EARTHQUAKE OBSERVATION OF UNDERGROUND STRUCTURE AND ASEISMIC DESIGN

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1. Summary

In order to clarify the dynamic characteristics of underground structures during earthquakes and obtain fundamental informations for the aseismic design, earthquake observations have been carried out on three kinds of underground structures.

By the study of earthquake records close correlations were found between dynamic strains of underground structures and those of the surrounding ground. Based on the results of the observations a numerical model was proposed to obtain the behavior of the underground structures during earthquakes. By using this model dynamic strains of underground structures were calculated and stress evaluation charts for the aseismic design were prepared.

2. Profiles of Underground Structures

Earthquake observations and numerical analyses have been carried out on the following structures.

Underground Tank

It is constructed for water storage in the reclaimed ground with 150m/sec shear wave velocity, and its diameter, depth and wall thickness are 24m, 10.3m and 0.9m, respectively as shown in Figure 1.

Rock Tunnel

It is constructed in sound slate with about 2000m/sec shear wave velocity. This tunnel is 4670m in length and its section is 4.8 x 6.1m horseshoe shape with 0.3m thickness concrete lining as shown in Fig. 2.

Submerged Tunnel

It consists of 9 reinforced concrete elements and each element is connected with flexible joints. The element has 37.4m x 8.8m rectangular section and 115m length as shown in Fig. 3. The surrounding ground of the tunnel is soft alluvial layer with about 100m/sec shear wave velocity.

3. Earthquake Observation

The locations of accelerometers and strain meters of each structure are also shown in Fig. 1~3. From the studies reported[1),2)] already, followings have been known about the characteristics of the acceleration of the underground structures and the ground. The accelerations of underground structures are very similar to those of the ground. The dominant periods of accelerations of the structures and surrounding ground are almost the same, and any influence of the natural vibration due to the inertia force of the structures can not be found.

About the characteristics of the dynamic strain of each structure, the following results can be obtained.

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Underground Tank

As shown in Fig. 4(a) circumferential strains on the inner surface of the tank wall has a good similarity to the relative displacement (DIY-D3'Y) between the two points on the ground surface which are distant from the tank wall with about one diameter. The dynamic strain of the underground tank is about 5% of that of the ground calculated from the relative displacement.

Rock Tunnel

As shown in Fig. 5(a), (b) the axial strain of the tunnel lining has a good similarity to the strain of the rock in the axial direction. The strain of the rock was obtained as the ratio of the particle velocity to the phase velocity of the acceleration on the assumptions that the recorded seismic wave was consisted of only the body wave and the phase velocity was constant. The time lag along the tunnel was obtained by the cross-correlation function.

Furthermore, as shown in Fig. 6(a), (b) the circumferential strain at the arch of the cross section is also very similar to the shear strain γyz of the rock which was obtained by multi-reflection theory.

The dynamic strain of the tunnel lining in axial direction is about 35% of that of the rock, and also about 60% in circumferential direction.

Submerged Tunnel

According to Fig. 7 a close correlation can be found between the axial strain of the submerged tunnel and that of the ground. The strain of ground is also obtained as the ratio of the particle velocity to the phase velocity. The strain of the submerged tunnel is about 15% of that of the ground.

4. Numerial Analysis

The deformations and the strains of underground structures during earthquakes were analyzed on the following assumptions based on the results of the earthquake observations.

(1) The inertia forces of the underground structures are not taken into account of the analysis since those effects upon the strains of the underground of structures can be considered to be very small.

(2) The deformations of the structures are calculated from the following static equilibrium equation.

$$[Ks]\cdot\{Ws\}=[Kg]\cdot(\{Wg\}-\{Ws\}) \qquad \text{(Eq. 1)}$$

Where the matrixes [Ks] and [Kg] represent the stiffness of the structure and the ground, respectively. The deformation of the underground structures {Wg} can be obtained from the given displacement of free field ground {Ws} at each time step.

Underground Tank

Fig. 8(a) shows the numerical model of the underground tank. The underground tank is modelled to an axisymmetric shell supported by soil springs Kr, Kø, Kz. Fig. 8(b) shows the calculated circumferential strains of the wall and a good agreement is found between the calculated strains and the observed ones.

Rock Tunnel

Circumferential strains of the tunnel lining were calculated by finite element model in which 54m x 26m rock area was modelled as shown in Fig. 9(a). Equivalent displacements to rock strains were enforced on the boundary of the model. The normal strains γzz, γyy and the shear strain γyz of the rock were obtained on the following procedure. The strains γzz and γyy were assumed to be caused by the seismic motion that vibrate and propagate in z direction or y direction respectively, while γyz was assumed to be caused by the motion that vibrates in y direction and propagates in z direction. Relaxed zones around the cavity by the excavation and small gaps between the lining and the rock were taken into account in the model. The strain calculated by a model without the relaxed zones and the gaps is considerably greater than the measured by the effect of the strain concentration around the cavity. The calculated strain at the crown agree well with the measured one as shown in Fig. 9(b).

Submerged Tunnel

The numerical model of the submerged tunnel for the seismic motions with comparatively long periods such as surface waves is shown in Fig. 10(a). The tunnel is modelled as a beam on a elastic foundation of the ground. The dynamic response of the surface layer was not considered. Fig. 10(b) shows the calculated axial strains of tunnel and a good agreement with the measured strain can be seen.

5. Aseismic Design

From the earthquake observations and the numerical analyses, it was clarified that the dynamic strain of underground structures during earthquakes was determined by that of the surrounding ground.

Generally, the dynamic strain of underground structures can be written as follows:

$$\varepsilon_S = \alpha \cdot \varepsilon_G \qquad \text{(Eq. 2)}$$

where ε_S and ε_G are the dynamic strain of the underground structure and the ground, respectively. α is assumed to be constant in frequency domain and determined as a function of the stiffness ratio between the structure and the ground.

Underground Tank

Fig. 11(b), (c) shows the examples of the stress evaluation charts calculated by the shell model, where non-dimensional parameters $Kr \cdot r^2/E.d$, $d/2r$ and $k\phi/Kr$ are used, which are determined from concrete Young's modulus E, thickness of the wall d, radius of shell r and coefficient of subgrade reaction Kr in radius direction and $K\phi$ in circumferential direction. The ordinate shows the ratio α of the strain of the tank wall to that of the ground γxx, γxy. σ_M/E is the strain due to the bending deformation and σ_N/E is that due to the circumferential deformation. In these figures circles show the results of the underground tank where the earthquake observation was carried out.

From these charts the following characteristics were obtained.

(1) The strain due to the bending deformation is larger than that due to the circumferential deformation in the case of the tank constructed in the soft alluvial layer, because the parameter $Kr \cdot r^2/E \cdot d$ can be estimated to be

smaller than 0.1.
(2) The infulence of the coefficient of the subgrade reaction upon the bending strains is small because the ratio d/2r is estimated to be 0.02∿ 0.04 generally.

Submerged Tunnel

Fig. 12(a), (b) are examples of the charts calculated by the beam model, where non-dimensional parameters $L\cdot\sqrt{K_1/EA}$ and EA/L/Ko are used, which are determined from concrete Young's modulus E, cross area A, element length L, joint rigidity Ko and coefficient of subgrade reaction K_1 in axial direction. The ordinate shows the ratio α of the strain of the element εp or the pseudo-strain of the joint εj to the strain of ground εg. In these figures, circles show the results of the submerged tunnel where the earthquake observation was carried out.

6. Conclusion

Through the earthquake observations and numerical analyses, dynamic characteristics of three kinds of underground structures, tank in the alluvial layer, rock tunnel and submerged tunnel in the sea bed, were discussed.
(1) According to the earthquake observations, the dynamic strains of underground structures had close correlations to the relative displacements or the velocity of the ground, namely the dynamic strain of the ground.
(2) The numerical models proposed on the reference of earthquake observation results, where the static equilibrium was considered, introduced good agreements of the calculated strain with the observed.
(3) Stress evaluation charts for the aseismic design of underground structures were prepared, where the ratio of the dynamic strain of structures to that of the ground during earthquakes was estimated by the function of the ratio of the structure's stiffness to the ground's. For example the dynamic strain of the submerged tunnel in the soft alluvial layer is only 15% of the ground strain but the dynamic strain of the tunnel in sound rock is 60% of the rock strain.

References

1. M. Hamada, S. Sato; Behavior of Underground Tank during Earthquake, 6WCEE, VOL. IV pp.49 ∿ 54, 1976
2. M. Hamada, T. Akimoto and H. Izumi; Dynamic Stress of a Submerged Tunnel during Earthquake, 6WCEE, VOL. IV, pp.55 ∿ 60, 1976

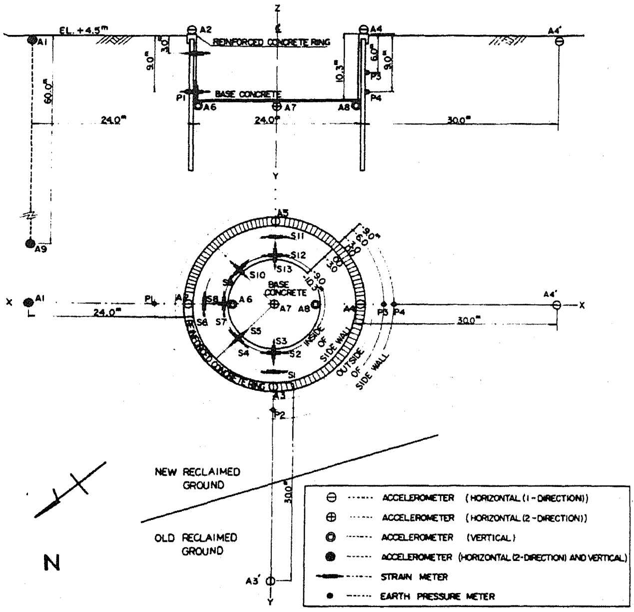
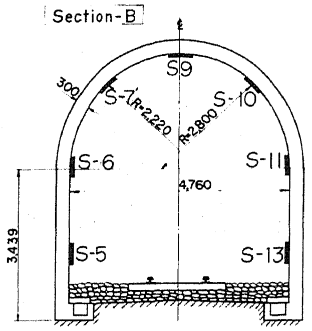
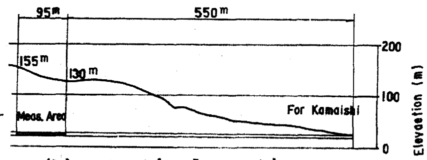


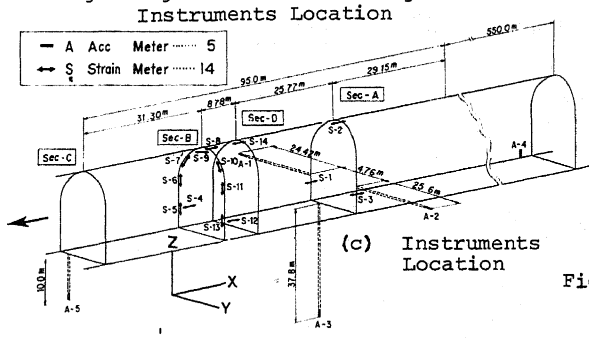
Fig.1 Gegeral View of Underground Tank and Instruments Location



(a) Cross Section



(b) Vertical Section



(c) Instruments Location

Fig.2 Rock Tunnel

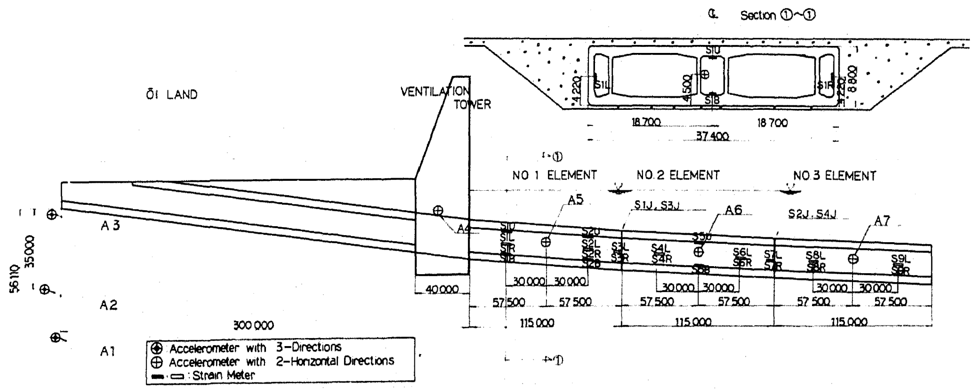
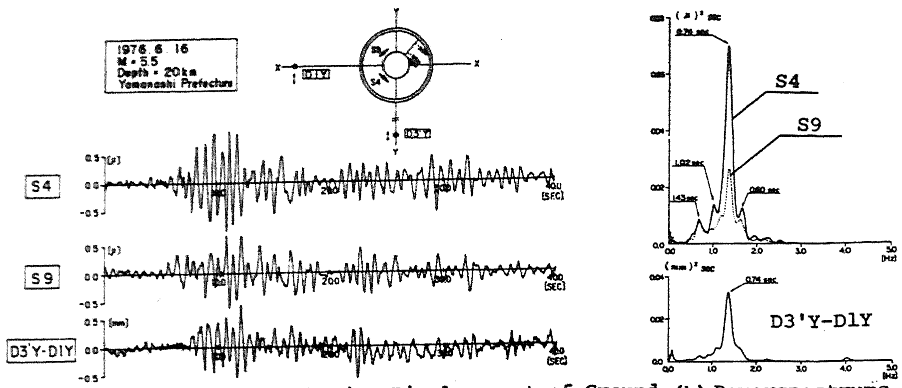
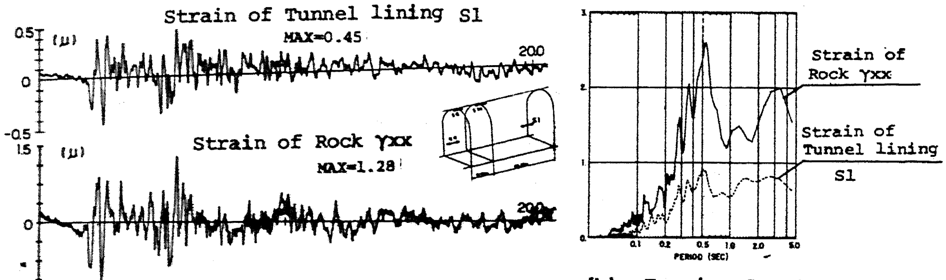


Fig.3 General View of Submerged Tunnel and Instruments Location



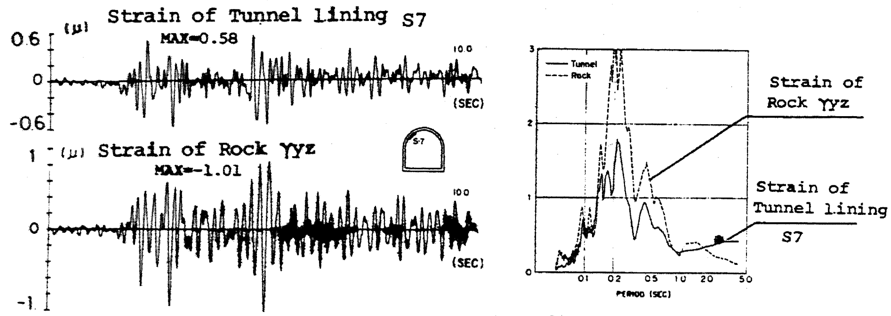
(a) Strain of Tank and Relative Displacement of Ground (b) Powerspectrums

Fig.4 Circumferential Strains of Tank and Relative Displacement of Ground



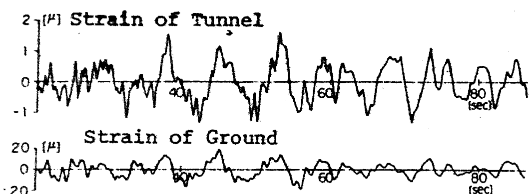
(a) Strain of Tunnel Lining and Rock (b) Fourier Spectrums

Fig.5 Strain of Tunnel Lining and Rock in the Axial Direction



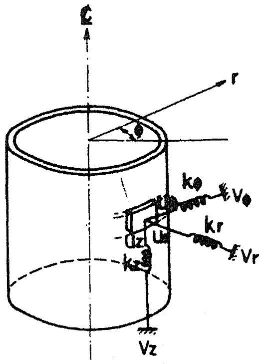
(a) Circumferential Strain and Shear Strain (b) Fourier Spectrums

Fig.6 Circumferential Strain of Tunnel Lining and Shear Strain of Rock γyz

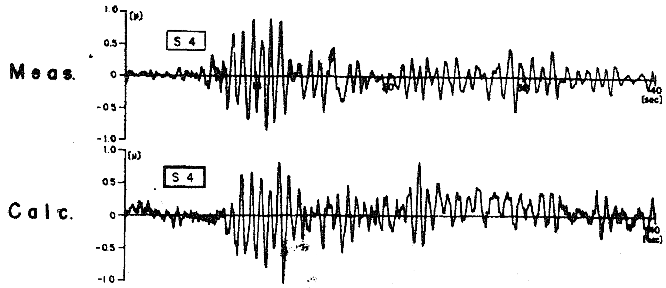


(Near Izu Oshima Earthq.
of 14th Jan., 1978,
M=7.0, Δ=100km, D<10km)

Fig.7 Axial Strain of Submerged Tunnel and Strain of Ground



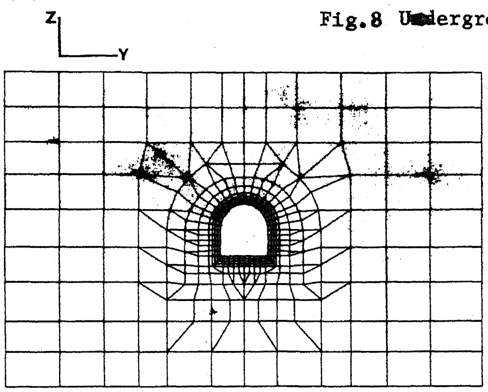
(a) Numerical Model



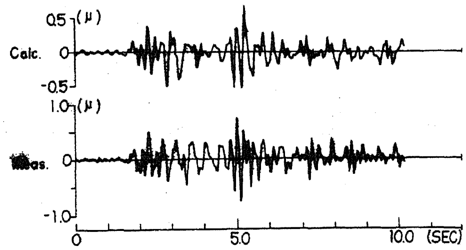
(b) Measured and Calculated Strain

(East Yamanashi Earthquake of 16th June, 1976)

Fig.8 Underground Tank

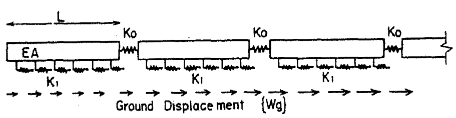


(a) Finite Element Model

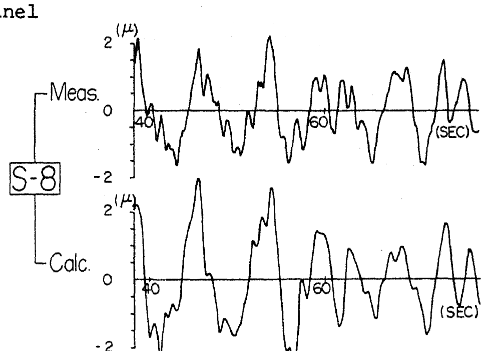


(b) Measured and Calculated Strains of the Crown (After Shock of Off Miyagi Earthquake of 21st June, 1978)

Fig.9 Rock Tunnel

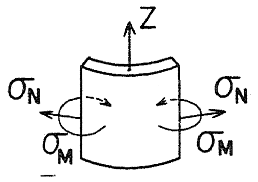


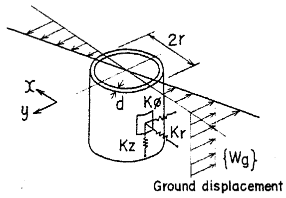
(a) Numerical Model



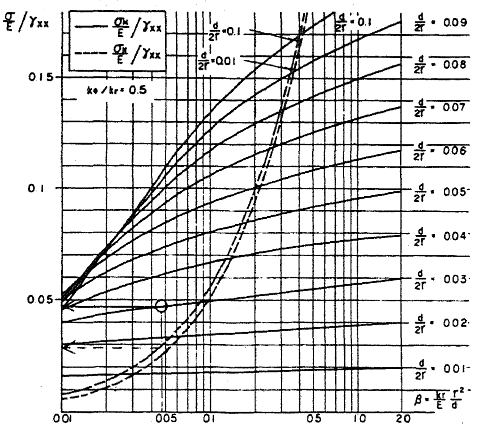
(b) Measured and Calculated Strains (Near Izu Oshima Earthquake of 14th Jan., 1978)

Fig.10 Submerged Tunnel

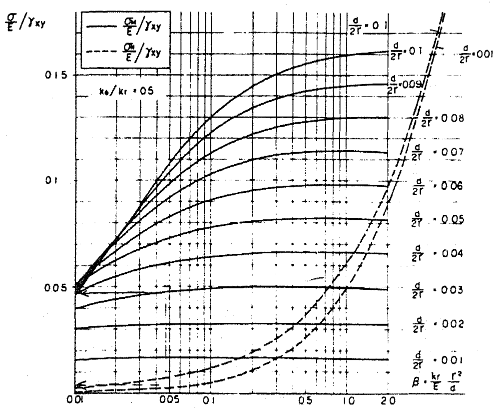




(a) Ground Strain γ_{yz}

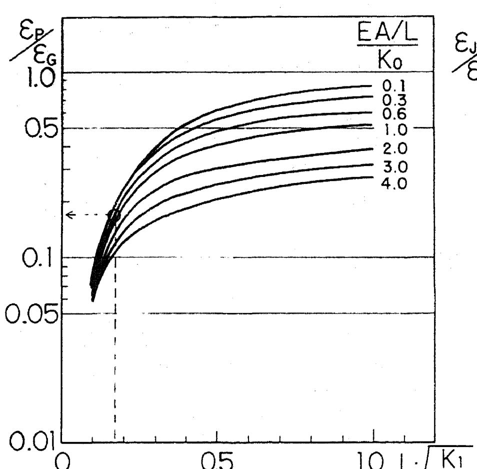


(b) Strain of Underground Tank by γ_{xx}

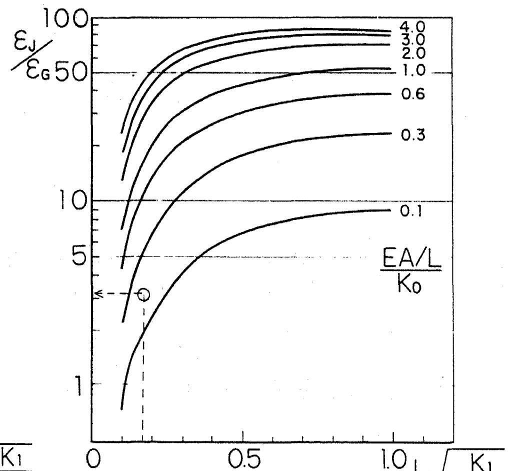


(c) Strain of Underground Tank by γ_{xy}

Fig.11 Stress Evaluation Chart for Underground Tank



(a) Axial Strain of Submerged Tunnel



(b) Strain of Flexble Joint

Fig.12 Stress Evaluation Chart for Submerged Tunnel