DYNAMIC STRESS OF A SUBMERGED TUNNEL DURING EARTHQUAKES

by

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SYNOPSIS

Earthquake Observations were carried out in order to clarify the dynamic behavior of a submerged tunnel and the interaction between the tunnel and the ground during earthquakes.

The dynamic strain of the tunnel was computed by using a new mathematical model which had been already proposed by one of the authors. The computed bending strain had a good agreement with the observed strain.

1. Earthquake Observations

The tunnel where the earthquake observation was carried out is located at the First Route of Tokyo Port and its length is 1035m. It is a reinfored concrete structure with a rectangular section of 37.4m in width and 8.8m in height, as shown in Fig. 1. It is composed of 9 elements and each element is 115m long and connected by a flexible joint of corrugated steel plates.

The soil profile of the site is shown in Fig. 1. The alluvial layer has a thinkness of 20m～35m and is composed of a very soft clay of N-value smaller than 5. The tunnel is laid in this clay layer. The diluvial layer is composed of sand and gravel and the N-value of this layer is 30~40. The elevation of the Tertiary layer is AP-42m~AP-55m at the Oi Land and AP-50m~AP-60m at the Land No. 13.

From the seismic wave prospecting on the Oi Land and on the Land No.13, the velocities of the transverse wave are presumed to be 150m/sec. in the alluvial silt layer, 260m/sec. in the alluvial sand layer, 300m/sec.~400m/sec. in the diluvial gravel layer and sand layer and 700m/sec. in the Tertiary layer.

The location of accelerometers and strain meters are shown in Fig. 2. Three accelerometers were installed on the Tertiary layer (AP-56m), on the gravel layers (AP-35m) and on the ground surface of the Oi Land, while four accelerometers were placed in the ventilation tower and in the tunnel.

Dynamic strains during earthquakes were measured in 9 cross sections of the tunnel. In each section four strain meters were set up on the side walls of the ventilation ducts and on the bottom and the upper slab.

Fig. 3~Fig. 7 show the records of two earthquakes. One of the earthquakes occured on August 12, 1975, near Torishima Island, 700km south to Tokyo (M=7.0, Depth=360km) and the other occured on December 15, 1975, in the center of Chiba Prefecture, 60km to Tokyo Port (M=4.6, Depth=70km). In the former earthquake record the vibration with comparatively long periods (about 1.0sec.) is predominant while in the latter record the vibration with short period below 0.5sec. is dominant and the duration of the main portion of the earthquake is very short, 3~4 sec.

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Dynamic characteristics of the submerged tunnel and the ground obtained by the earthquake observations are summarized below;

(1) The power spectra of the acceleration in the longitudinal direction at the two observation points A5X and A7X in the tunnel have almost the same form and are very similar to that at the observation point A3X on the ground surface (see Fig. 6(a)). This similarity indicates that the tunnel vibrated uniformly along the tunnel axis during the earthquake.

On the other hand, the power spectra of the acceleration in the lateral direction at these observation points are different from each other and dominant periods of the acceleration varies along the tunnel axis. This results show that the tunnel is more flexible in the lateral direction than in the longitudinal direction and the lateral deformation of the tunnel is influenced strongly by the motion of the surrounding ground.

The accelerations at the observation point of the ventilation tower (A4X and A4Y) are smaller than the others and the vibration with high frequencies which can be found in the acceleration at the other observation points diminishes on account of the rigid foundation of the tower.

(2) In the power spectra of the axial and the bending strain, as shown in Fig. 6 (b), comparatively low frequencies of about 1.0Hz. is dominant and the high frequencies of 3.0Hz$\sim$4.0Hz which are dominant in the acceleration records can not be seen.

(3) The dominant periods longer than 3.0 sec. can be seen in the axial strain but these periods can not be found in the bending strain. Furthermore in the case of the earthquake (August 12, 1975) the bending strain is larger than the axial strain for the first 50 sec. duration (see Fig. 4), while the bending strain is smaller for the following 50 sec. duration (see Fig. 7). These results shows that the bending strain dominates for the vibration with high frequencies and the axial strain dominates for the vibration with low frequencies.

(4) Fig. 8 shows the strains by the bending deformation around the horizontal axis calculated from the strain records of the upper and the lower slab. These strains can be considered to be related to the vertical component of the earthquake motion. The bending strain around the horizontal axis at the point A1 is comparable with the axial strain, but is very small, almost 1/3 of the axial strain at the point S7.

2. Numerical Analysis

Dynamic strains of the tunnel were computed by a new mathematical model. In this model the tunnel is assumed as a beam on an elastic foundation and the deformation of the tunnel is calculated from the displacements of the ground along the tunnel. The displacements of the ground are calculated by the fundamental shear vibration of the surface layer above the seismic bedrock.

The ground along the tunnel axis is divided into a number of segments, and each segment of the ground is replaced with one mass-one spring model having the same period with the fundamental natural period of the ground segment. Two adjacent masses are connected by the spring of the ground which resists the relative displacement between two adjacent segments.

The mathematical model used in this analysis is shown in Fig. 9. The diluvial gravel layer was assumed to be the seismic bedrock and the surface layer above this gravel layer was modelled. The fundamental periods of the ground were assumed to be 0.80sec. at the Oi Land, 1.07sec. near the ventilation tower and 0.75sec. at No.4 tunnel element in the sea-bottom, with the reference to the results of the seismic wave prospecting, the micro-tremor observation and the earthquake observation. The coefficients of the subgrade reaction were calculated by the two- and three- dimensional finite element method, using the elastic moduli obtained from S-wave velocities. The strain computed by using the coefficients of the subgrade reaction above mentioned, was much larger than the observed values. In the case where the coefficient was decreased to 1/2 in the lateral direction and 1/3 in the longitudinal direction, the computed strains had a good results and in this paper the results of this case are discussed.

The horizontal acceleration records on the gravel layer (GL-35.0m) were used as the input seismic waves. The damping ratio of the ground was assumed to be 5%.

Fig. 10 (a) shows the distribution of the maximum bending moment along tunnel axis. The magnitudes and the distribution form of the maximum bending moment have a good agreement with the observed values. The time histories of the bending moment at the points S1, S6, and S9 are shown in Fig. 11 (a). At the points S1 and S6 the wave forms of the calculated moment are similar to the observed wave forms except the vibrations with high frequencies, but at the point S9 there are some phase lag between the calculated and the observed strain.

Fig. 10 (b) shows the distribution of the maximum axial force along the tunnel axis. The calculated axial forces do not so agree with the observed values as the bending moment. The time histories of the calculated axial force, shown in Fig. 11 (b) have a considerable difference from the observed axial force.

As a cause of the disagreement between the calculated and the observed axial force it can be considered that the tunnel is very rigid in the longitudinal direction relative to the surrounding ground and the deformation curve of the tunnel is smooth along the tunnel axis. And then it is necessary for a good agreement between the calculated and the observed axial force that the mathematical model of the ground in the longitudinal direction have a well similarity to the actual ground with a large extent along the tunnel axis. Further, it can be considered that the time lag of the input seismic wave on the bedrock has a considerable influence upon the axial strain.

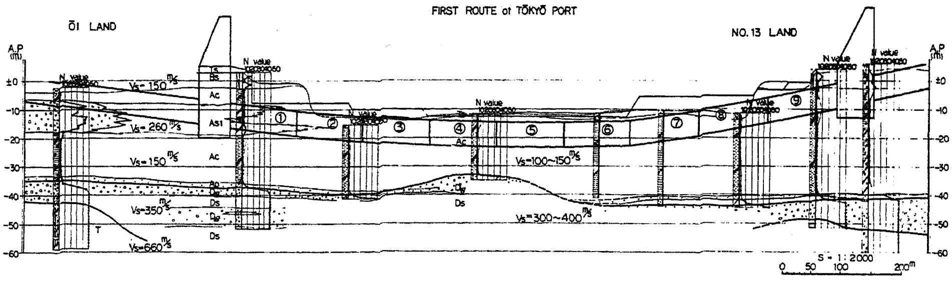
3. Conclusion

(1) The frequency characteristics of the strains of the tunnel are very similar to that of the accelerations on the ground surface and in the tunnel except the high frequency vibration.

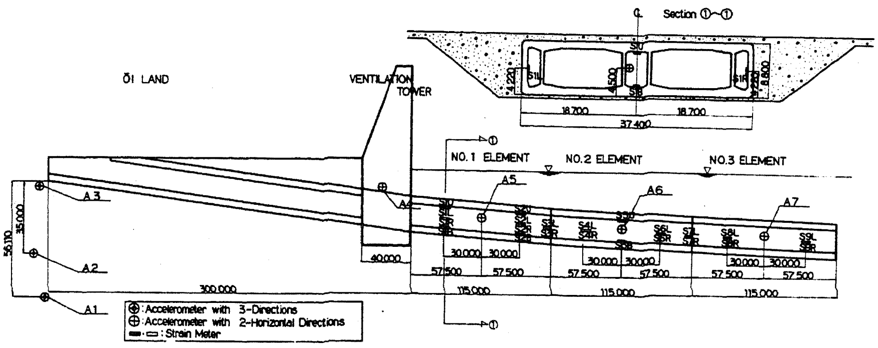
(2) At the time of the earthquakes in which the vibration with long periods are dominant, the axial strain is larger than the bending strain, while at the time of the earthquake in which the vibration with short periods are dominant, the bending strain is larger than the axial strain.

(3) The bending strain calculated by using a new mathematical model had a sufficient agreement with the observed strain.

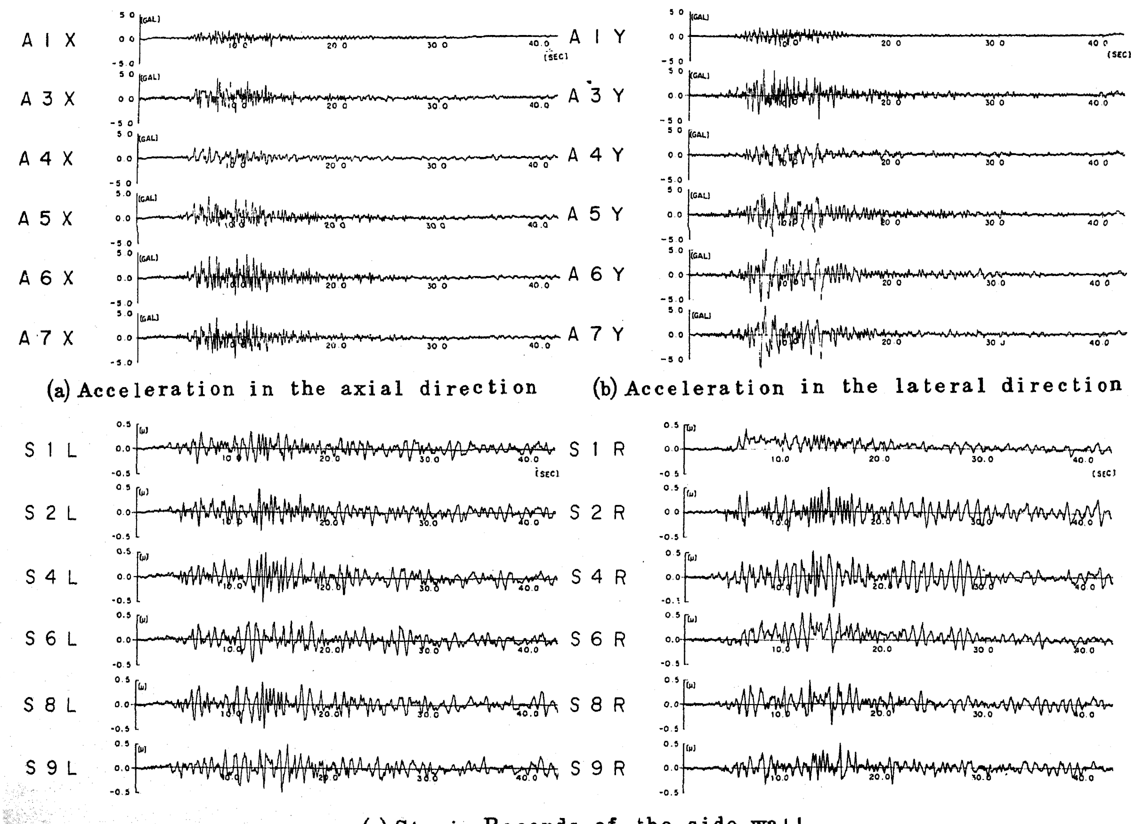
Reference: C. Tamura, S. Okamoto and M. Hamada ,,Dynamic Behavior of A Submerged Tunnel during Earthquakes" Report of the Institute of Industrial Science, The University of Tokyo.



Fig·1 General View of Tokyo Port Undersea Tunnel and Soil Profile



Fig·2 Location of Seismometers and Strain meters

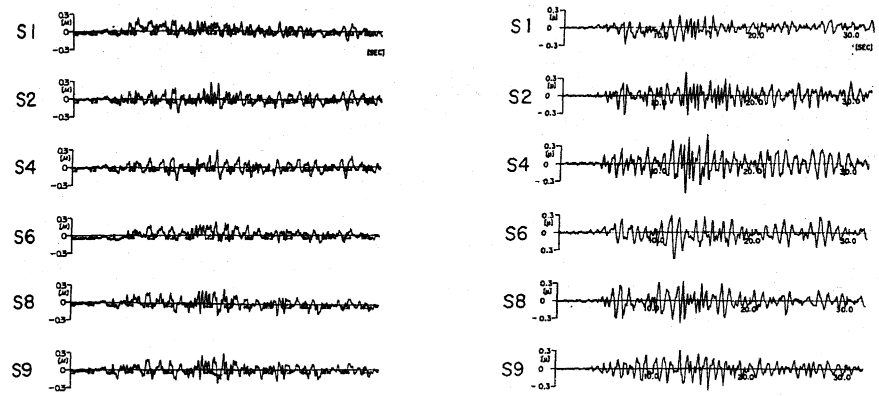


(a) Acceleration in the axial direction

(b) Acceleration in the lateral direction

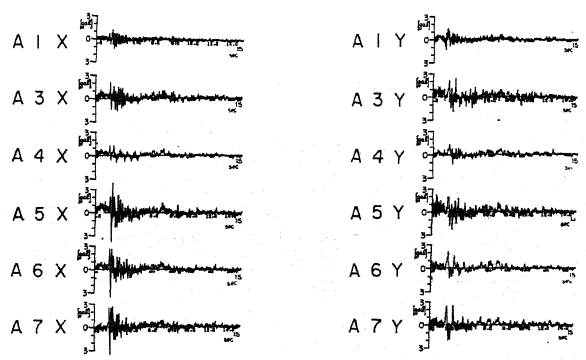
(c) Strain Records of the side wall

Fig·3 Earthquake Records (August12,1975,M=6.9,Depth=400Km, Δ=600Km)



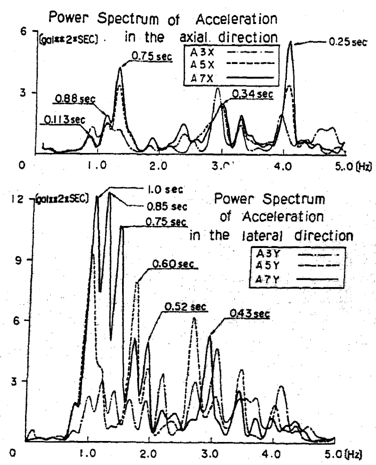
(a) Axial Strain (b) Bending Strain

Fig·4 Axial Strain and Bending Strain (August12,1975)

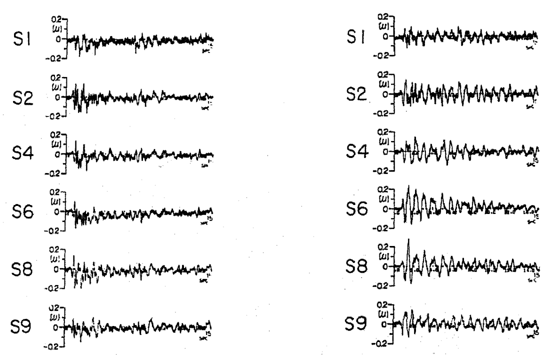


(a) Acceleration in the axial direction

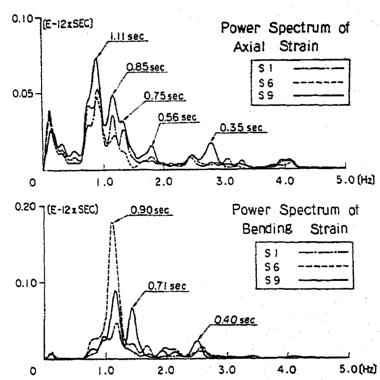
(b) Acceleration in the lateral direction



(a) Power Spectra of Acceleration



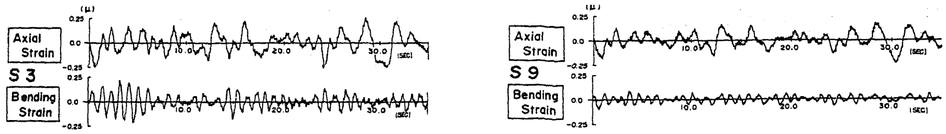
(c) Axial Strain (d) Bending Strain



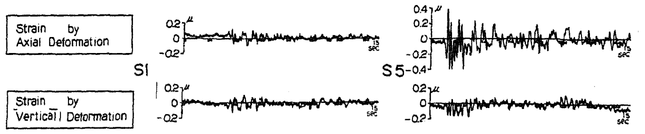
(b) Power Spectra of Strain

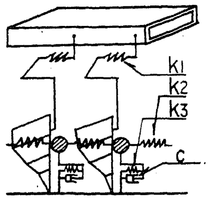
Fig·5 Earthquake Records (December15,1975)

Fig·6 Power Spectra of Acceleration and Strain (August12,1975)

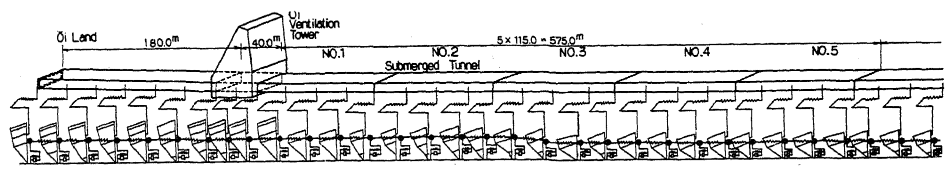


Fig·7 Axial Strain and Bending Strain(August12,1975, t=75sec~110sec)

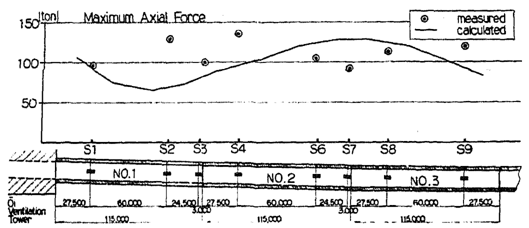




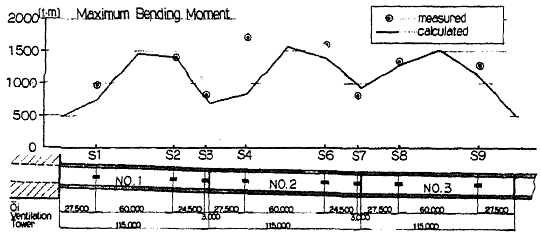
Fig·8 Axial Strain and Bending Strain by Vertical Deformation(August12,1975)



Fig·9 Model of Numerical Analysis

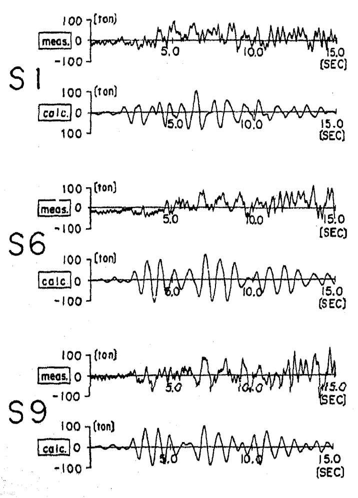


(a) Maximum Axial Force

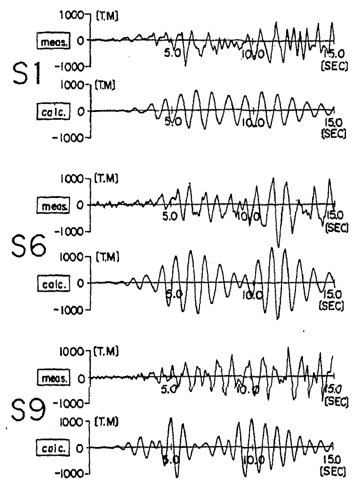


(b) Maximum Bending Moment

Fig·10 Maximum Axial Force and Maximum Bending Moment

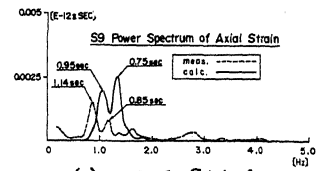


(a) Axial Force

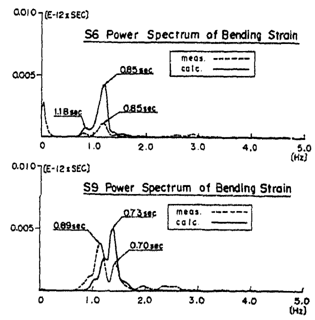


(b) Bending Moment

Fig·11 Time History of Axial Force and Bending Moment



(a) Axial Strain



(b) Bending Strain

Fig·12 Power Spectra of Axial Strain and Bending Strain

DISCUSSION

Y.C. Das (India)

The authors have considered tunnel as a beam on elastic foundation. How many foundation parameters have been considered ?

Y.S. Lou (U.S.A.)

Since the Tunnel was constructed by nine blocks and was connected by flexible joints. How did the authors simulate these flexible joints in their analytical model ?

Author's Closure

Not received.