# 4.4.4.1 Overview of the MIU-3 investigations <sup>(41,83)</sup>

# **Concept of the investigations**

The main aim was to provide data to assess and confirm the existing rock mechanics conceptual model and to expand the conceptual model of the rock mass to include the footwall side of the Tsukiyoshi Fault.

# Scope of the investigations

With the existing rock mechanical model in mind, test locations were established in order to facilitate acquisition of data on mechanical properties, mainly on the footwall side of the Tsukiyoshi Fault. On the hanging wall of the Tsukiyoshi Fault, samples in the structural zones defined in the rock mechanics conceptual model (See Section 4.4.3) were also required. From the footwall of the Tsukiyoshi Fault, as many samples as possible at equal intervals (some 100 m) were expected. MIU-3 intersects the Tsukiyoshi Fault at 693 to 709 m depth. Details of physical/mechanical property tests and measurement depths of the in situ stress measurements are shown in Tables.4.34 and 4.35, respectively.

	Item	Specification	Number
			of tests
	Apparent density	ISRM method	40
Physical	Effective porosity	ISRM method	40
property	Water ratio	ISRM method	40
	Seismic wave velocity (P and S waves)	Receiver and transmitter: 100kHz	40
Maghaniaal	Uniaxial compression test	Strain rate (0.1%/min.)	10
property	Brazilian test	JIS M0303	10
property	Triaxial compression test	ISRM method	30

Table 4.34 Details of physical/mechanical property tests for MIU-3

Table 4.35 Measureme	nt depth of in situ stress	measurements at the MIU-3
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Test	Point	Measurement depth (m)			
AE/DRA	10	602.15-602.29; 626.00-626.12; 661.62-661.88; 697.54-698.45; 754.45-754.67; 799.00-799.12; 850.70-850.82; 905.43-905.55; 949.00-949.12; 1.002.60-1.002.72			
Hydraulic fracturing	10	122.0; 266.0; 338.0; 462.0; 509.0; 589.0; 847.0; 858.0; 946.0; 988.0			

# **Results of the investigations**

Results of the physical and mechanical property tests in MIU-3 are shown in Table 4.36 and Figure 4.61. Vertical in situ stresses obtained by AE/DRA tests on cores from MIU-3 and in situ stress states on horizontal planes obtained by hydraulic fracturing tests are shown in Figures 4.62 and 4.63, respectively. However, hydraulic fracturing tests carried out at two depths (338 m and 462 m) in MIU-3 did not produce longitudinal fractures, in order to satisfy the theoretical assumption.

	Item	Unit	
Physical property	Apparent density	-	2.61 to 2.65
	Effective porosity	%	1.2 to 1.7
	Water ratio	%	0.45 to 0.65
	Seismic wave velocity (V <sub>p</sub> )	km/s	5.4 to 6.0
	Seismic wave velocity (V <sub>s</sub> )	km/s	3.0 to 3.5
Mechanical property	Uniaxial compression test	Mpa	50 to 200
	Young's modulus (E <sub>50</sub> )	Gpa	20 to 62
	Poisson's ratio	-	0.30 to 0.40
	Tensile strength (by Brazilian test)	Mpa	3 to 8
	Cohesion	Mpa	20 to 50
	Internal friction angle	Degree	48 to 60

Table 4.36 Results of physical/mechanical property tests for MIU-3

# **Evaluation of results**

It is known from the previous investigations that the Tsukiyoshi Fault is associated with an approximately 100 m-wide fracture zone on each side. Accordingly, it is assumed that 100 m-wide areas on the both sides of the main part of the Tsukiyoshi Fault (693.2 to 719.3 m depth) are affected by the fault. Comprehensive examination of the distributions of physical/mechanical properties and this assumption suggests that the granite intersected by MIU-3 could be divided into the following three zones. These vary with depth: that is, approximately 0 to 300 m, 300 to 600 m and 600 to 800 m depth. Each of these has the following characteristics.

# **Zone 1:** 0 to 300 m in depth

Although there were a small number of tests, water content and effective porosity have a tendency to increase slightly with depth. No change was found in apparent density and seismic wave velocity. Young's modulus, uniaxial compressive strength and Poisson's ratio tend to increase slightly with depth, whereas tensile strength (by Brazilian test) decreases.

# Zone 2: 300 to 600 m in depth

Apparent density tends to increase with depth, whereas effective porosity and water content tend to decrease. Seismic wave velocity shows no change with depth. Erratic changes were recognized in Young's modulus, uniaxial compressive strength and Poisson's ratio, whereas only tensile strength shows a slight increase with depth.

# Zone 3: 600 to 800 m in depth

Individual physical properties vary discontinuously compared with those in Zones 1 and 2. As a whole, effective porosity and water content increase and seismic wave velocity decreases with depth, but the variations are small. Values of mechanical properties show remarkable changes with depth. Young's modulus, uniaxial compressive strength and Poisson's ratio increase, whereas tensile strength decreases.

The dispersion of AE test results is smaller than that of DRA tests at the same depths. Therefore, the distribution of vertical in situ stresses was assessed mainly by the AE test results. Values of vertical stresses

obtained by AE tests are a little larger than the overburden pressures estimated in the hanging wall of the Tsukiyoshi Fault but smaller than those in the footwall of the fault. They vary abruptly around the Tsukiyoshi Fault.

In situ stress states in horizontal planes obtained by hydraulic fracturing tests tend to increase with depth. The values of the maximum stress drop at about 600 m and below 700 m depth in the footwall of the Tsukiyoshi Fault.

Assuming that vertical stress is equal to overburden pressure, 3-D stress states expected are:

- surface to 550 m: Reverse-fault-type  $(_{H} > _{h} > _{v})$ ,
- about 600 m: Strike-slip-fault-type  $( _{H} > _{v} > _{h})$
- deeper than 700 m: Normal-fault-type (v > H > h)

The maximum principal stress trends:

- N-S at about 100 m in depth and
- NNW-SSE deeper than 300 m.

Thus, the rock mass around MIU-3 was divided into three sections: 0 to 550 m, around 600 m and deeper than 700 m in depth.

Vertical variations in the number of fractures in MIU-3 are shown in Figure 4.64. While they show a trend somewhat similar to the trends in MIU-1 and 2, the vertical variations in the number of fractures is not as distinct. However, the vertical distribution of the fracture numbers change abruptly at similar depths to those of the physical property changes in MIU-3. These results are conformable with the structure predicted by the rock mechanics conceptual model based on the investigation results of MIU-2.

# 4.4.4.2 Comparison between the results of the MIU-3 investigations and the rock mechanics conceptual model (See Section 4.4.3)

The mean values of results obtained by physical/mechanical property tests carried out in AN-1 and MIU-1, 2 and 3 are shown in Table 4.37.

Specifically, physical properties in MIU-3, such as apparent density, effective porosity, water content and seismic wave velocity, are all larger than those of AN-1 and MIU-2. Mechanical properties, such as Young's modulus, uniaxial compressive strength, and tensile strength, are the smallest of the four boreholes. Values of cohesion, internal friction angle and Poisson's ratio are almost the same as those of MIU-1.

		AN-1	MIU-1	MIU-2	MIU-3
Physical property				-	
Apparent density	Average	2.61	2.62	2.61	2.62
( )	Standard deviation	0.01	0.01	0.03	0.01
Effective porosity	Average	1.40	1.33	1.19	1.41
(%)	Standard deviation	0.26	0.25	0.27	0.14
Water ratio	Average	0.23	0.44	0.36	0.52
(%)	Standard deviation	0.05	0.08	0.07	0.06
Seismic wave velocity (P wave)	Average	4.51	5.48	5.12	5.60
( km/s )	Standard deviation	0.37	0.27	0.52	0.15
Mechanical property					
Young's modulus (E50)	Average	47.28	55.95	49.97	47.15
( GPa )	Standard deviation	8.05	5.94	7.45	12.76
Uniaxial compressive strength	Average	197.16	180.11	165.92	131.21
( MPa )	Standard deviation	44.70	38.30	34.53	50.97
Poisson's ratio	Average	0.34	0.32	0.37	0.36
( )	Standard deviation	0.03	0.04	0.04	0.05
Tensile strength (by Brazilian test)	Average	8.47	7.18	7.92	6.25
( MPa )	Standard deviation	1.82	1.83	1.42	1.47
Cohesion	Average		39.04	22.79	35.07
( MPa )	Standard deviation		8.91	4.89	8.92
Internal friction angle	Average		52.60	57.72	53.07
( degree )	Standard deviation		4.58	2.50	3.34

Table 4.37 Results of physical/mechanical property tests in AN-1, MIU-1, 2 and 3

The vertical distributions of all the physical properties in the four boreholes (Figure 4.61) are dissimilar, to varying degrees. Though variations in vertical distribution of physical properties tend to increase from AN-1 toward MIU-2 (from south to north), the variations in MIU-3 are almost the same as those in MIU-1. This indicates that there is no effect of fault formation on the variations. Vertical distributions of mechanical properties are also uneven. The extent of variations in MIU-2 and 3 are larger than those in the AN-1 and MIU-1. While physical properties in the MIU-3 change non-systematically immediately above the Tsukiyoshi Fault, they start to change about 400 m above the fault in MIU-2. These results indicate that physical/mechanical properties of the rock mass in the Shobasama Site are different enough vertically to allow dividing the rock into zones. The changes in physical/ mechanical properties are probably generated by not only mechanical damage by the formation of the Tsukiyoshi Fault but other factors.

Vertical in situ stresses in the hanging wall of the Tsukiyoshi Fault vary widely but are nearly equal to the estimated overburden pressures (Figure 4.62). On the other hand, vertical stresses are smaller than the estimated overburden pressures in the footwall of the fault. It suggests that vertical stresses are released or decoupled or that there are stress conditions that would cause stress redistribution around and below the fault.

Principal stresses on horizontal planes tend to increase with depth (Figure 4.63) to allow dividing the rock mass down to 1,000 m in depth into zones with different stress states. Based on the investigation results, the rock on the hanging wall side of the Tsukiyoshi Fault is divided into three zones: 0 to 300 m, 300 to 600/700 m and deeper than 600/700 m in depth; on the other hand, although based on a limited database, the footwall seems to form a single zone. In AN-1 the azimuths of principal stresses measured rotate about

45° at 300 m depth, while in MIU-2 it rotates from N-S to WNW-ESE in the sections from 0 to 400 m and 400 m to 700 m. The maximum compressive stress axis in the regional stress field in the Shobasama Site also trends WNW-ESE. Therefore, the maximum principal stress is thought to generally trend WNW-ESE at 300 to 1,000 m in depth in the Shobasama Site.

# 4.4.4.3 Revision of the previous rock mechanics conceptual model <sup>(84)</sup>

The validity of the previous rock mechanics conceptual model for the hanging wall of the Tsukiyoshi Fault was confirmed by the investigation results in MIU-3. Also, with the acquisition of rock mechanical data from the footwall in MIU-3, the rock mechanics conceptual model of the footwall was developed. However, the rock mechanical data of the rock mass on the footwall side is restricted to the depth below 900 m in MIU-2 and 700 m in MIU-3. To compensate for this information shortage, the rock mechanics conceptual model of the footwall was examined using the data on the basement granite obtained by rock mechanical investigations <sup>(84, 85)</sup> in the Tono Mine and the measurement results <sup>(65)</sup> in the DH-9 borehole drilled for the RHS Project <sup>(86)</sup>. DH-9 is a 1,000 m-deep borehole drilled about 1 km north of the northern border of the Shobasama Site and on the footwall side of the Tsukiyoshi Fault. Results of mechanical tests of the rocks on the footwall side in MIU-3 and the borehole 99SE-02 (200 m-deep) are shown in Figure 4.66<sup>(85)</sup>. Though the upper 50 m-thick part of the basement granite in 99SE-02 is too intensely weathered to collect cores, values of mechanical properties below the weathered part tend to increase with depth. Accordingly, none of the mechanical properties obtained in this borehole probably represent the sound granite with the exception of the data in the deepest part. Rocks in the lowermost part of the borehole (207m in depth) have rock mechanical properties, such as apparent density of 2.62 t/m<sup>3</sup>, E<sub>50</sub> of 50GPa, and uniaxial compressive strength of about 150 MPa. They are almost the same as the physical/mechanical properties on the footwall side in MIU-3 and similar to the mean values obtained on the hanging wall side.

The information on the stress states on the footwall side of the fault was provided by hydraulic fracturing tests carried out deeper than 900 m in MIU-2, deeper than 700 m in the MIU-3, and in four boreholes drilled in the Tono Mine (TM-1, 2, 98SE-01 and 99SE-02). The measurement results are shown in Figure 4.67. The four boreholes in the Tono Mine intersect the Tsukiyoshi Fault and the basement granite at different depths. Therefore, the measurement results of the individual boreholes are arranged from south (hanging wall side) to north (footwall side). Values of principal stresses on horizontal planes measured in the basement granite tend to clearly decrease from the hanging wall side to the footwall side. The minimum principal stresses are nearly equal to the overburden pressures in the northernmost borehole, 99SE-02 and the maximum principal stresses are 1.4 to 1.7 times the values of the minimum principal stresses. On the other hand, stresses in the Tono Mine trend NNW-SSE to NW-SE, except near the boundary between granite and sedimentary rock.

The investigation results <sup>(65)</sup> in DH-9 were used for geological structure investigations of the rock mass on the footwall side of the fault. Results of BTV investigations, seismic wave velocity logging and density logging in the individual boreholes (MIU-1, 3 and DH-9) are shown in Figure 4.68. This figure shows that the number of fractures in DH-9 is much smaller than those in the rock mass on the hanging wall side in

MIU-2 and 3. Seismic wave velocity and density drastically drop in highly fractured parts in MIU-2 and 3 and DH-9. As for the rest of the rock mass, seismic wave velocity changes a little where the fracture numbers abruptly change. Sections with more fractures show larger velocity variations, and vice versa. There is little change in seismic wave velocity in DH-9 except for the highly fractured parts. Results of density logging seem to show a similar trend, though their trend is not as clear as the results of seismic wave velocity logging.

Based on the investigation results from MIU-3, the RHS Project and the studies in the Tono Mine, the rock mechanics conceptual model was revised. The revised models for the hanging wall and the footwall of the Tsukiyoshi Fault are shown in Figure 4.69. Furthermore, the following hypotheses were proposed on mechanical properties and stress states of the rock mass on the footwall side.

- According to the results of laboratory tests on cores obtained from the boreholes in the Tono Mine and MIU-3, it is extremely unlikely that mechanical properties of the intact rock or matrix in the "Moderately fractured zone" differ a great deal from those on the hanging wall side.
- According to the results of in situ stress measurements by hydraulic fracturing tests in the Tono Mine and on the footwall side in MIU-3, stress in the footwall side is thought to be considerably lower than that in the hanging wall side. This is supported by the fact that there are a small number of fractures but a highly weathered fracture zone develops deeper than 600 m depth. In general, the apertures of fractures are closely related to stress states. It is presumable that a small number of fractures, which develop under weak stresses in the footwall, cause larger apertures to facilitate infiltration of groundwater near the ground surface. Also, on the footwall side in DH-9, quite a few vertical stress variations are expected to occur, taking the development of considerably thick, highly fractured zones into consideration. However, the extent of the variations would not be as remarkable as in the hanging wall due to the weak stresses. The measurement data in the boreholes in the Tono Mine and MIU-3 suggest that the maximum principal stresses in horizontal planes generally trend NNW-SSE to NW-SE like in the hanging wall of the fault, though there is no data at intermediate depths.

The rock mechanics conceptual model of the footwall of the Tsukiyoshi Fault has the following characteristics.

- Physical/mechanical properties of the rock matrix in the footwall are almost the same as those in the hanging wall. Their vertical variations are not large.
- Fractures are so few in the footwall that mechanical properties of the in-situ rock mass are better than those on the hanging wall side.
- The minimum principal stresses are equal to the estimated overburden pressures or smaller. The difference between the maximum and minimum principal stresses is small. The maximum principal stresses trend WNW-ESE to NW-SE and don't change vertically a great deal.







Tsukiyoshi Fault

98SE-01



TM-1





Figure 4.67 Results of the stress measurements with hydraulic fracturing in the Tono Mine<sup>84)</sup>







# Characteristics of each zone

	Zone 1	Zone 2	Zone 3
Fracture frequency	High (subhorizontal - horizontal)	Low	High (subvertical)
Deformability of matrix	Relatively small	Relatively large	Relatively small
Anisotropy of mechanical     properties of rock matrix	Relatively small	Relatively large	Relatively small

(a) Rock mechanics conceptual model of hanging wall of the Tsukiyoshi Fault <sup>77)80)</sup>



(b) Rock mechanics conceptual model of footwall of the Tsukiyoshi Fault

# Figure 4.69 Rock mechanics conceptual model of hanging wall and footwall of the Tsukiyoshi Fault

# 4.4.5 Summary

Based on a comprehensive assessment of the results of physical/mechanical property tests and in situ stress measurements in AN-1 and MIU-1, 2 and 3, a rock mechanics conceptual model from the ground surface to 1,000 m in depth was developed. The model is shown in Figure 4.70. Its characteristics are as follows.

- The rock mass on the hanging wall side of the fault is divided into three zones characterized by different physical/mechanical properties and stress states. Specifically, Zones-1, 2 and 3 range in 0 to 300/400 m, 300/400 to 700 m and 700 to 1,000 m depth, respectively.
- The investigation results on the footwall side are restricted to 150 to 200 m and 800 to 1,000 m in depth. Therefore, the entire footwall side is assumed, for present purposes, to consist of a homogeneous rock mass. It is difficult to estimate the position and extension of fault-related and fracture-concentrated zones such as those recognized in DH-9. Therefore, the whole section is postulated to consist only of sound rock, without the zones described above.

Though the rock mechanics conceptual model is revised by adding the data on mechanical properties of the footwall, the basic concept of the model was unchanged. In this concept, the rock masses on the footwall side and the hanging wall side show mechanically discontinuous behavior. Furthermore, the hanging wall side of the Tsukiyoshi Fault is considered to be obliquely compressed against the footwall side by the regional tectonic stress. This hypothesis requires that the rock mass on the hanging wall side be divided into large-scale blocks bordered by N-S trending faults, besides the E-W trending Tsukiyoshi Fault. The presence of N-S trending lineaments identified by lineament surveys carried out in and around the Shobasama Site for the RHS Project is thought to support the above hypothesis.

#### 4.4.6 Future tasks

Based on the results of mechanical property tests in MIU-4 (drilling started in 2000 FY), mechanical properties of the Tsukiyoshi Fault and the associated fractured zones are expected to be further understood. Also, the validity of the rock mechanics conceptual model will be tested in the application of numerical analyses. Furthermore, mechanical properties of discontinuity planes should be assessed by joint shear tests. Physical properties of the in-situ rock mass should be evaluated taking the effects of fractures into consideration to quantify the rock mechanics conceptual model.

Stress state



#### Rock properties

		H anging w all		Footw all	NearTsukiyoshiFault	
		Zone 1	Z one 2	Zone 3	Zone 4	H anging w all. Footw all
M echanical	D eform ability	Low	H igh	Low	Low	Low est in Shobasam a site
m atrix	Anisotropy	?	Large	Small	Very small	?
Fracture	distribution	<ul> <li>H igh fracture frequency</li> <li>H orizontal~ Sub-horizontal</li> </ul>	• Low fracture frequency	• High fracture frequency • Sub-vertical	• Very low fracture frequency com pared with hanging wall	<ul> <li>H igh fracture frequency</li> <li>Frequency in hanging wall is higher</li> </ul>
Expected mechanical	Deformability	Lowerthan Zone 2	Highestin Shobasama site	Lowerthan Zone2	Same as hanging wall	Lowestin Shobasam a site (about 60 % of other zones)
properties of in-situ rock m ass	Localvariation	Large	Sm all	Large	Sm all (except for dam aged zone)	

Figure 4.70 Rock m echanics conceptual model