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DYNAMIC BEHAVIOR OF AN UNDERGROUND WATERWAY DURING EARTHQUAKES

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SUMMARY

In order to investigate the seismic behavior of an underground waterway, seismic observation has been carried on since July 1982. The characteristics of seismic motion and strain in the waterway are examined by analyzing 40 earthquake-data observed until Oct. 1985. The strain derived from the dynamic analysis by means of multiple mass-spring model is in good agreement with observed one. Seismic strain can be classified into the two types of pattern. In the Surface wave type earthquakes, the phase lag cannot be neglected in the input of seismic data.

INTRODUCTION

For the purpose of investigating the seismic behavior of underground structure, seismic observations in buried structures, such as gas distribution systems and submerged tunnels, were carried out by some groups. Consequently, multiple mass-spring model was proposed as the method of earthquake resistant design for submerged tunnels (Ref.1). Recently, the availability of this method is reported from observed data at submerged tunnels which had been designed using this method (Ref.2,3). Although the data observed in these structures are increasing gradually, seismic behavior of these structures are not yet clear.

Seismic observation has been carried on since July 1982, in order to examine the dynamic behavior of the waterway and interaction between this waterway and surrounding ground during earthquakes. In this paper, emphasis is placed on the following: to deduce the relation between seismic motion and strain in the waterway, and to examine the seismic strain observed in the waterway in comparison to the computed one on the simulation model.

OBSERVATION

The waterway (total length : about 1.6 km) constructed in soft alluvial deposits is composed of reinforced concrete elements. Each element measures 11m wide, 6 m high and 15 to 18 m long, and has two aqueducts of box section 4.5 m x 4.5 m. As be shown in Fig.2, the alluvial deposits of 20 to 25 m thick and diluvial clayey and silty layers of about 10 m in total thickness overlie diluvial gravel bed, whose N-value is about 50.

At five observation points on the waterway (see Fig. 1) each pair of longitudinal, that is, axial and transverse strainmeter are set up on the crest and on

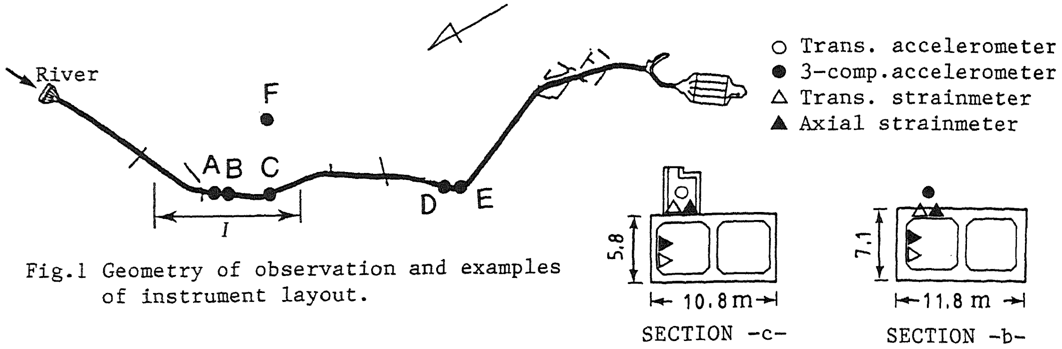


Fig.1 Geometry of observation and examples of instrument layout.

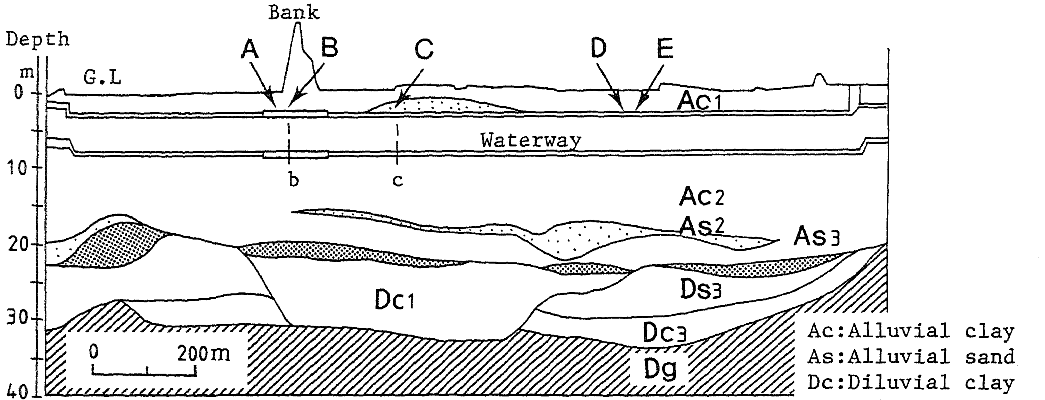


Fig.2 profile of strata along the waterway

the side wall of the left-hand aqueduct. Near the strainmeter on the crest, transverse accelerometer are installed on one of the straight element (Obs. pt. C) and on the curved one (Obs. pt. E), and a three-component accelerometer is on one of the elements across the embankment (Obs. pt. B). Three-component accelerometers are installed at the bottom of -7.0 m and of -34.6 m level in respective boreholes at the observation point about 300 m apart from the waterway (Obs. pt. F). The latter is concerned with the incident seismic waves on the diluvial gravel bed, the foundation of the waterway, and the former does with the earthquake motions in the alluvial deposits at the same level that the waterway lies buried.

Table 1 S wave velocity at Obs. pt. F

Depth (m)	Vs (m/s)	Density (g/cm³)
	85	1.60
2.3		
	190	1.90
8.8		
	125	1.65
20.3		
	165	1.75
22.3		
	230	1.90
32.3		
	670	2.10

Table 1 shows the S wave velocity profile at the observation point F (Ref.4). Corresponding to the velocity profile, the transfer function is derived from multiple reflection theory. It is found that the predominant frequency of this site is about 1.4 Hz.

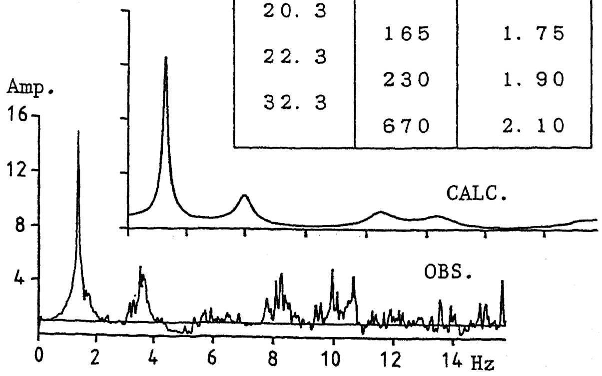


Fig.3 Transfer function between -7.0 m and -34.6 m at Obs. pt. F

DATA ANALYSIS

The magnitudes and the epicentral distances of 40 earthquakes, observed between July 1982 and Oct. 1985, are distributed from 4.2 to 7.3 and 21 km to 726 km, respectively. The seismograms observed by the accelerometers were analyzed by means of Fast Fourier transform, and velocity- and displacement-seismograms were integrated in frequency domain.

Observed seismic strain in the waterway The relation between the axial maximum strains and the maximum particle velocities observed at the observation point B is shown in Fig.4. The maximum strain ε is closely related to the maximum velocity v. The following relation is obtained by applying linear regression analysis,

$$\log \varepsilon = -0.237 + 0.81 \log v$$

Seismic strain can be classified into the two types of pattern. One is Body wave type, where the maximum strain is observed at the arrival time of S waves. The other is Surface wave type, where the maximum strain appears while the waterway is influenced by surface waves, induced due to large shallow earthquakes. A typical example of the latter is the case of the Naganoken-seibu earthquake of Sept.14, 1984. In this earthquake, Love waves were predominant as shown in Fig.5 (Ref.5). Time histories of the acceleration, particle velocity and strain, and corresponding Fourier spectra of longitudinal component at the observation point B, are shown in Fig.6. The strain and velocity are the same phase and have the period of 4 to 5 sec, while their amplitudes are maximum. The strain is closely similar to the velocity in frequency domain too. In order to examine the details of their relation in frequency domain, the spectrum ratios of strain to acceleration and to velocity were computed. They are shown in Fig. 7. In computation, small spectrum amplitudes were omitted, and common predominant frequency was remarked. The spectrum ratio of strain to velocity is almost constant for the periods. The value 0.8 is nearly equal to the constant 0.81 obtained by applying linear regression analysis (see Fig.4).

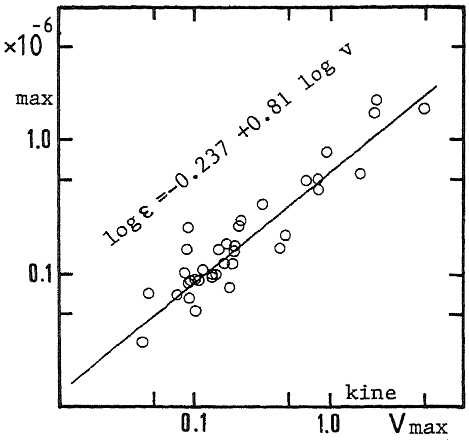


Fig.4 Relation between maximum axial strain and maximum particle velocity

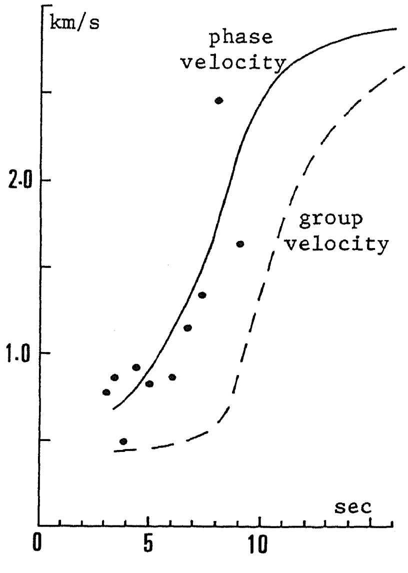
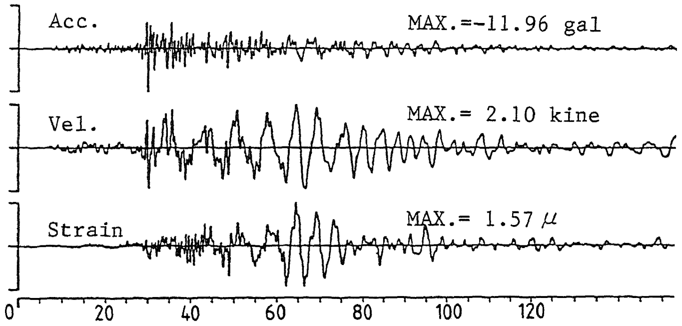


Fig.5 Dispersion curves derived from data at Obs. pt. B and F (Naganoken-Seibu Earthquake)

Generally, seismic ground strain ε_o induced by propagating wave is estimated from the equation: $\varepsilon_o = v / c$, in which, v is the particle velocity, c is the apparent propagating velocity. In the case of the Naganoken-seibu earthquake, the apparent propagating velocity is 1050 m/s, which is derived from the coefficient of cross correlation between the seismograms at the observation point B and F. Assuming that the particle velocity is 2.1 kine which is the maximum particle velocity obtained in the waterway (see Fig.7), the ground strain is estimated as 20×10^{-6}. If the actual ground strain is nearly equal to this value, strain in the waterway is under 10 % of the ground one, because the observed maximum strain is 1.6×10^{-6}.



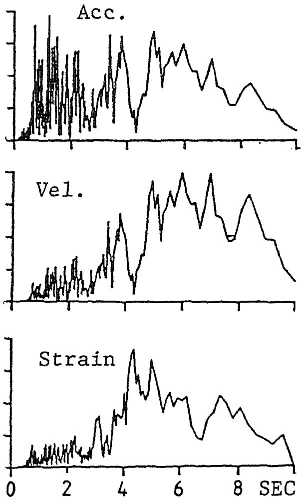


Fig.6 Time histories and Fourier spectra of the Nagano-ken-Seibu Earthquake (M=6.8, Depth 2km, Δ=183km)

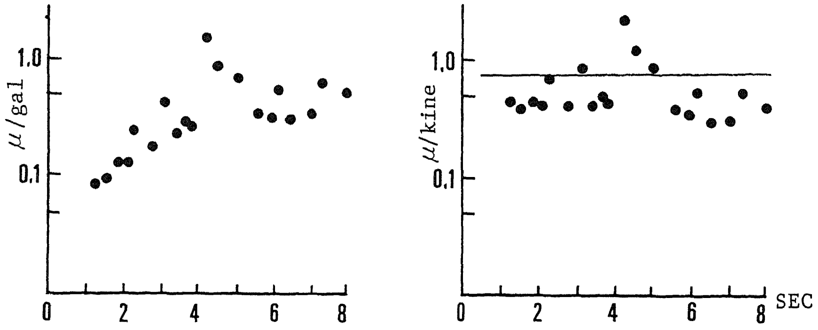


Fig.7 Ratios of spectra 1) Strain/Acc. 2) Strain/Vel.

EARTHQUAKE RESPONSE ANALYSIS

For explanation of seismic strain observed in the waterway, simulation was performed by means of multiple mass-spring model proposed as the method of earthquake resistant design for submerged tunnels by Tamura et. al (Ref.1). The multiple mass-spring model had been used in the earthquake resistant design for this waterway. In the simulation model, following assumptions are used: the inertia force of the waterway is ignored; the waterway is a beam on an elastic foundation; the section force of the waterway is derived from the displacement of ground along the waterway axis, by using the stiffness of waterway and the spring constant between ground and waterway.

Example of analysis model Dynamic analysis was applied to the division I containing observation points A, B and C of the waterway (see in Fig.1). Analysis was made by the Tamura's method with some modification. The waves propagating lateral direction could be inputted for the existence of surface waves in observed seismograms (e.g. Naganoken-seibu earthquake). Because that the waterway in the analyzed division is curved a little at its ends, the spring is assumed the longitudinal and transverse directions. The ground of analyzed division are divided into 36 masses. The ground constants (rigidity, density etc.) are refered to the results of PS logging. Damping constant of the ground is decided by the frequency response curve of observed data. It is assumed that the embankment has no influence to its surrounding ground in dynamic behavior. The waterway is regarded as the beam with its equivalent stiffness, and a linear spring is substituted for the joint between adjacent elements. This joint spring constants (e.g. 10,600 t/m for flexible joints) are estimated from the properties of the joint materials. Furthermore, dummy parts of 60 m are added to the ends of the analyzed division to neglect its boundary condition.

Results of analysis Analysis was performed on the Ibarakiken-nanbu earthquake (Oct. 4, 1985; M=6.1, Depth=78km, Δ=49 km) as a typical example for Body wave type, and on the Naganoken-seibu earthquake (Sept.14, 1984; M=6.8, Depth= 2Km, Δ=183 km) as one for Surface wave type. In computation, seismogram of the Ibarakiken-nanbu earthquake observed on the foundation of the waterway was simultaneously inputted as the incident waves, and one of the Naganoken-seibu earthquake was done with phase lag on the gravel bed. Because, in the latter case, it was thought that seismic waves of large amplitude might propagate as plane wave from west, the direction from the origin to observation points. Apparent propagating velocity 1050 m/s that is determined by the coefficient of cross correlation computed from the records of two points, is used as a phase lag. Figure 8 shows the observed and computed longitudinal strain time histories and corresponding Fourier spectra, at observation point B at the Ibarakiken-nanbu earthquake. From this figure, the computed strain is in good agreement with observed one. The same result of the Naganoken-seibu earthquake is shown in Fig.9.

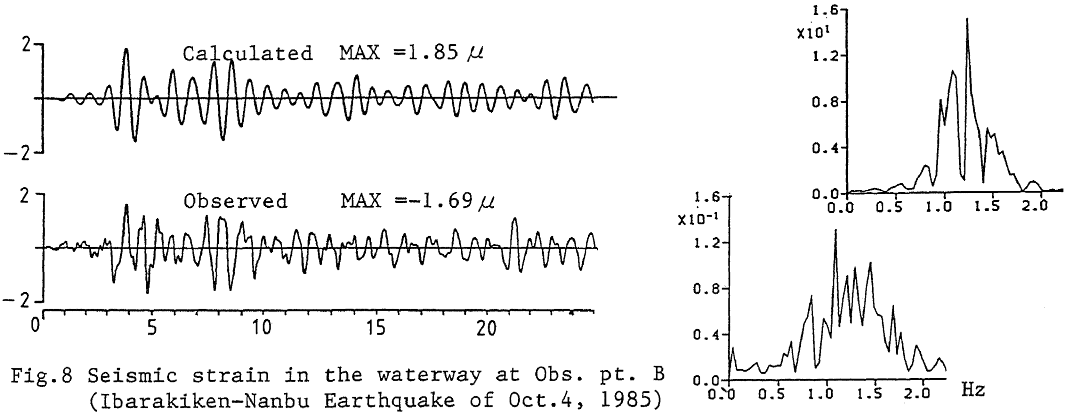


Fig.8 Seismic strain in the waterway at Obs. pt. B (Ibarakiken-Nanbu Earthquake of Oct.4, 1985)

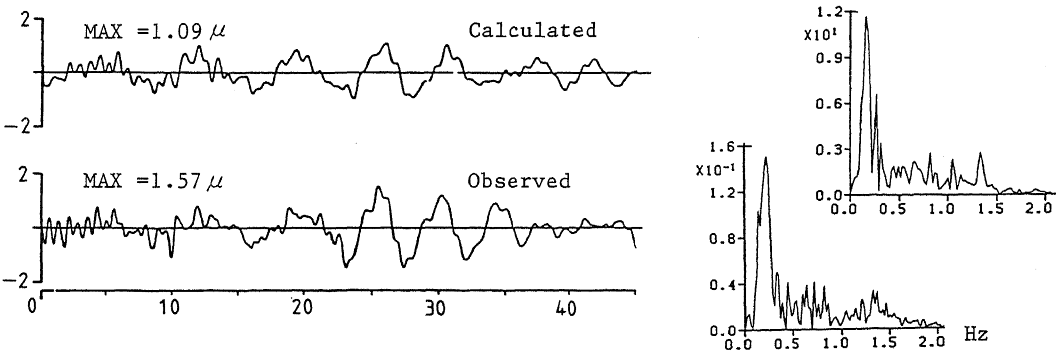


Fig.9 Seismic strain in the waterway at Obs. pt. B (Naganoken-Seibu Earthquake of Sept.14, 1984)

It is found that the computed strain generally agrees with the observed one as long as the incident seismic wave provided with a phase lag in the case of surface wave type, though both strains are almost in accord without consideration for a phase lag in the case of Body wave type. Figure 10 shows the change of axial force to the apparent propagating velocity in the case of the Naganoken-seibu earthquake. Axial force, v = 1050 m/s, is almost two times compared to one without phase lag.

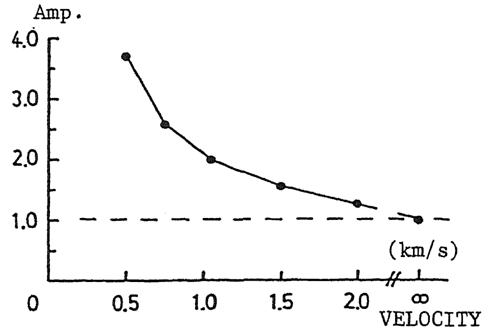


Fig.10 Relation between propagation velocity and axial force of a waterway

CONCLUSION

From earthquake observation and its data analysis, the following results are obtained,

The maximum strain in the waterway is observed when S wave with the maximum amplitude reaches to the waterway in most cases. As large shallow earthquakes are apt to predominant surface waves, the maximum strain appears while the waterway is influenced by surface waves. In the Surface wave type, strain is very similar to the particle velocity as well as the equation $\varepsilon_0 = v / c$ which is cited usually, and so in frequency domain. When we want to decide the ground strain by using this equation, the strain in the waterway is estimated under 10% of the ground one.

The characteristics of two types (Body wave type and Surface wave type) of strain obtained in the waterway is almost explained with some modification to the input condition of multiple mass-spring model. So it is necessary to separate the incident seismic wave according to the pattern of waves. In the surface wave type earthquakes, the phase lag cannot be neglected in the input of seismic data. In particular, the absolute value of section force is severely affected by the phase lag: one with the phase lag corresponding to phase velocity 1050 m/s is two times of one without phase lag. The characteristics of strain for only the fundamental shearing mode of ground, elucidate well the observed one.

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