SEISMIC BEHAVIOR OF SHIELD TUNNEL ACROSS ACTIVE FAULT

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SUMMARY

In aseismic design of underground structures, it is important to comprehend the seismic behavior of the part of structure crossing significantly different grounds, and that of the part connecting different structures (e.g., joint part between shaft and tunnel). Although a number of studies have been conducted to investigate the seismic behavior of those special parts of underground structure, the behavior of underground structure across active fault has not been clarified. In this paper, the seismic behavior of shield tunnel across active fault is investigated through analysis of observed earthquake responses and 2-D FEM analysis. The main outcomes are as follows: 1) through the observed strains of tunnels, it is confirmed that the deformation of tunnel inside soft ground is large; and 2) the basic seismic characteristics of the part of tunnel across active fault are clarified through 2-D FEM analysis.

INTRODUCTION

In aseismic evaluation of underground structures, it is important to investigate the behavior of the structure part crossing significantly different grounds and that of the part connecting completely different types of structures [Kawashima (1994)]. During Hyogoken-Nanbu Earthquake occurred in 1995, many earthquake-induced damages of underground structures were found in the joint region between different structures [Geotechnical Society (1996)]. As the seismic behavior of the underground structure crossing significantly different grounds or with remarkable variation of structure type, is three dimensional, the aseismic design of such structures is not simple although the seismic characteristics have been clarified somehow through dynamic analysis and earthquake observation [Ohbo (1993)]. Especially, there have been very few studies focused on the seismic behavior of tunnel crossing active fault, where the ground condition significantly varies.

The authors have conducted earthquake observation at a utility tunnel (shield tunnel) crossing an active fault since April 1996 [Ohbo, (1997), (1998)], in order to clarify the seismic behavior and confirm the aseismic capability. In this paper, the earthquake response characteristics of the shield tunnel crossing an active fault are analyzed through the observed records, and the dynamic analysis by two-dimensional FEM.

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SITE CONDITION AND OUTLINE OF STRUCTURE

The shield tunnel was constructed crossing Takeyama fault at several places. The seismic activity rank and certainty of fault existence (called occurrence possibility in figure) is are evaluated as A class and I degree, respectively. Figure 1 shows the geological section of the site where shield tunnel crosses the active fault, based on boring data and various geological information. The tunnel crosses the hard clay region (Mmd) on the side of Tsukui pump station side to reach the active fault, and then crosses silt sand stone region (Hsd) and tufaceous sand stone region on the side of Nishi filtration center.

Through the components analysis during excavation progress of shield tunnel, it was confirmed that less clay with high cohesion was found when it was close to the active fault, and more sandy components could be found after the fault was crossed.

The shield tunnel with diameter of 3.05m, where earthquake observation is being conducted, was constructed using concrete segments. Enforced plastic composite pipe with diameter of 0.9m for sewage and steel pipe with diameter of 1.2m for water supply were set inside the tunnel, as shown in Fig. 2. Considering the importance of the facility, countermeasure against the large deformation of tunnel due to active fault activity is employed to guarantee the performance of pipes.

Including the part under the sea, the Takeyama fault that the shield tunnel crosses, has a length of 20km. The predicted magnitude is 7 with occurrence period of 500—4000 years, and the transverse displacement towards the right side is supposed to be 1.6m [Research Group on Active Fault (1991)].

OUTLINE OF EARTHQUAKE OBSERVATION

Objectives

As the seismic behavior of shield tunnel crossing active fault has not been clarified and evaluation method of aseismic performance has not been established, the earthquake response investigation has become an urgent task. The objectives of the earthquake observation are as follows:

a) Understanding of response differences of tunnel due to differences of geological conditions on the both sides of active fault.
b) Investigation of activity of active fault
c) Feedback to aseismic design of shield tunnel

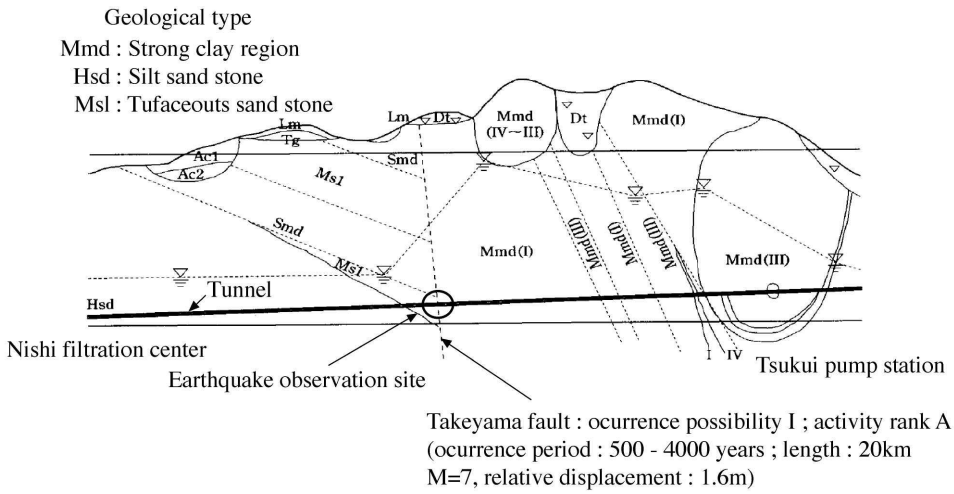


Figure 1: Geological section of observation site

Arrangement of Observation Instrument

Based on the results of geological survey and boring data during excavating progress of shield tunnel, the measuring instruments were set at the place where the tunnel crosses the Takeyama fault, and at the places 20m apart from the fault on both rock ground side and crushed ground side, which are indicated by circle mark in Fig. 1. In detail, the observation instruments were set inside the tunnel at the position where the tunnel right crosses the active fault (hereafter called fault), and at the positions 10m from the fault on both rock ground side and crushed ground side (strong clay layer). Displacement recorders with 4 channels were set in order to measure the longitudinal displacement between segments at fault position and on crushed ground side, strain gauges with 4 channels were set 10m from the fault to observe circumferential strain

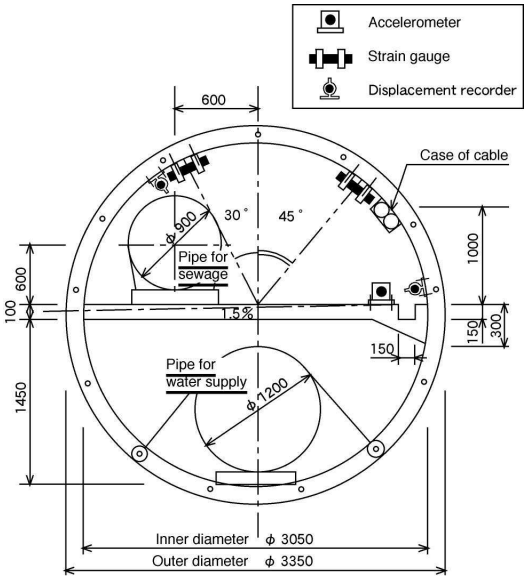


Figure 2: Arrangement of observation instruments

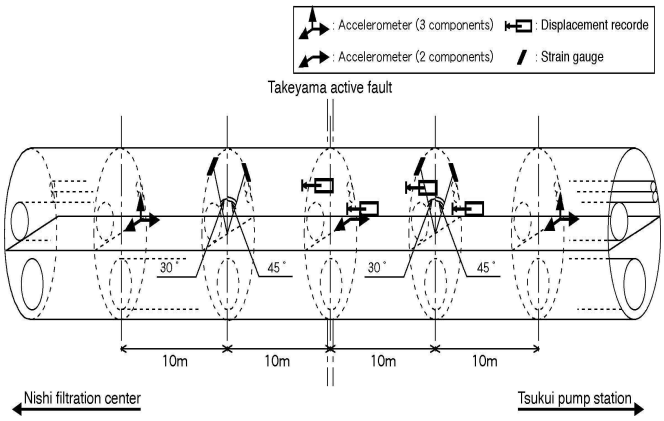


Figure 3: Arrangement of observation instruments

on rock ground side and crushed ground side, and accelerometers with 8 channels were prepared to measure longitudinal, transverse and vertical accelerations at fault and on rock ground side and crushed ground side. In total, 16 channels of records could be observed. The arrangement of accelerometers, displacement recorders and strain gauges is shown in Fig. 2 and 3.

Observation system

The tunnel part near the fault where the observation instruments with 16 channels are set is about 2km from the pump station. The instruments are prepared to record the observed signals at pump station, which are connected to the observation instruments inside tunnel through cables. The sampling frequency is 100Hz, and the delay time is 20 seconds. The observation system is triggered when acceleration observed is larger than 1 Gal (cm/sec^2). The observed data of this system is transferred by phone line. In addition, the value of observed acceleration will be displayed in data processing room at pump station when seismic intensity is larger than 3.

OBSERVED RECORDS

69 earthquakes have been recorded from April 1996 to the end of 1998. Table 1 shows the epicenter, magnitude, maximum acceleration, maximum strain and displacement for 19 earthquakes, of which the seismic intensity in Yokosuka city is larger than the JMA intensity 2 and the maximum recorded acceleration amplitude inside tunnel is bigger than 5 Gal. The maximum acceleration of about 15 Gal was observed during No.18 earthquake with epicenter in TOKYO BAY, and the maximum strain of about 14micron was recorded during No.3 earthquake with epicenter at E OFF CHIBA PREF. There has been no observed record for earthquakes with

epicenter on the active fault. The earthquake, of which the epicenter is the closest to the tunnel, is with magnitude of 4.1, the epicenter is at SAGAMI BAY, and the epicenter distance is 12km.

EARTHQUAKE RESPONSE CHARACTERISTICS OBTAINED FROM OBSERVED RRCORDS

Acceleration response characteristics

Figure 4 shows longitudinal (X direction) and transverse (Y direction) accelerations observed on rock ground side (hereafter called Rock in figure) and crushed ground side (hereafter called Soft in figure) during the No. 3 earthquake, which resulted in the largest strain of tunnel together with the Fourier spectra of accelerations. The larger acceleration is found on crushed ground side in longitudinal direction, and is observed on rock ground side in transverse direction.

At the frequencies below 2Hz, the predominant frequencies and peak amplitudes on rock ground side and crushed ground side are almost the same regardless of the observation direction. At higher frequencies, however, the predominant frequencies and peak amplitudes on the two sides are different in both longitudinal and transverse directions, which is caused by the difference in the geological conditions on the two sides.

Figure 5 indicates the ratios between spectrum of acceleration at fault and that on rock ground side, and the ratios between spectrum of acceleration on crushed ground side and that on rock ground side in longitudinal, transverse and vertical directions. The ratio of spectrum between rock ground side and fault part is close to 1.0, which demonstrates that the ground structure does not change significantly

Table 1: Observed earthquake

Event No.	Region	Time	Mj	X	Amax (Gal)	Strain (μ)	Dmax (Cm)
1	SAGAMI BAY	96: 07: 10: 23: 06	4. 1	12	2. 5	2. 1	0. 01
2	E YAMANASHI PREF	96: 08: 09: 03: 16	4. 6	71	6. 5	4. 7	0. 02
3	E OFF CHIBA PREF	96: 09: 11: 11: 37	6. 2	148	6. 6	13. 8	0. 06
4	E YAMANASHI PREF	96: 10: 25: 12: 25	4. 5	65	4. 6	4. 3	0. 03
5	S CHIBA PREF	96: 11: 15: 10: 30	4. 0	28	3. 2	2. 5	0. 03
6	SE OFF BOSO PENINSULA	96: 11: 20: 11: 27	6. 0	176	2. 4	5. 2	0. 02
7	SE OFF BOSO PENINSULA	96: 11: 28: 16: 40	5. 2	89	6. 4	9. 6	0. 04
8	S IBARAKI PREF	96: 12: 21: 10: 28	5. 4	102	3. 1	6. 6	0. 02
9	NW CHIBA PREF	97: 07: 09: 18: 36	5. 0	60	4. 2	6. 6	0. 05
10	TOKYO BAY	97: 09: 08: 08: 40	5. 1	50	8. 1	9. 1	0. 07
11	NW CHIBA PREF	98: 01: 14: 02: 17	4. 9	68	3. 9	6. 0	0. 05
12	S CHIBA PREF	98: 01: 16: 10: 57	4. 6	59	11. 2	9. 7	0. 05
13	E OFF IZU PENINSULA	98: 04: 26: 07: 37	4. 7	50	3. 0	3. 2	0. 05
14	E OFF IZU PENINSULA	98: 05: 03: 11: 09	5. 7	51	4. 7	8. 9	0. 05
15	S CHIBA PREF	98: 05: 16: 03: 45	4. 8	38	14. 1	10. 8	0. 06
16	E OFF CHIBA PREF	98: 06: 14: 22: 17	5. 6	105	2. 4	5. 9	0. 05
17	NEAR TORISIMA	98: 08: 20: 15: 40	7. 1	701	2. 3	-	-
18	TOKYO BAY	98: 08: 29: 08: 46	5. 1	57	14. 8	-	-
19	NW CHIBA PREF	98: 11: 08: 21: 40	4. 6	59	4. 7	-	-

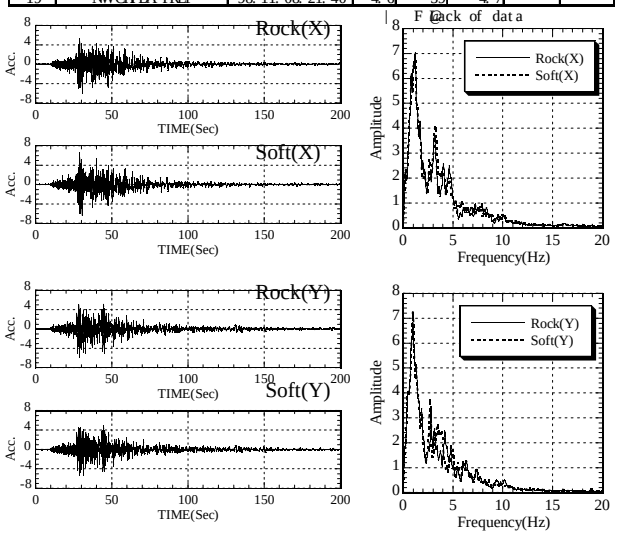
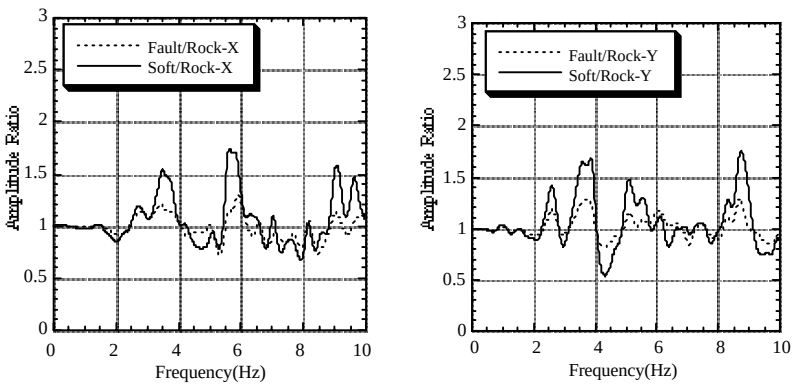


Figure 4: Observed accelerations and their Fourier spectra



(a) X-direction **(b) Y-direction**

Figure 5: Ratio between Fourier spectra of accelerations

in the region. On the other hands, clear peaks could be observed in the ratio of spectra between crushed ground side and rock ground side at 3.5Hz, 5.5Hz and 9Hz in longitudinal direction, and 3.5Hz, 5Hz and 9Hz in transverse direction. The predominant frequencies in longitudinal and transverse directions are different. The

occurrence of clear peaks is thought to be caused by the difference of ground structure on the two sides, and the difference in the predominant frequencies in the two vibration directions is due to the three dimensional behavior of the tunnel.

Circumferential strain of tunnel

Figure 6 shows the strain amplitude ratio between circumferential strain on crushed ground side and that on rock ground side. Although the strain amplitudes at the position with 45 degrees (hereafter called R in figure) on crushed ground side and rock ground side are close during the Event No. 9 and 12 Earthquakes, in all other cases, the circumferential strain on crushed ground side is always larger than that on rock ground side. It has to be mentioned that the strain was not observed during Event No. 17, 18 and 19 earthquakes because of the observation instrument troubles.

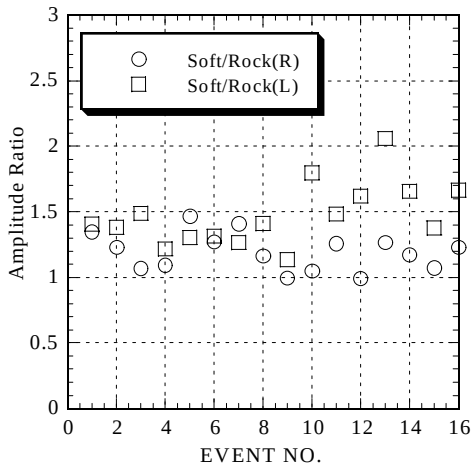


Figure 6: Ratio between strain amplitudes

Figure 7 indicates the comparison of circumferential strains at the position 10m from the fault during Event No.15 earthquake. The comparison of Fourier spectra of strain waveforms is also shown in the same figure. The maximum observed acceleration during Event No. 13 earthquake is 14.1 Gal, which is the second largest one in all observed records. The maximum strain during the earthquake was observed at the position with 45 degrees. However, as signal-to-noise ratio of the observed strain waves at the position was not good, the observed strain waves at the position with 30 degrees from the vertical plane is shown in the figure. It can be seen that the maximum strain on crushed ground side is larger than that on rock ground side. As for the predominant frequencies around 3.5Hz, the predominant frequency on crushed ground side is slightly smaller and the peak amplitude is larger than that on rock ground side. In the frequency range from 1.5 to 4Hz, the amplitude on crushed ground side is always larger.

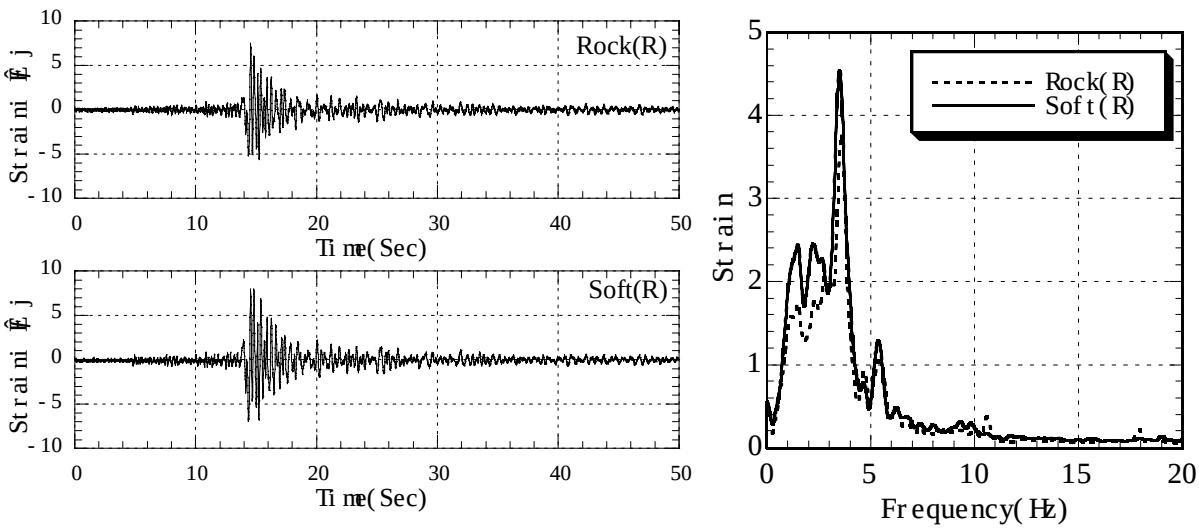


Figure 7: Comparison of circumferential strains

EARTHQUAKE RESPONSE CHARACTERISTICS OBTAINED THROUGH DYNAMIC ANALYSIS

Figure 8 shows the 2-D FEM model in transverse direction and vertical geological structure on Nishi filtration center and Tsukui pump station side. The FEM model is constructed based on the sectional geological conditions and boring data around tunnel. The lateral boundary is treated as horizontal roller, and viscous boundary is assumed at bottom of model. The segment of tunnel is modeled using beam element. As for the bottom rock layer, which is the base for both sides, as there is no survey results the material parameters for the tufaceous sand stone at the bottom of Nishi filtration center are employed. The input wave is applied from the bottom rock layer.

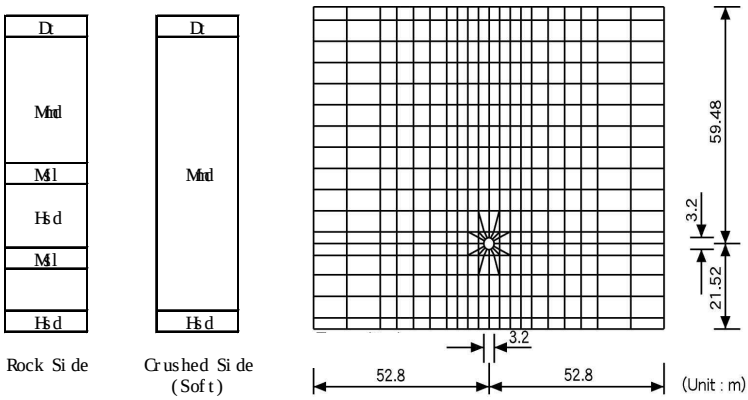


Figure 8: 2-D FEM model and outline of ground structure

Determination of input wave

As all the observation instruments are set inside the tunnel, there is no observed record at base layer, which is necessary for numerical simulation. In this study, the records observed during the same earthquake (Event No.15) at Hemi filtration plant, which is about 9km north of the observation site of tunnel, is adopted to determine the input wave. As the observed acceleration of base layer at Hemi filtration plant includes the effects of vibration properties of surface layer, the inverse numerical simulation is performed to obtain the acceleration at free base layer. The details of analysis model and outline of earthquake observation at Hemi filtration plant are introduced by Yamazaki [Yamazaki (1993)].

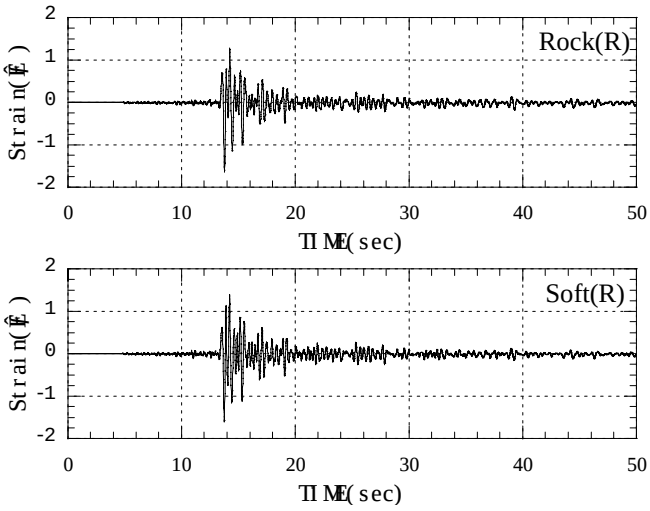


Figure 9: Strain waveforms

Comparison of strain waveforms

The strain waveforms at the position with 45 degrees, which is 10m from the fault, on rock ground side and crushed ground side are shown in Fig. 9. The maximum observed and simulated strains are 7.5micron and 1.5micron on rock ground side, and 7.9micron and 1.8micron on crushed ground side. The trend that the strain on crushed ground side is larger can be observed both from observed results and from simulated results. However, the simulated results are about 1/4 of observed ones. Therefore, further detailed study is required including the study of the method for determining the input wave at bottom rock layer.

Comparison of frequency characteristics

As the computed maximum acceleration is about 1/3--1/4 of the observed one, it is necessary to study the validity of ground structures of analysis model. Figure 10 shows the comparisons of Fourier spectra of acceleration and strain waves between observation and simulation. Although the spectrum amplitudes of observed results are larger than those of simulated ones, the observed and simulated frequency characteristics are quite similar. Therefore, it may be inferred that the analysis model is appropriate while the amplitude level of input wave is not correctly set.

CONCLUSIONS

In order to comprehend the fundamental response characteristics of a shield tunnel crossing an active fault, the observed results are analyzed, and numerical simulation by two-dimensional FEM model is performed. The main results are as follows.

1) Based on the maximum acceleration and vibration features, the difference in response characteristics on the two side of fault could not be clearly confirmed.
2) From the observed circumferential strains of tunnel, it is confirmed that the deformation of tunnel on crushed ground side is larger than that on rock ground side.
3) The difference between fundamental response characteristics on crushed ground side and rock ground site is clarified through two-dimensional FEM analysis.

Although the displacement recorder has been set, the displacement waveform with good accuracy has not been observed. In order to investigate the deformation characteristics of tunnel during earthquakes, further study will be performed using observed strain waveforms and the displacement waves obtained by integration of observed acceleration waveforms at the three sites inside the tunnel. In addition, analysis model considering the deep ground structure is going to be constructed because the present model does not reflect the effects of deep ground structure and only consider the surrounding ground conditions.

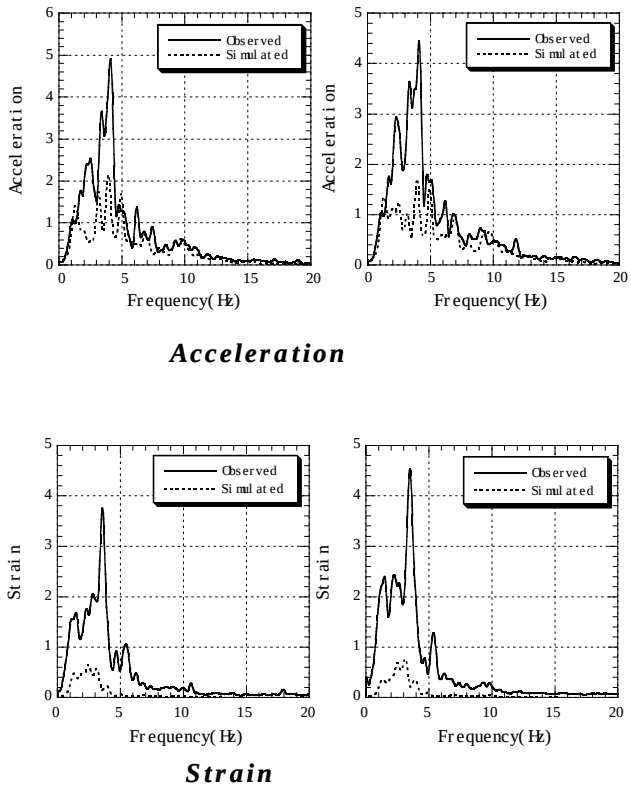


Figure 10: Comparisons of Fourier spectrum of acceleration and strain waveforms

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