EARTHQUAKE OBSERVATION AND STRAIN MEASUREMENT IN A SUBMARINE TUNNEL

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Summary In a submarine tunnel, the earthquake observation and the strain measurement are being continued in parallel since 1975. Among the earthquakes hitherto observed, a discussion is made mainly of the result obtained at the time of the Off Miyagi Prefecture earthquake of 12th June, 1978. The power spectrum curves are constructed for the observed axial and bending strain waves for a comparison. The axial strain predominates against the bending strain. Further, the result suggests that, in general, the strains are superior in magnitude during a stage of the surface waves of the earthquake.

Submarine tunnel As has been cited in our previous paper compiled in the Proceedings of the 6th WCEE (New Delhi), (see, Ref.1),the tunnel lies across the sea-bottom of the Keihin Canal so as to connect the land (Mizue in the city of Kawasaki) and a reclaimed island called Ohgishima. It has a total length of 1,540m, including 660m of a part which is the submarine tunnel constructed by the submerging method. See, "Fig.1". The width of the tunnel measures 21.6m, and the height 7.05m. The bottom of the tunnel is laid at a level of -21.5m such that it rests on a alluvial clayey silt layer about 10m thick.

The submerged part of tunnel is composed of six elements of steel-cell-caisson, each being 110m long. The steel-cell of each element is constructed one by one in a dry dock on the land. Then, it is taken to the sea and moored to the fitting-out pier, and there the concrete placing work is done inside of the floating steel-cell. After this work is finished, the element is carried to the appointed place and submerged. The connection between the pre- and newly submerged elements is performed by a method specially developed by the Nippon Kokan Kabushiki Kaisha. Finally, the tunnel is buried with soil and sand, filling the gap between the tunnel and the trench as shown in Fig.1(lower).

Seismographs and strainmeters The distribution of the measuring instruments is shown in Fig.1 (upper). Eight sets of acceleration seismographs (manufactured by Kinemetrics Co.,U.S.A.) are used, of which six sets are installed in the tunnel, (at points B,C,D,E,G and H), and two sets are on the ground one by one near the embankments lying on both sides of the canal, (at points A and J). On the Ohgishima side, two sets of another type of acceleration seismographs are installed on the ground and in the underground at a depth of 60m, (at points J and J').

In four cross-sections of the tunnel, (at D,E,F and H), ten strainmeters (W.S.G.type) are installed such that by fours in section D, and by twos in cross-sections E,F and H. Further, eight steel-strainmeters are stuck in cross-sections F and H by fours.

The starter, amplifiers, recorders and other equipments are installed in a vault in the shaft driven on the Ohgishima side.

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Earthquake observation   Since the beginning of the earthquake observation (March,1975), seven earthquakes were observed up to date with the results as have been reported elsewhere. At Yokohama, the intensities of five of these earthquakes were assessed at III on the J.M.A. scale, approximately equivalent to IV~V on the M.M. scale, while those of other two earthquakes were at IV on the J.M.A. scale, equivalent to VI~VII on the M.M. scale.

One of these two earthquakes occurred on 12th June,1978, and is called the Off Miyagi Prefecture earthquake. It was destructive in the coastal region of the Miyagi Prefecture facing the Pacific Ocean, especially in the city of Sendai. As the epicentral distance of this earthquake measured from the tunnel was farther than 300 km, the earthquake motion was not so severe as to cause a damage in the tunnel. "Figs.2 and 3" show the acceleration seismogrammes obtained in this earthquake at points A,B,D,I and J. In the former figure, are shown the component motions in a direction parallel to the axis of tunnel, while in the latter figure are shown those in a lateral direction.

In the preliminary part of the earthquake motion, the waves of comparatively short periods can be seen prevalently, whereas the waves of periods of about 1.0 sec are seen predominantly after 20 sec from the beginning of registration and later on, that is, the ground motion becomes slower with a lapse of time. Setting aside this fact, we can see that the acceleration waves which were recorded on the ground (at A and J) and in the tunnel (at B, D and I) show a similar feature to each other. The maximum values of acceleration, however, are larger on the ground than at other places. In the shaft (at I), the maximum acceleration becomes 70~80 % of that on the ground, and the value at the centre of the tunnel (at D) is more or less larger than that in the shaft

The power spectrum curves were constructed for the acceleration waves observed on the ground and in the tunnel, and are shown in "Fig.4". The curves for the waves at points A and J show approximately a similar feature, but, strictly speaking, at point A (at Mizue) the predominant period in the longitudinal direction is a little shorter than that at point J (at Ohgishima). Comparing the curves drawn for the accelerations on the ground and in the shaft (curves A and B, or curves I and J), it will be seen that the motion of the shaft does not always follow the ground motion in the range of high frequency. At the centre of the tunnel(at D), the waves of high frequencies appear which can be seen on the ground.

Strain measurement   The strain measurement was successful at the time of the Off Miyagi Prefecture earthquake of June,1978, aforementioned. For example, the result obtained at point H will be reported here.

In the upper two figures in "Fig.5" are shown the strain waves which were produced in the walls of tunnel lying on the Tokyo side and the Yokohama side, respectively. These strain records were obtained simultaneously with the acceleration records as already shown in Figs.2 and 3. It will be seen that the damping of strain waves is feeble as compared with that of the ground acceleration waves. However, a tendency is similar to that of the ground motion that the period of the strain wave becomes longer with a lapse of time.

The strain analysis is made after the recorded strain waves are all digitized. Then, we have the axial strain produced in the tunnel by adding the strain waves on the Tokyo side and the Yokohama side, and subtracting the waves on these sides, we have the bending strain. The strain waves thus obtained are shown in the lower two figures in Fig.5. As will be seen clearly in these figures, the axial strain is larger than the bending strain throughout the earthquake, such that the maximum value of the former strain is 2.5 times as large as that of the bending strain. Similar results have been obtained for the strain waves observed at other points.

The power spectrum curves were constructed for the strain waves as shown in Fig.6. In the curve drawn for the bending strain, the predominant frequency is seen at 1 Hz, whereas in the curve for the axial strain, it appears at 0.5∼1.0 Hz, that is at lower frequency than the bending strain. This fact tells us an important behaviour of tunnel during the earthquake. This matter will be cited again later.

Vibrational characteristics of the ground and tunnel From the analyses of the motions of the ground and tunnel made in the cases of seven earthquakes, including that of 1978, the following results have been obtained as to the vibrational characteristics of the ground and the tunnel.

1) The ground motion presents various characteristics according to the kind of earthquake. For example, the vertical motion is said generally to be smaller than the horizontal motion, but in the case of a very near earthquake, the vertical motion becomes comparable with the horizontal motion in their maximum values. In our case, this fact can be seen when the epicentre is located in the northern part of the Bay of Tokyo.
2) Generally speaking, the submarine tunnel seems to move nearly in the same manner as the surrounding ground, and practically there is no perceptible relative motion between. But, when the tunnel vibrates with short periods, its motion, especially the motion of the shaft does not follow the ground motion.
3) Excluding the near earthquake mentioned above, in all earthquakes, the axial strain in tunnel is greater than the bending strain. It is found that the waves of long period predominate in the axial strain rather than in the bending strain, that is, for the ground motion of long periods, the axial strain predominates, whereas for the ground motion of short periods, the bending strain becomes superior in magnitude.
4) The strain in the tunnel does not depend directly on the acceleration of the earthquake motion, but it varies according to the velocity of seismic wave and the amplitude of ground motion. In general, a large strain is produced when the waves of long periods are involved in the ground motion. Actually, the strain becomes predominant against the earthquake motion which may be thought as the surface waves.

Method of analysing the seismic response of submarine tunnel Taking into account the results of our observations of earthquake and strain, a method of analysing the seismic response of the submarine tunnel was studied, and the outline of which will be introduced.

Before entering the explanation of the method, it will be convenient to make some remarks. In a past earthquake, it has been recognized experimentally that the seismic waves which exerted the most powerful effect upon the underground pipe-lines were the surface waves of Love-type, or the likes. An another study shows that the propagation of the seismic waves during the strong earthquake motions is akin to that of the surface waves such as those mentioned above, and is hardly interpretable by the multiple reflection of S waves.

The method of determining the ground motion at the time when the surface waves are propagated has been investigated by J.Lysmer (see, Ref.2), and our method is mostly based on his method. In our method, however, the following assumptions are made such as, 1) only the surface waves are the in-put waves; 2) the motion of the ground is not influenced by the existence of tunnel; 3) the tunnel is a flexible beam supported by elastic-plastic springs.

The adopted conditions of the ground at the site of the tunnel, such as the thickness of the superficial soil layer, the velocities of the seismic waves, etc., are the same as those determined previously by the seismic prospecting. In this method, the calculation is made mainly for the following aims.

1) To determine the distribution of the displacements at arbitrary points when the surface waves are propagated. These points lie on the ground where the tunnel is planned to be laid. In this calculation, the displacements will be determined as those of the stationary vibrations.
2) To determine the displacements (amplitudes) of various modes of vibrations at arbitrary points, the calculation is repeated for various frequencies. After summing up the various modes of vibrations, the transient displacements at arbitrary points are determined by inverse Fourier transform.
3) By using the transient displacements determined in 2) as the in-put waves together with the stiffness matrices of the ground and the tunnel, the response displacements of the structure are determined.

It should be added here that the seismogrammes as shown in the foregoing figures are used, for convenience, to determine the numerical values of the amplitudes of the calculated in-put waves so as to fit the actual waves. The method mentioned above is usable not only in the case of a uniform superficial soil layer, but also in the case of an irregular soil layer, though the calculation becomes somewhat complicated.

In "Fig.7" are shown the distributions of the maximum axial and bending strains along the tunnel at the time of the Off Miyagi Prefecture earthquake of 1978. The calculated strains show a fairly good agreement with the observed strains. In "Fig.8" are shown the calculated and observed strain waves for a comparison. The upper two figures relate to the axial strain, while the lower two figures to the bending strain. In these figures, a better agreement can be seen between the calculated and observed strain waves in the case of the axial strain than in the case of the bending strain. The calculated bending strain waves show a somewhat complicated feature, because of the short period waves involved therein.

REFERENCE

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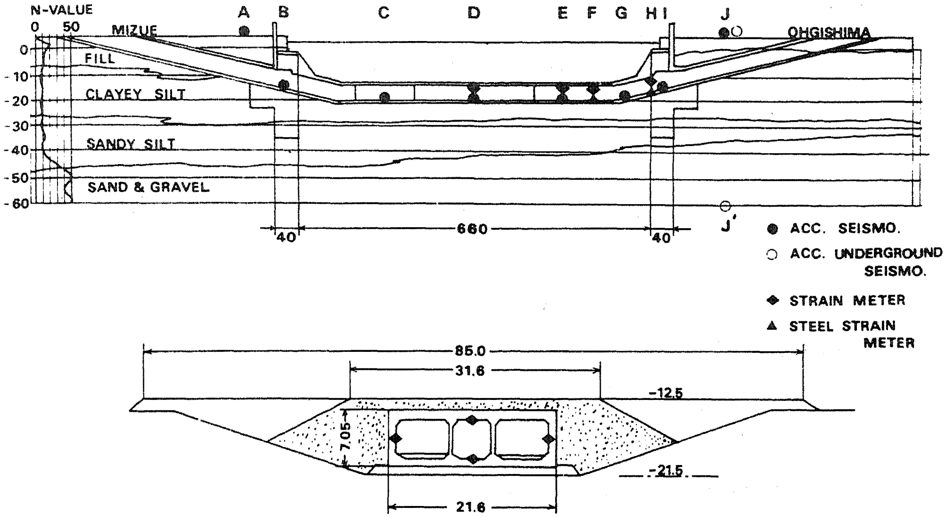

Fig.1 General view of the tunnel and location of instruments.

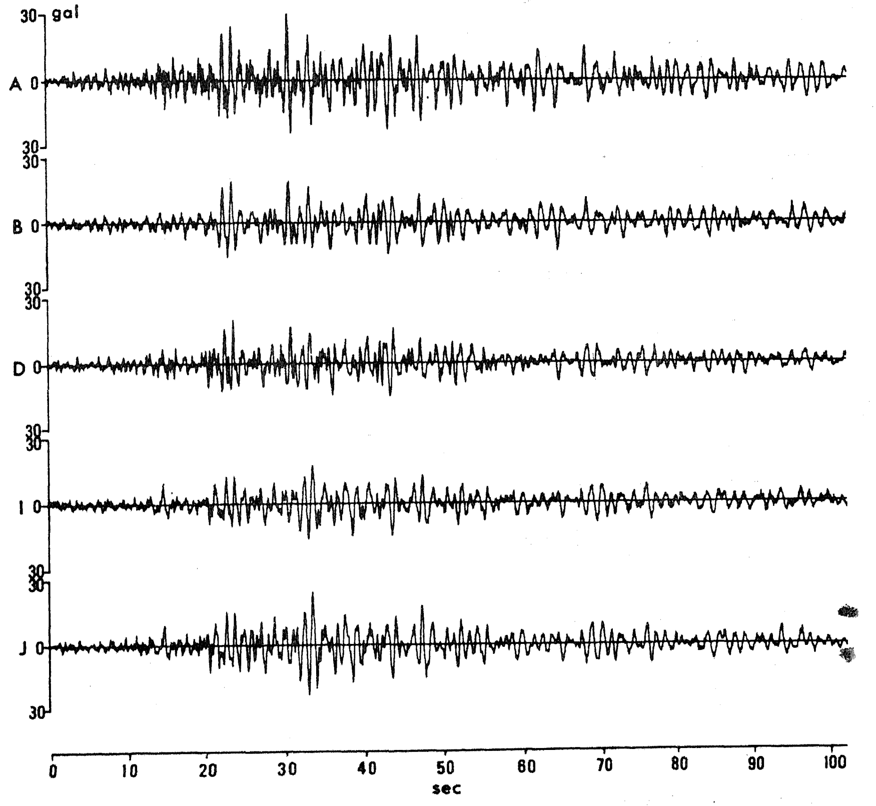

Fig.2 Acceleration records in the longitudinal direction (June 12,1978).

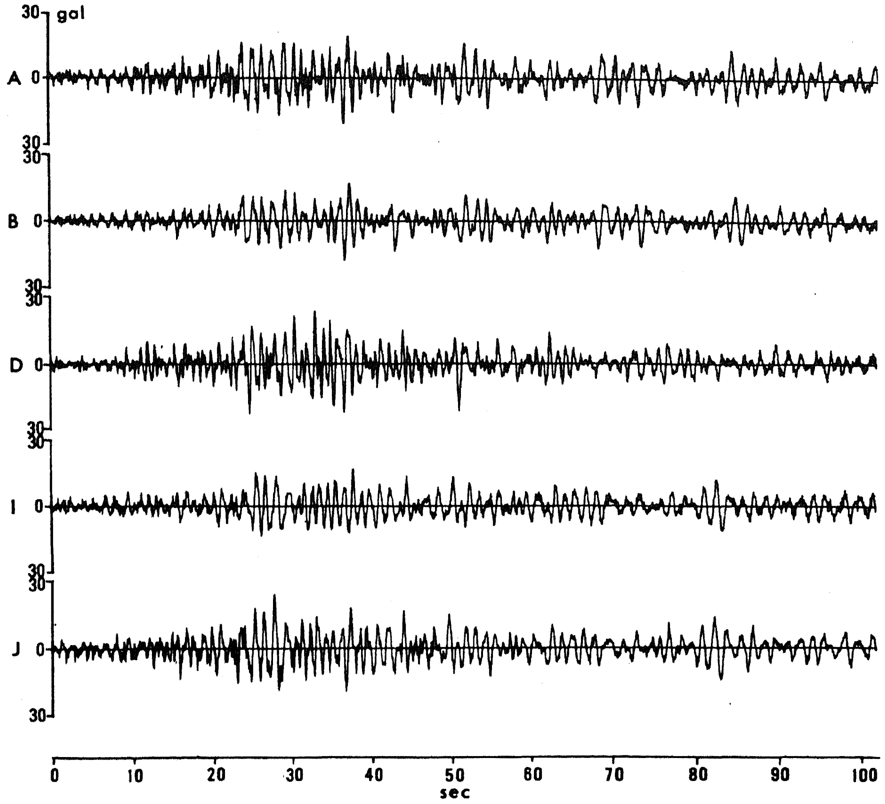

Fig.3 Acceleration records in the transverse direction (June 12, 1978).

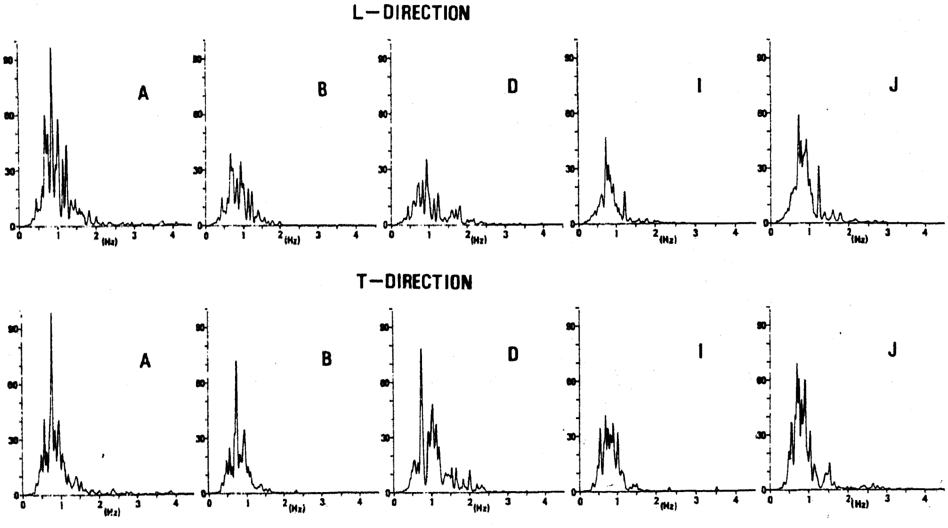

Fig.4 Power spectra of acceleration records (June 12, 1978).