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Overview of the Excavation Disturbance Experiment at the Kamaishi Mine

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Introduction

Excavation of an underground drift disturbs the rock mass around the opening by each of the following processes:

- Fracturing in the vicinity of opening induced by the excavation work and stress concentration.
- Changes in the apertures of existing fractures due to stress redistribution.
- Changes in water pressure around the opening due to water inflow and chemical changes due to the increased oxygen supply to the rock and such phenomena as degassing of groundwater.

All of these mechanical, hydrological, and chemical changes to the rock mass are termed excavation disturbance and the affected area is called the "Excavation Disturbed Zone (EDZ)". The portion of the EDZ in which the rock mass is fractured due to excavation is called the "Excavation Damaged Zone".

This experiment is focused on the mechanical and hydrological property changes caused by excavation, the degree and extent of which is important for the design, excavation and support of underground openings. The relevance of the EDZ for the geological isolation of nuclear waste disposal may be summarized as:

1) Relevance to near-field performance assessment
The EDZ is of importance for near-field performance assessment, as the development of new fractures and the opening of existing fractures due to excavation may create preferential pathways for mass transport from the engineered barrier system to natural transmissive flowpaths.

2) Relevance to the design, excavation and sealing of a repository
The excavation method affects the properties and the extent of the excavation damaged zone. The shape and the scale of the underground opening, and whether the underground opening is backfilled after excavation, will affect the final stress state. It is important to understand the EDZ for the design, excavation and sealing of a repository.

3) Initial and boundary conditions of in situ experiments
Information about the EDZ is necessary for the design and interpretation of certain *in situ* experiments.

Objectives

The main objectives of the experiment are:

- To estimate the spatial extent and the magnitude of the rock property changes in the EDZ.
- To understand the processes related to rock property changes in the EDZ.
- To assess the effect the excavation method on excavation disturbance.

Geological Setting and *In Situ* Stress Field at the Study Site

Rock properties:
The host rock at the study site is predominantly Kurihashi granodiorite. The average mechanical properties of the Kurihashi granodiorite at the 250m level of the Kamaishi mine are:

Unit weight:	2.755 ± 0.022	[g/cm^3]
Porosity:	0.509 ± 0.145	[%]
P-wave velocity:	5.813 ± 0.092	[km/s]
S-wave velocity:	3.252 ± 0.065	[km/s]
Uniaxial compressive strength:	151.9 ± 11.5	[MPa]
Young's modulus:	64.28 ± 5.73	[GPa]
Poisson's ratio:	0.238 ± 0.046	

(number of samples = 44)

Fracture distribution at the study site:
Three fracture sets having different orientations were found at the study site. The orientations of the fracture sets are N25E°80°NW, N85°E85°SW, and N20°W75°NE -75°SW. The average fracture frequency is about 3.1/m. The fractures with reddish colored hydrothermal alteration, which form the dominant fracture set, strike N85°E. The trace lengths of these fractures, over 40 m, are the largest in the area. These fractures are confirmed to extend continuously.

In situ stress field:
Figure 1 shows the *in situ* stress data obtained by hydraulic fracturing and overcoring before excavation of the measurement drift. According to the overcoring stress measurements, the maximum principal stress is about 44 MPa, oriented NS with a dip of about 20°. The minimum principal stress is 18 MPa, oriented EW with a dip of about 6°. The maximum principal stress direction was found to be approximately NS for both measurement techniques, but the dips differed for the two methods used. After the measurement drift was excavated, the results of the two methods were evaluated based on the final shape of the measurement drift and other stress measurement results. The re-constructed stress field is shown in Figure 2 (Matsui *et al.*, 1997).

In Situ Tests, Experimental Layout and Excavation Method

Two new drifts, the measurement drift and the test drift were excavated in this study. Figure 3 shows the configuration of the boreholes and the drifts. The following *in situ* tests were carried out:

- Geological investigations, involving BTV (Borehole TeleVision), core logging in all boreholes, and fracture mapping in the test and measurement drifts.
- Investigations related to the excavation damaged zone, involving AE (Acoustic Emission) measurements, vibration measurements during the excavation of the measurement and test drifts, geophysical measurements, such as P- and S-wave logging, seismic refraction surveys, laboratory testing of core samples, and observations of fractures in the excavated drifts.
- Investigations related to the stress-redistributed zone, involving displacement measurements, strain measurements in the intact rock, fracture displacement measurements during the excavation of the test drift, and hydraulic testing before and after the excavation of test drift.

The main investigation area was within 7 m (drift diameter = 3.5 m) from the test drift wall where the major stress change was expected. The test and measurement drifts were excavated sub-parallel to the dominant fracture orientation and perpendicular to the maximum principal stress direction to maximize the excavation disturbance around the test drift.

The test and measurement drifts were excavated by blasting because other excavation methods, such as mechanical excavation, could not be used for practical reasons including cost, time constraints, problems of safety, *etc.* Both normal blasting (NB) and smooth blasting (SB) techniques were used to excavate portions of both drifts to assess the role of excavation method on excavation disturbance. Figure 4 shows the basic blasting pattern used with both the NB and SB methods in the excavation of the test drift.

Results and Discussion

1) The processes related to the rock property changes within the EDZ

Excavation damaged zone:

Figure 5 shows the distribution of AE, together with the computed source mechanisms and energy levels. The area of tension cracks induced by blasting is in good agreement with the expected damage zone created by the blasting-induced compressional shock wave. Laboratory tests show that AE generated by breaking granite have high energy levels, which could correspond to 80 dB *in situ*. AE energy levels over 80 dB were only observed in the sections excavated by the NB. The AE events show both tension and shear mechanisms. The S-wave (shear wave) with the highest amplitude was also observed during vibration measurements. The results suggest that the greatest damage was caused by the NB, and that the failure modes were tension and shear. On the other hand, some AE events that were observed in both the NB and SB sections correspond to the locations of pre-existing fractures and reflectors detected by radar measurements (Kinashi *et al.*, 1998).

The BTV observations were performed in eleven boreholes before and after the excavation of the test drift. New fractures were observed in only one borehole. Only a small number of new fractures were identified due to the low resolution (0.5 mm) of the BTV used in the experiment.

Small rock bursts occurred at the upper, right-hand corners of both drifts (as seen looking toward the east) during excavation, where numerical modelling work suggests that the stress concentrations should occur and where a notch can be seen in portions of the roof. These results indicate rock failure caused by stress concentration (Figure 6). A small-scale ultrasonic tomography survey carried out in the measurement drift and velocity and strain measurements made under hydrostatic pressure on core samples retrieved from the drift walls also suggested fracturing related to stress concentration (Carlson, *in prep*).

In conclusion, the excavation damage was mainly induced by P- and S-waves generated by blasting, but a failure zone caused by the stress concentration is also indicated.

Stress redistributed zone:
In general, the largest strains and rock mass displacements were observed near the drift wall. The largest measured changes, both in the intact rock and the fractures, occurred during blasting (Figure 7). The displacement and strain results are not in agreement and are quite different from the trends estimated by classical elastic theory. On the other hand, fracture displacements occurred more than 7 m away from the drift wall. Also, different directions of shear displacement occurred on specific measurement points on the same fractures (Figure 8).

Large fracture openings (2-3 mm) were also observed during direct fracture displacement measurements (Figure 8). However, such large fracture openings could not be found during BTV observations following the excavation of the test drift. Moreover, convergence measurements show displacements below 1 mm. Numerical simulation by UDEC-BB, which is the simulation code on distinct element method, shows that small fracture opening (below 1 mm) should occur where the fracture displacements were measured (Figure 9). Therefore, it is thought that the fracture openings measured by fracture displacement measurements are unreliable.

In conclusion, displacement of intact rock and fracturing are induced by stress redistribution due to the creation of the opening. The deformation is thought to be dominated by shear movements along pre-existing fractures, particularly the major hydrothermally-altered fracture set.

2) *The spatial extent of the EDZ and the degree of the rock property change due to the excavation*

Spatial extent and physical property changes in the EDZ:
Figure 10 shows the measured shape of the drift, the distribution of the low velocity zone and the damaged zone estimated from the vibration measurements. The actual drift area in cross-section is larger than the planned shape for the test drift. The extent of the actual area agrees with the extent of the damaged zone estimated from the vibration measurements. This means that the major part of the damaged zone induced by blasting has been removed except for the floor.

The extent of the low velocity zone, which is about 20~50 cm from the drift wall, is very similar for both the SB and NB sections. The velocity in the vicinity of drift wall drops by at most 60% compared to the intact host rock (6 km/sec). The average velocities found for the SB section (1st layer: 2.5 km/sec, 2nd layer: 4.0 km/sec) are smaller than for the section constructed by NB (1st layer: 2.6 km/sec, 2nd layer: 4.3 km/sec). This implies that the elastic modulus in the low velocity zone is reduced by as much as 90% compared to the host rock, if the rock is assumed to be a continuum elastic media. This huge reduction seems unrealistic, as the drift wall should not be stable in such a case.

The elastic modulus of the low velocity zone detected by the seismic refraction survey in 250 m level drift was also measured directly with a borehole jack test (Figure 11) (Matsui *et al.*, 1996; Sugihara *et al.*, 1996). The results show that the extent of the low elastic modulus zone is in agreement with the thickness of the low velocity zone observed during the seismic refraction survey. The elastic modulus was reduced by a maximum of 50% in the low velocity zone, *ie* P-wave velocity dropped by about 50%.

Laboratory tests on core samples taken from short boreholes drilled from the test drift show no relationship between distance from the drift wall and mechanical and hydraulic properties of intact core.

The results of connected permeability tests and hydraulic tests in short sections (10 cm) show no correlation between low velocity and high permeability except for measurements in the drift floor (Figures 12, 13). The permeability in the low velocity zone of the drift floor is about two orders of magnitude higher than in the undamaged part. This is considered to be evidence that the major part of the zone damaged by blasting is removed except for the floor.

In conclusion, velocity changes due to fracturing occurred in the vicinity of the drift wall. There are no significant changes in the physical properties of the intact portion of the rock mass. The extent of the damaged zone is conservatively assumed to be the combined extent of loosened rock and the low velocity zone. The elastic modulus of the rock in the damaged zone is considered to decrease at most 50% compared to that of the intact host rock. The permeability of the rock in the drift floor is increased by two orders of magnitude in the low velocity zone compared to the permeability of the intact host rock.

Spatial extent and physical property changes of the stress redistributed zone:
Figure 14 shows the distribution of the displacements, strains and permeabilities before and after the excavation of the test drift. As shown in previous section, the stress redistributed zone is estimated to extend over 7 m from the drift wall, about two drift diameters.

The permeability measured after excavation is about one order of magnitude lower than that measured before excavation. A comparison of the results of the various rock deformation measurements made around the test drift suggested no obvious reason for the decrease. Laboratory permeability tests of fractured core samples have been performed to find the reason for the permeability decrease, but the main factor has not yet been found.

The results indicate that the stress redistributed zone extends about two drift diameters or 7 m into the rock mass. Unfortunately, permeability changes due to rock deformation were not measured in the stress redistributed zone.

3) The dependence of excavation disturbance on the excavation method (NB or SB)
As discussed above, the seismic refraction surveys show some differences between the velocity change caused by NB and SB. The AE and vibration measurements show that NB induced more damage than SB because of the higher amount of charge in NB design.

In conclusion, it is evident that the blast design has an effect on the degree and extent of excavation damage.

Conclusions

1) The processes related to the rock property change in the EDZ
The greatest damage was induced by the compressional waves generated by blasting and damage was also caused by stress concentrations. Displacements of intact rock and fractures were induced by the redistribution of stresses following excavation. At this site, shear movements are considered to be the dominant motions along the major fractures.

2) The extent of the EDZ and degree of the rock property changes due to the excavation
The measured velocity changes are considered to be induced by fracturing and stress concentrations except in the drift floor. There are no significant property changes within the intact rock. The extent of the damaged zone is defined as the area where the rock is loosened and where a low velocity zone is developed. The extent of the zone where intrinsic rock properties are changed is about 1 m from the drift wall. Mechanical properties in the damaged zone have decreased by at most 50% compared to the mechanical properties of the intact host rock. The maximum permeability may have increased by two orders of magnitude in the low velocity zone compared to the host rock in the floor of the drift. The extent of the stress

redistributed zone is over two drift diameters from the drift wall (drift diameter = 3.5m). Permeability changes in the sides of the drifts before and after excavation of the test drift were not measured.

3) The dependence of excavation disturbance on the excavation method
It is confirmed that the excavation method has an influence on excavation disturbance as measured by seismic velocity changes.

Figure 15 summarizes, graphically, the conceptual model for the excavation disturbance at the Kamaishi mine.

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References

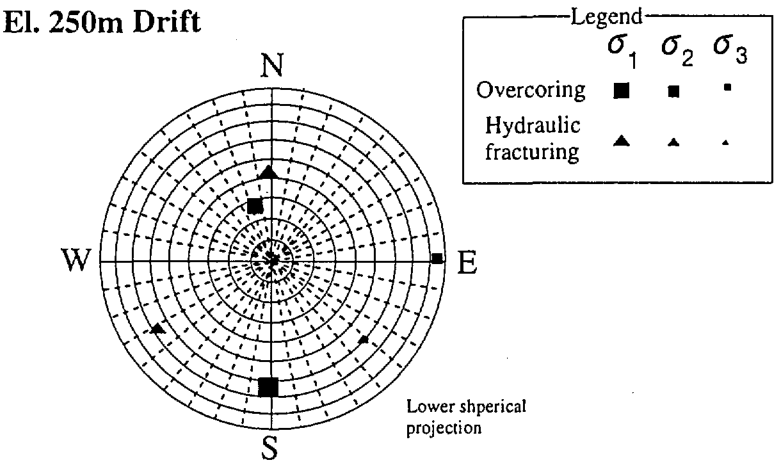
Carlson,S.R.: Investigation of an excavation damaged zone at the Kamaishi mine. (*in prep*)

Kinashi,H., Hata,K., Matsui,H., Sugihara,K., 1998: Estimation of drift excavation damage with acoustic emission technique. *In:* Proceedings of the 10th Japan Symposium on Rock Mechanics, 611-616. (*in Japanese*)

Matsui,H., Sato,T., Sugihara,K., 1996: Investigation of the excavation damaged zone around a drift in crystalline rock by seismic survey. *In:* Proceedings of the 27th Symposium of Rock Mechanics in Japan, 336-340. (*in Japanese*)

Matsui,H., Sato,T., Sugihara,K., Nakamura,N., 1997: Comparison of the results of stress measurements determined by various methods at the Kamaishi mine. *In:* Proceedings of the International Symposium on Rock Stress, Japan, 95-100.

Sugihara,K., Matsui,H., Ishijima,F., Sato,T., 1996: Study on excavation disturbance in the Kamaishi mine, Japan. *In:* International Conference on Deep Geological Disposal of Radioactive Waste, Canada.



Principal stress(MPa)

	σ_1	σ_2	σ_3
Overcoring	43.8	26.8	17.8
Hydraulic fracturing	26.0	15.1	11.4

Figure 1 Summary of the results of the stress meaurements in the study sites (el. 250m drift)

Assumption

- σz = Overburden pressure
- The directions of $\sigma 1$, $\sigma 2$ and $\sigma 3$ correspond to the directions of the principal stresses estimated by overcoring method

Magnitude — Direction cosine

$\sigma 1$: 27.97≒28.0MPa, (0, 0.896, 0.443)
$\sigma 2$: 18.08≒18.1MPa, (0, -0.443, 0.896)
$\sigma 3$: 14.5MPa , (1, 0, 0)
τyz = 3.929 ≒ 3.93MPa

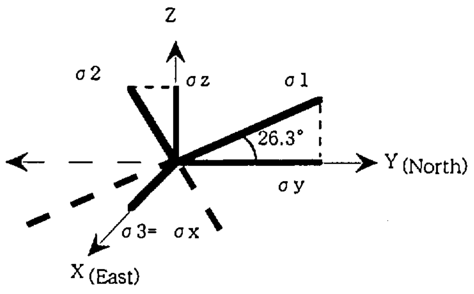
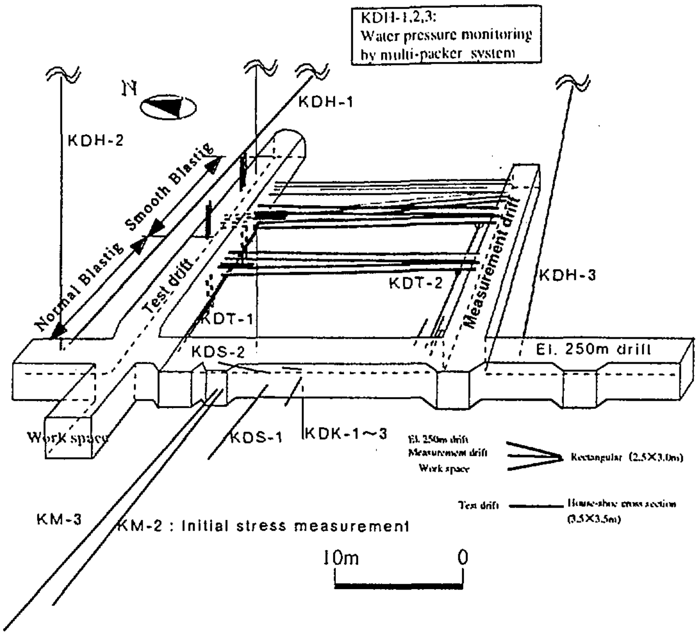


Figure 2 Modified initial stress field



Master schedule

Items	Period
Study on excavation disturbance around el.250m drift	April,1994～March,1995
Excavation of measurement drift Preliminary test for AE, vibration and PAC-EX	April,1995～November,1995
Drilling of the boreholes for measurement	December,1995～July,1996
Excavation of Test drift The measurement before , during and after excavation of test drift	September,1996～February,1997
The detail investigation after excavation of test and measurement drift	June,1997～February,1998

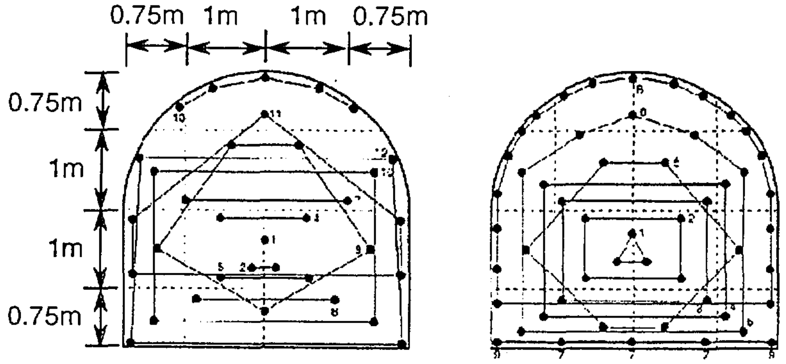
Figure 3 Master schedule, configuration of the drift and boreholes

Normal Blasting

Smooth Blasting

Area in a cross section: 10.33 m^2

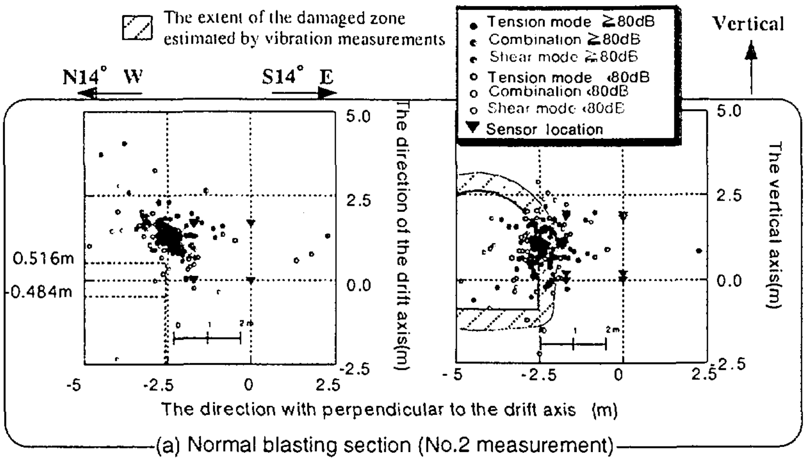
Excavation progress : about 1m per round



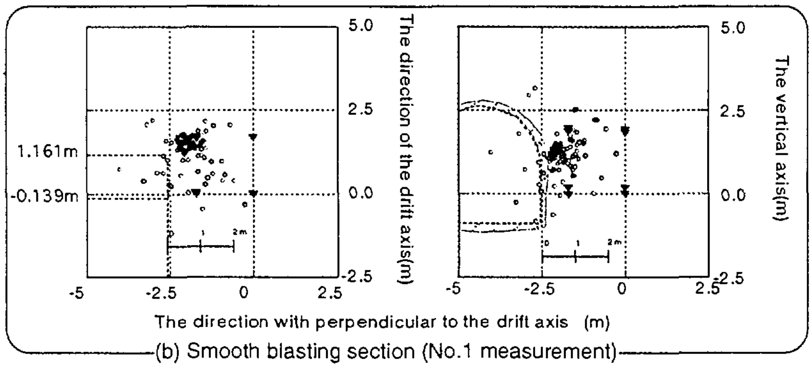
- Contour hole(No.12,13)
- Amount of charge is about1kg for all holes
- Total amount of charge: about 37 kg ($3.4kg/m^3$)

- Contour hole(No.8)
- Amount of charge is about 1kg for the holes except contour hole
- Amount of charge for contour holes is about 0.35kg
- Total amount of charge : about 45kg ($4.4kg/m^3$)

Figure 4 Applied blasting design



(a) Normal blasting section (No.2 measurement)



(b) Smooth blasting section (No.1 measurement)

Figure 5 Source location of AE events around the test drift during the excavation

Detected AE were distinguished by source mechanisms and energy level.

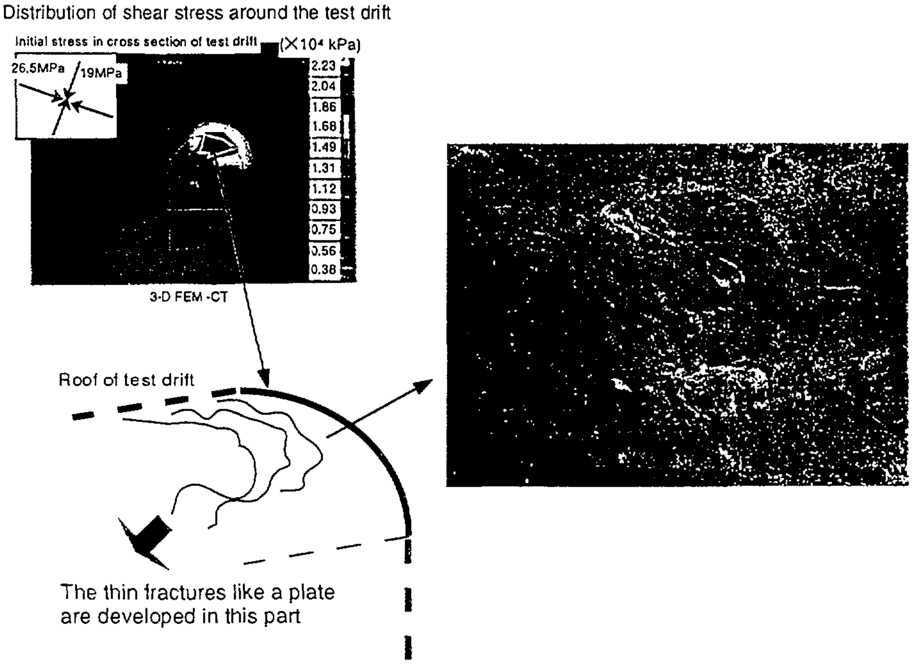
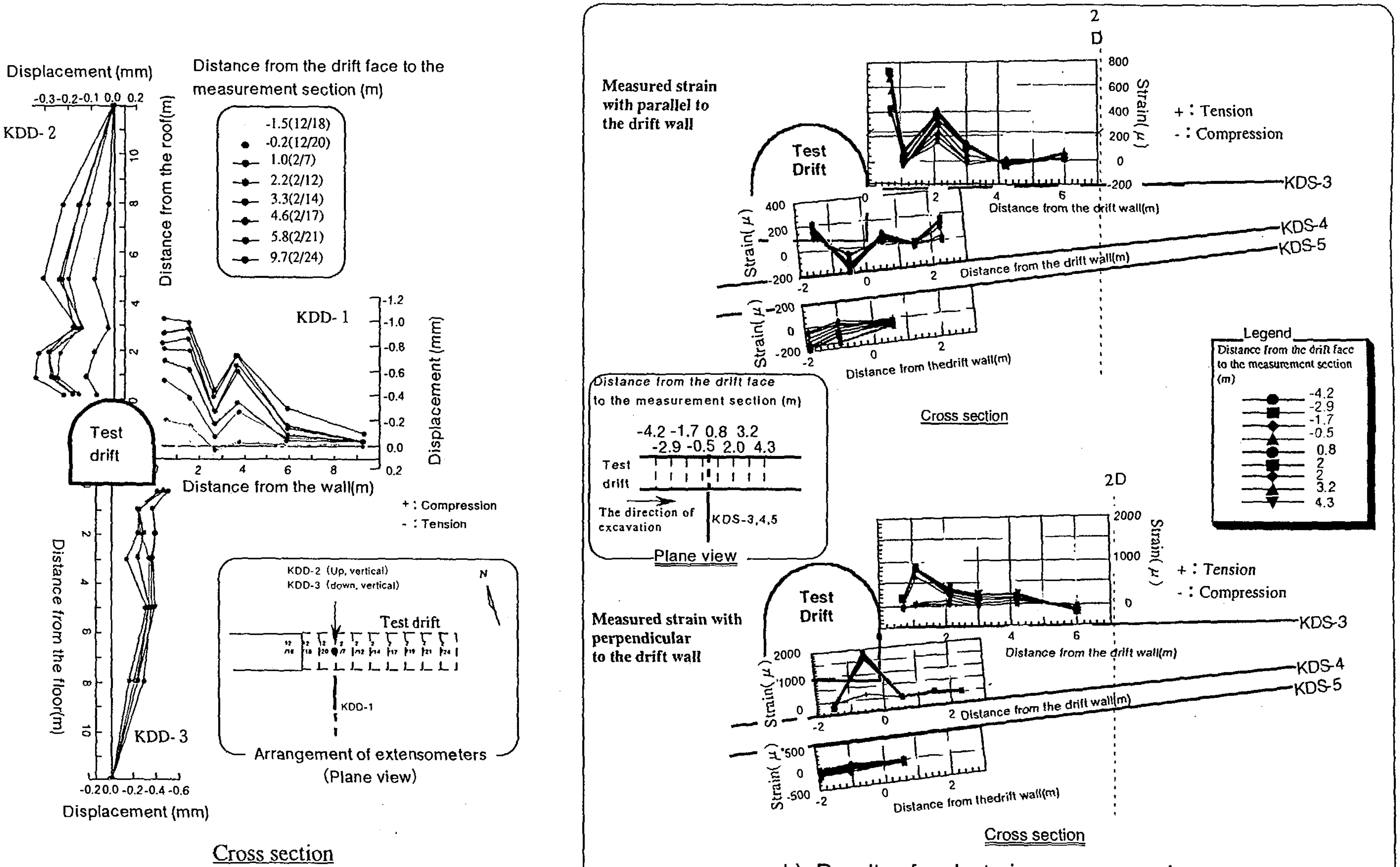


Figure 6 Stress distribution around the test drift and obseved fractures induced by stress concentration



a) Rock displacement during the excavation of the test drift

b) Results of rock strain measurements during the excavation of the test drift

Figure 7 Rock deformation around the test drift during excavation

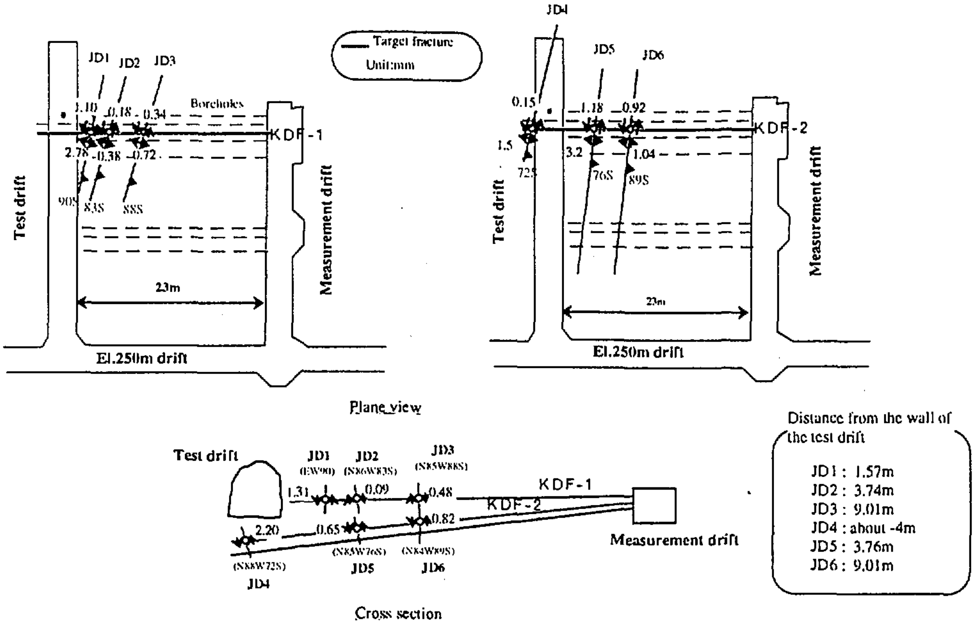
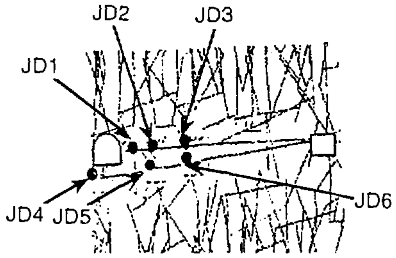
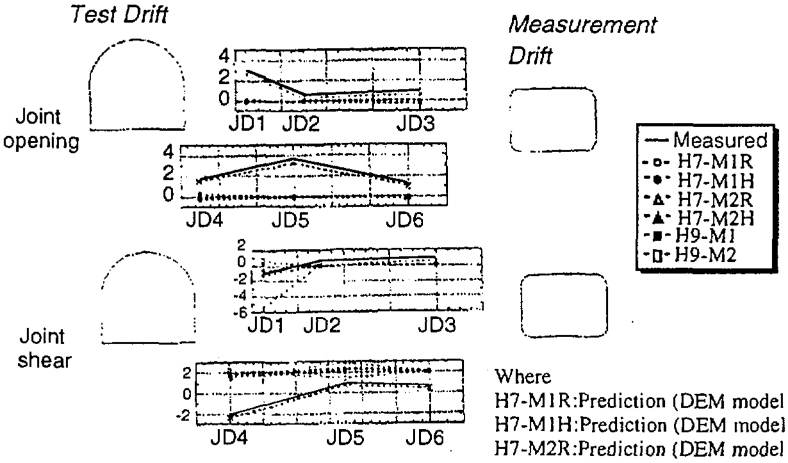


Figure 8 Fracture displacements after the excavation of the test drift



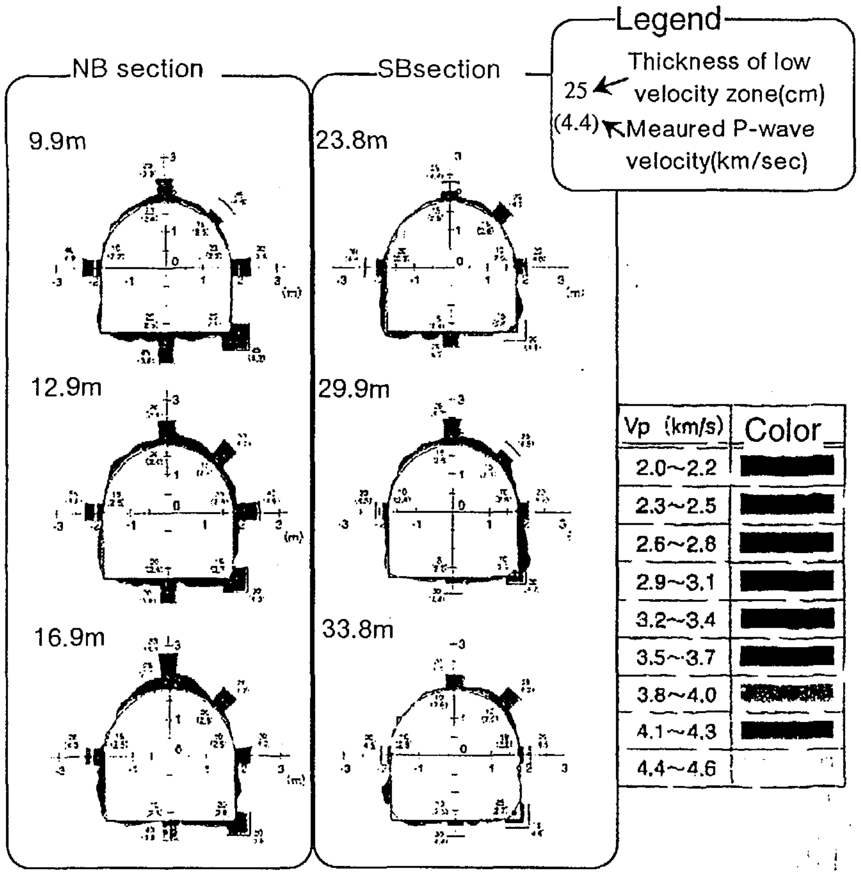
a) Location of fracture displacement measurement on DEM model



Where
H7-M1R:Prediction (DEM model 1, Initial stress: Overcoring)
H7-M1H:Prediction (DEM model 1, Initial stress: Hydraulic fracturing)
H7-M2R:Prediction (DEM model 2, Initial stress: Overcoring)
H7-M2H:Prediction (DEM model 2, Initial stress: Hydraulic fracturing)
H9-M1:Interpretation (DEM model 1)
H9-M2:Interpretation (DEM model 2)

b) Comparison of measured and calculated fracture displacement

Figure 9 Results of numerical simulation



■ This zone shows the difference between the planned drift shape and real drift shape

Figure 10 Results of drift shape measurement and seismic refraction survey

Three different velocity structures were assumed on analysis of seismic refraction survey.

The results of seismic refraction survey in the el.250m drift
Thickness of low velocity zone :About 50cm
P-wave velocity of the zone : 50%~80% of host rock

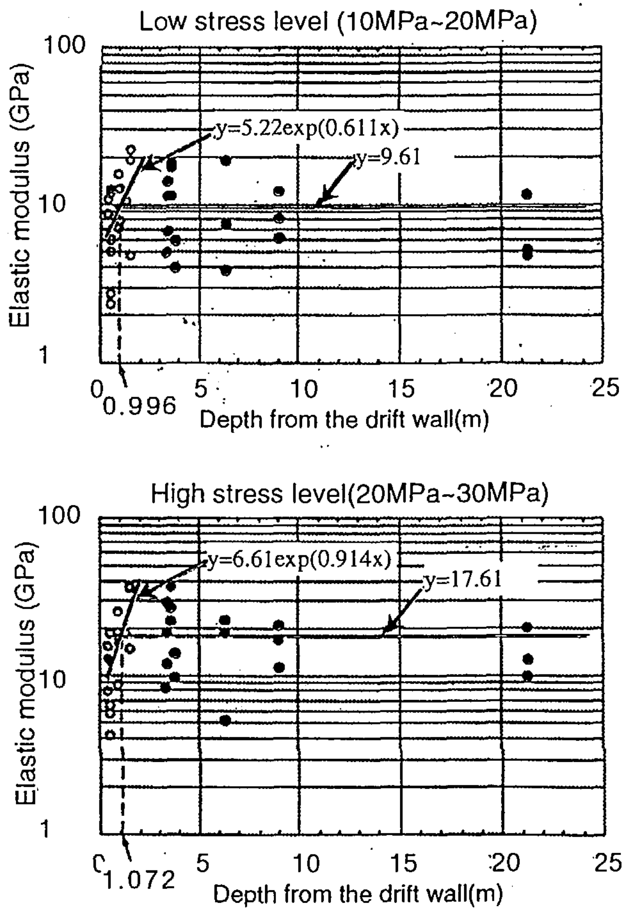
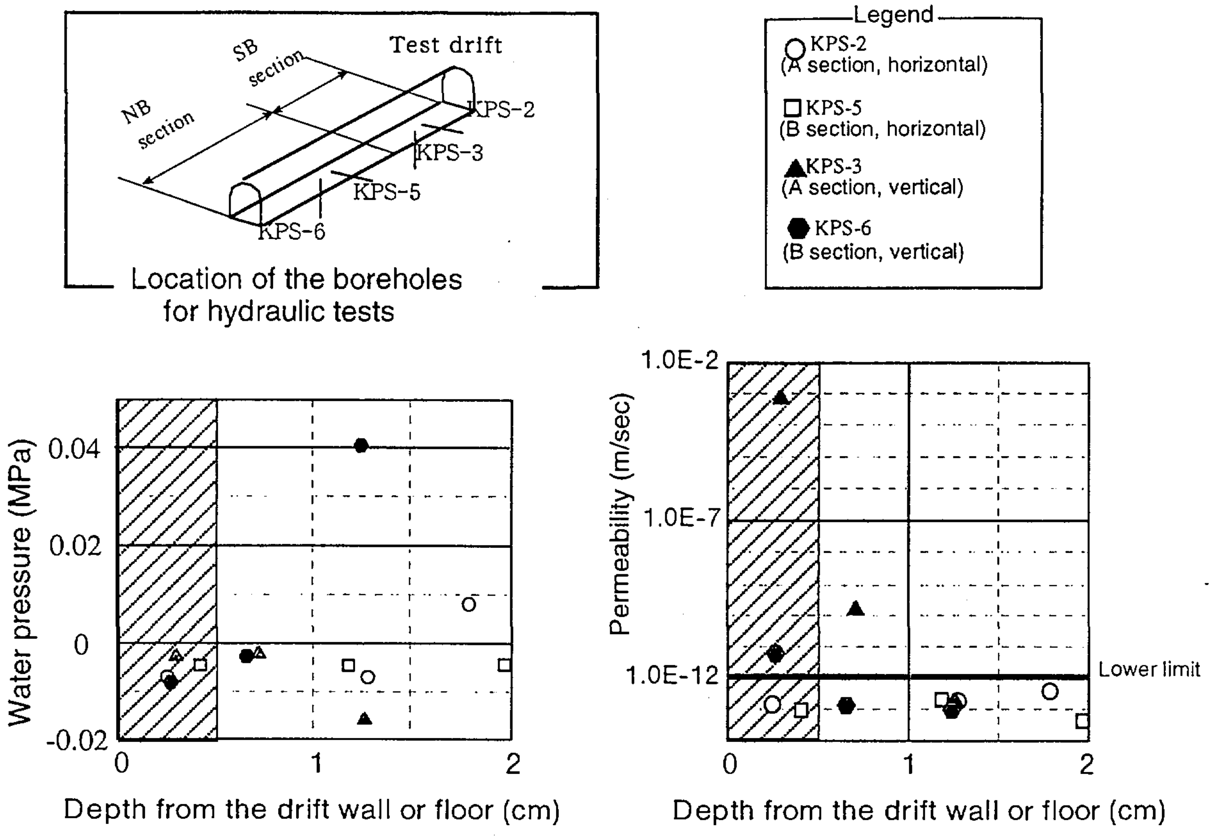
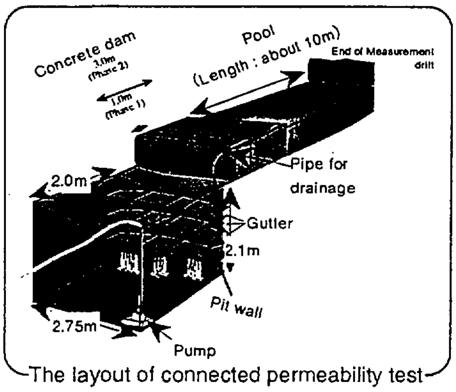


Figure 11 The results of borehole jack test and seismic refraction survey (el. 250m drift)



▨ : Average thickness of low velocity zone estimated by seismic refraction survey

Figure 12 Results of the hydraulic test with short section length (10cm)



The layout of connected permeability test

i) Estimated average permeability(Phase 1)

Level	Section	Section area cm²	Hydraulic gradient	Inflow rate ml/min.	Av. Permeability m/sec	Av. Permeability at level (m/sec)
Level 1 (0.5m below the floor)	1 L	4648	0.76	0.13	6.1E-9	2.6E-4
	1 C	3760	0.76	7920	4.6E-4	
	1 R	3782	0.76	6540	3.6E-4	
Level 2 (1.0m below the floor)	2 L	4150	1.00	0.00	0.0E-0	1.2E-5
	2 C	4000	1.00	750	3.1E-5	
	2 R	2700	1.00	25	1.5E-6	
Level 3 (1.5m below the floor)	3 L	4150	1.12	0.00	0.0E-0	1.1E-7
	3 C	4500	1.12	7	2.3E-7	
	3 R	2300	1.12	0.83	5.4E-8	

ii) Estimated average permeability(Phase 2)

Level	Section	Section area cm²	Hydraulic gradient	Inflow rate ml/min.	Av. Permeability m/sec	Av. Permeability at level (m/sec)
Level 1 (0.5m below the floor)	1 L	4648	0.35	0.2	2.0E-8	1.2E-5
	1 C	3760	0.35	210	2.7E-5	
	1 R	3782	0.35	100	1.3E-5	
Level 2 (1.0m below the floor)	2 L	4150	0.49	0.00	0.0E-0	3.6E-7
	2 C	4000	0.49	3	2.6E-7	
	2 R	2700	0.49	8.5	1.1E-6	
Level 3 (1.5m below the floor)	3 L	4150	0.60	0.00	0.0E-0	1.3E-7
	3 C	4500	0.60	5	3.1E-7	
	3 R	2300	0.60	0.09	1.1E-8	

▨ : Average thickness of low velocity zone estimated by seismic refraction survey

Figure 13 Results of connected permeability test (measurment drift)

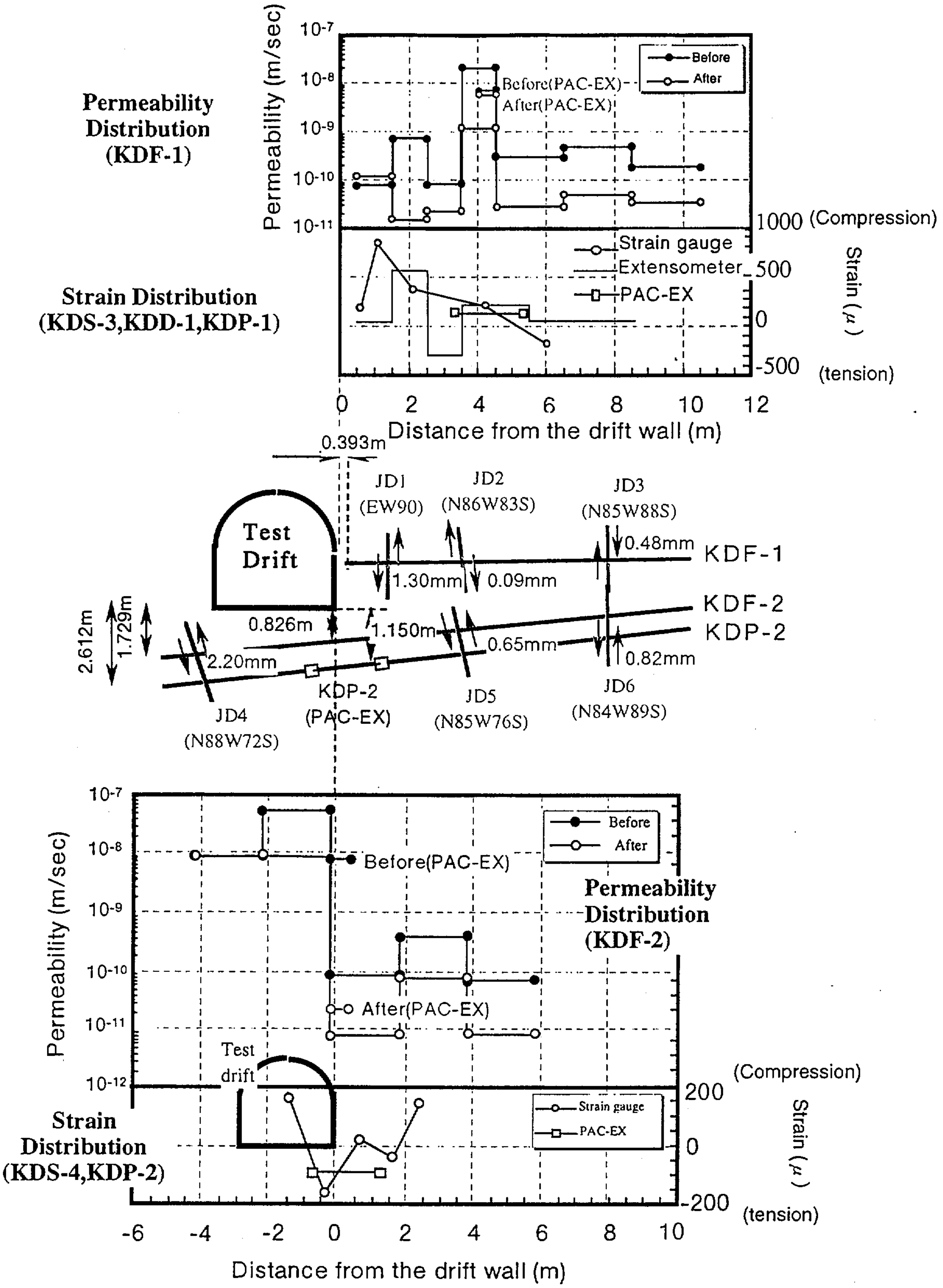
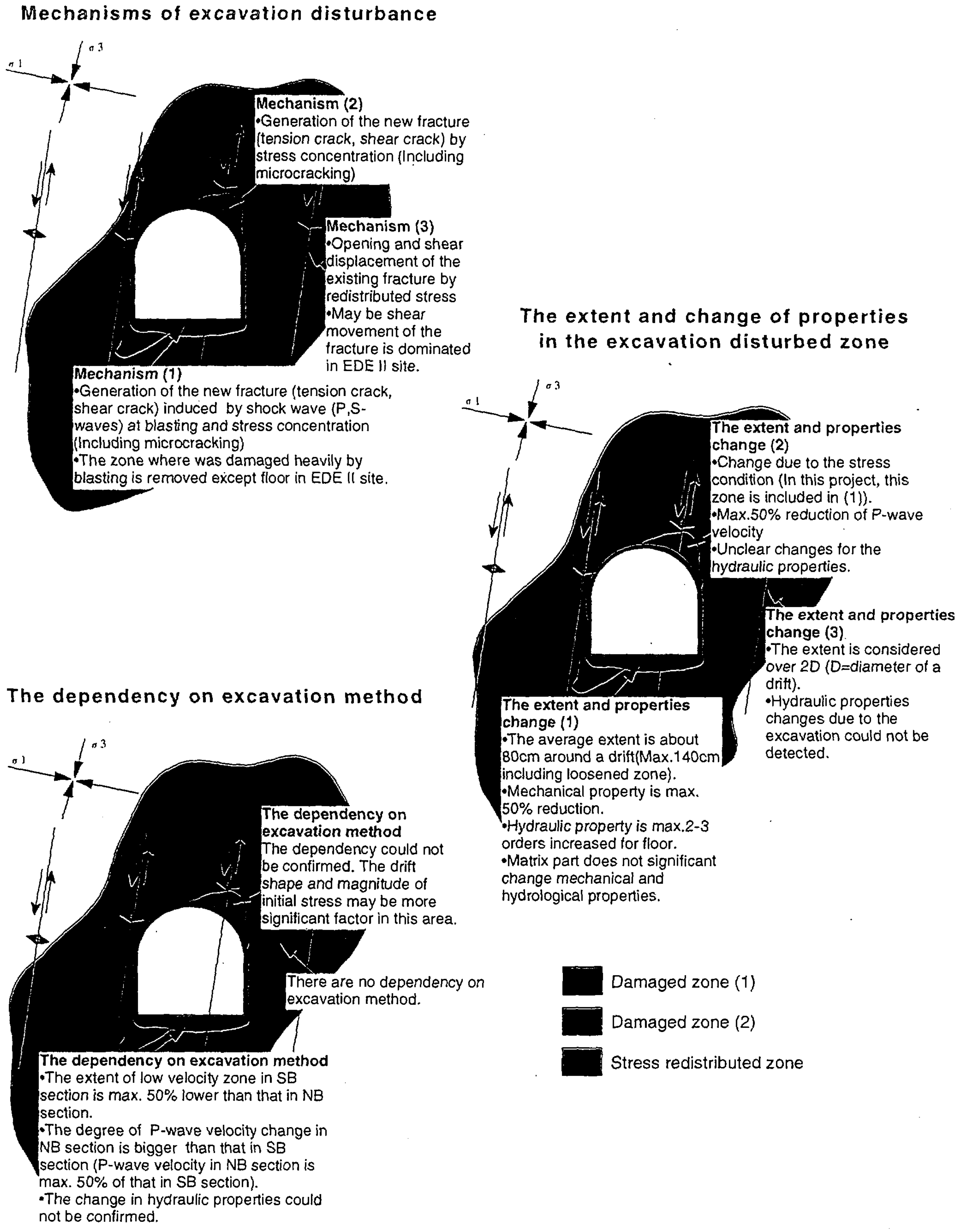


Figure 14 The results of all measurements in stress redistributed zone



Mechanisms of excavation disturbance

Mechanism (2)
- Generation of the new fracture (tension crack, shear crack) by stress concentration (Including microcracking)

Mechanism (3)
- Opening and shear displacement of the existing fracture by redistributed stress
- May be shear movement of the fracture is dominated in EDE II site.

Mechanism (1)
- Generation of the new fracture (tension crack, shear crack) induced by shock wave (P,S-waves) at blasting and stress concentration (Including microcracking)
- The zone where was damaged heavily by blasting is removed except floor in EDE II site.

The extent and change of properties in the excavation disturbed zone

The extent and properties change (2)
- Change due to the stress condition (In this project, this zone is included in (1)).
- Max.50% reduction of P-wave velocity
- Unclear changes for the hydraulic properties.

The extent and properties change (3)
- The extent is considered over 2D (D=diameter of a drift).
- Hydraulic properties changes due to the excavation could not be detected.

The extent and properties change (1)
- The average extent is about 80cm around a drift(Max.140cm including loosened zone).
- Mechanical property is max. 50% reduction.
- Hydraulic property is max.2-3 orders increased for floor.
- Matrix part does not significant change mechanical and hydrological properties.

The dependency on excavation method

The dependency on excavation method
The dependency could not be confirmed. The drift shape and magnitude of initial stress may be more significant factor in this area.

There are no dependency on excavation method.

The dependency on excavation method
- The extent of low velocity zone in SB section is max. 50% lower than that in NB section.
- The degree of P-wave velocity change in NB section is bigger than that in SB section (P-wave velocity in NB section is max. 50% of that in SB section).
- The change in hydraulic properties could not be confirmed.

■ Damaged zone (1)
■ Damaged zone (2)
■ Stress redistributed zone

Figure 15 The illstration of the conceptual model for excavation disturbance
Integrated results for all measurements and analyses