OBSERVATIONS ON DYNAMIC STRAINS OF SUBMERGED TUNNEL DURING EARTHQUAKES

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I. Foreword

A submerged tunnel is usually constructed in soft ground and it is difficult for the structure to vibrate freely based on its own inertia forces as in the case of a structure on land. Further, since it is a long structure, it is necessary to investigate the properties of earthquake motion along the axis of the tunnel in order to investigate its behavior during earthquakes. There is already several tunnels designed to be earthquake resistant taking into consideration displacement and deformation of ground during earthquake, but in evaluation of the earthquake resistance of a submerged tunnel, it is needless to say that knowing the behavior of this type of tunnel during earthquakes would be a fundamental condition.

From this viewpoint, the authors since April 1970 have been conducting earthquake observations on a submerged tunnel for a railway constructed at the mouth of the Tama River flowing down the southwestern boundary of Tokyo with the main purpose being measurement of strains of the tunnel during earthquakes. It has been possible to record more than 20 earthquakes up to this time. Of these, there are included near earthquakes but of small magnitudes and distant earthquakes but of large magnitudes. A part of these has previously been reported. In this present report the major of these records are taken up and the results of their analyses are described.

II. Ground Conditions at Tunnel Site and Outline of Tunnel

As shown in Fig. 1, there is a Quatenary alluvial silt layer on top of a Tertiary diluvial silt layer at the construction site and there are intercalations of more or less horizontal fine sand layers in the alluvial layer. The thickness of the alluvial layer is ten odd meters at the bank on the Kawasaki side opposite Tokyo and 35 to 40 meters at the middle of the stream.

The tunnel has a total length of 480 meters comprised of 6 steel-shell elements of egg-shaped section each 7.35 meters high, 13 meters wide and 80 meters long. The tunnel on the Kawasaki side is partly in the Tertiary layer which comes close to the surface at that

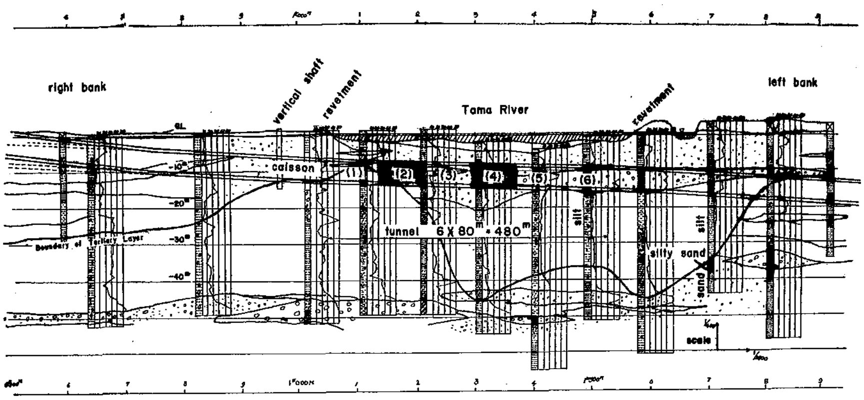

Fig. 1

side, and at the middle of the stream is submerged near the surface of the soft alluvial layer approximately 40 meters thick.

Earthquake observations are being conducted at the No. 2 Element partly in the Tertiary layer at the Kawasaki side and at the No. 4 Element at the middle of the stream. The arrangement of instruments is as indicated in Fig. 2 with accelerometers installed at each element in the direction of the horizontal axis. Strain meters are mounted at two places on the left and right side walls of the tunnel in a manner to sandwich the accelerometer locations. Strains of the left and right side walls at points 30, 155 and 205 meters distant on the axial line are measured with strain gauges in attempting to observe axial direction strain, bending strain, and further, differences according to location on the axial line. The accelerometers are of the moving-coil type with natural period of 0. 33 sec. The strain meter is an apparatus detecting the relative change during earthquake between an Invar bar one meter long and distance between datum points established one meter apart on the tunnel wall using a resistance wire strain gauge. Sensitivity is extremely good and it is possible to detect strain of 1×10^{-7}.

Recording of these observation values is carried out with an oscillograph installed for each element. The two oscillographs are activated simultaneously by a signal from an acceleration-type vibration sensor. The speed of recording paper is approximately 3 cm/sec.

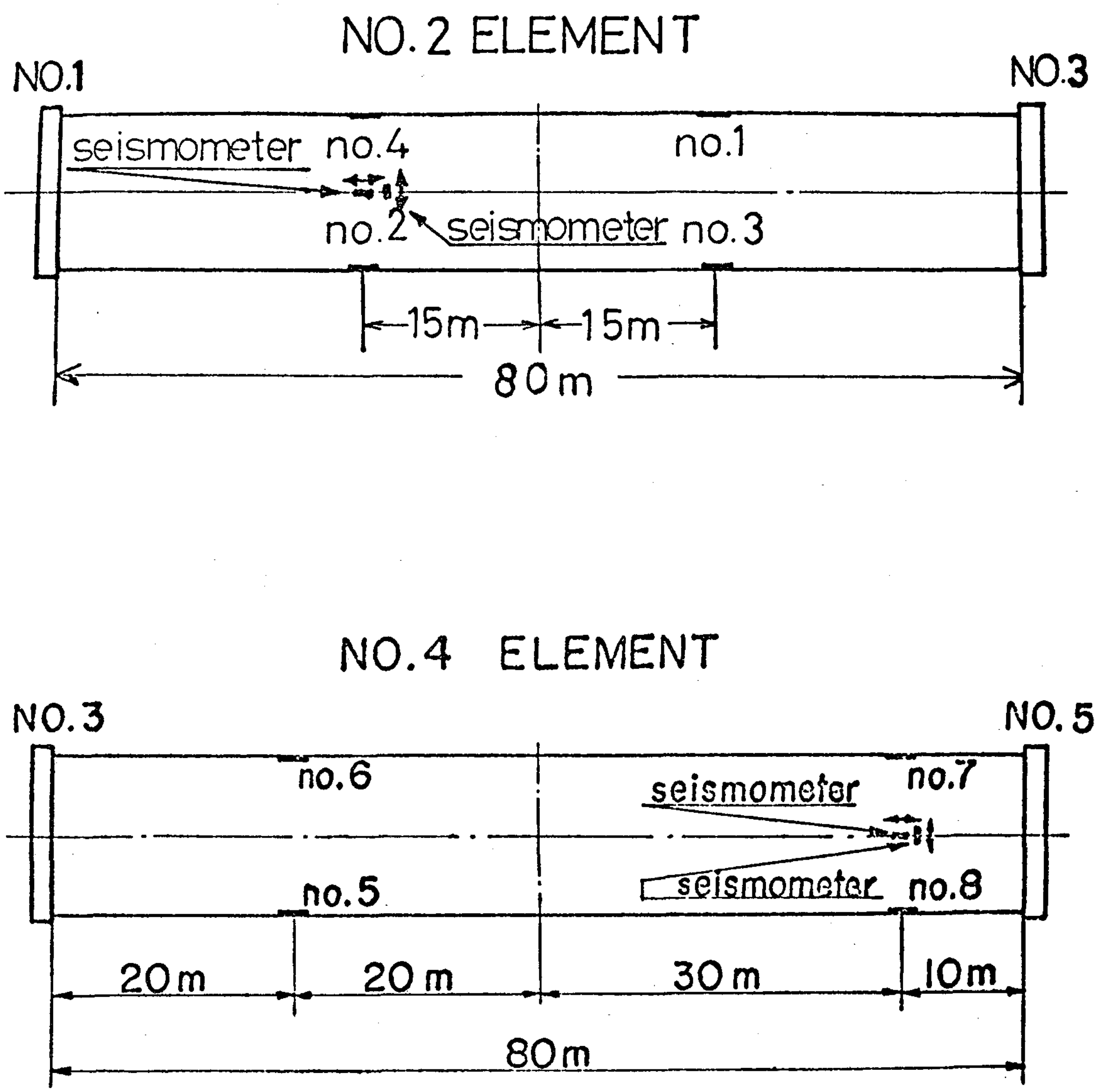

Fig. 2

Arrangement of Seismometer and Strain-meter in No. 4 Tube Element

The oscillographs are adjusted to work automatically for approximately 32 seconds with a single starting signal and stop in case there is no starting signal following.

III. Earthquake Records

Of the earthquakes recorded there are included such as an earthquake of M = 7.2 with its focus at a depth of 60 kilometers approximately 100 kilometers east of Hachijo Island which occurred on December 4, 1972 and an earthquake of M = 4.8 with an epicentral distance of only 12 kilometers.

Although 4 accelerometers and 8 dynamic strain gauges have been installed, all twelve records have not necessarily been obtained for every earthquake. Looking at maximum accelerations and maximum strains out of those recorded irrespective of location and direction of seismograph, earthquakes which had maximum accelerations of 5 gal or more or maximum strain at side wall exceeding 1×10^{-6} would be as indicated in the table. Magnitudes, depths and locations are according to Japan Meteorological Agency data. From an overall view of these records they may be classified into 3 types --- A, B and C (see classifications in Table).

A : Records of near earthquakes such as the earthquake of September 30, 1970 (M = 4.8, Δ = 12 km), the earthquake of December 8, 1972 (M = ?, Δ = 20 km) and the earthquake of March 27, 1973 (M = 4.9, Δ = 17 km) in which accelerations are small, waveforms are of impact-type and vibration components of comparatively short period (several Hertz) are predominant.

B : Records of medium and distance earthquakes such as the earthquake of September 14, 1970 (M = 6.2, Δ = 420 km) and the earthquake of August 31, 1972 (M = 6.0, Δ = 270 km) in which there are little differences in frequency characteristics between acceleration waveforms and strain waveforms and vibration components of around 1 cycle or less are predominant.

C : The record of the earthquake of December 4, 1972 (M = 7.2, Δ = 280 km) in which vibration components of 0.16 ~ 1 Hertz are predominant and vibrations of periods of 4 ~ 7 seconds are predominant after the major vibrations.

Figs. 3 ~ 5 show the records of the earthquakes, No. 2, No. 5 and No. 8 out of Earthquakes No. 1 No. 10 as examples of the groups A, B and C respectively. The numbers 1, 2 and 3 in Fig. 3 are the numbers of strain

Earth-quake No.	Date	Location of Origin		Depth (km)	Magni-tude	Epicentral Distance (km)	Max. Ac-celeration (gal)	Maximum Strain ($x10^{-6}$)	Classi-fication
		N	E						
1	Sep. 14, 1970	38°41'	142°20'	40	6.2	420	2.6	1.7	B
2	Sept. 30, 1970	35°29'	139°38'	40	4.8	12	12.1	1.2	A
3	Jan. 4, 1972	35°52'	140°32'	40	5.0	80	1.9	1.0	B
4	Jan. 27, 1972	35°41'	139° 7'	40	4.8	60	6.8	0.8	A
5	Aug. 31, 1972	35°53'	136°46'	10	6.0	270	2.7	2.6	B
6	Sep. 25,.972	38°21'	142° 4'	50	5.5	380	1.6	1.7	B
7	Oct. 6, 1972	34°24'	138°31'	30	5.5	160	10.9	3.5	B
8	Dec. 4, 1972	33°12'	141° 5'	50	7.3	280	14.7	20.9	C
9	Dec. 8, 1972	35°35'	140° 0'	90	?	20	15.0	1.2	A
10	Mar. 27, 1973	35°31'	139°56'	60	4.9	17	13.6	2.0	A

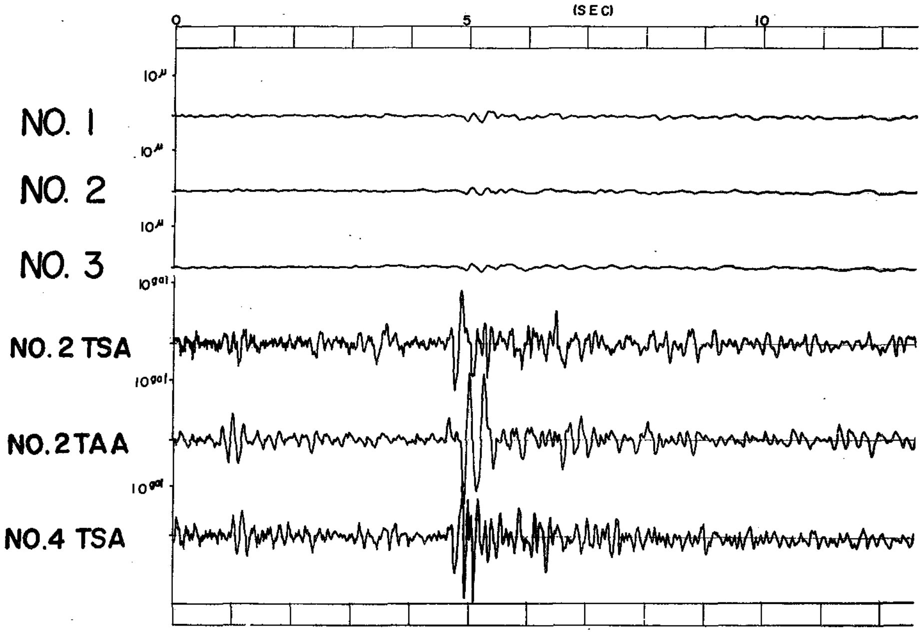

Fig. 3 Records of the Earthquake (Sep. 30, 1970)

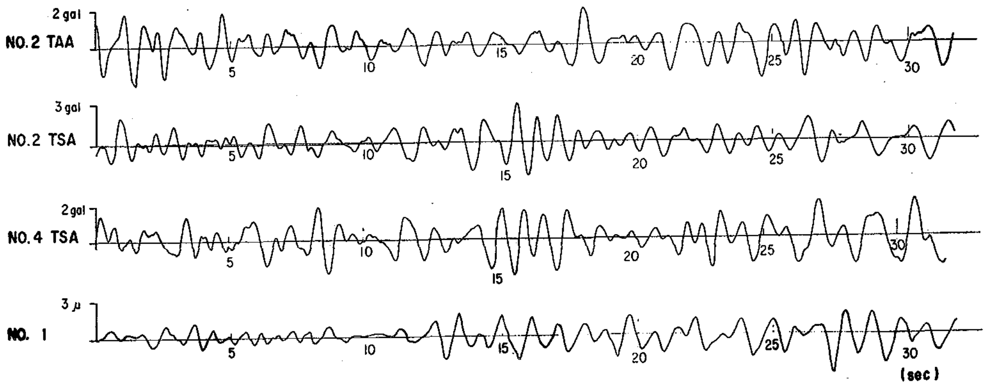

Fig. 4-(1) Records of the Earthquake (Aug. 31, 1972)

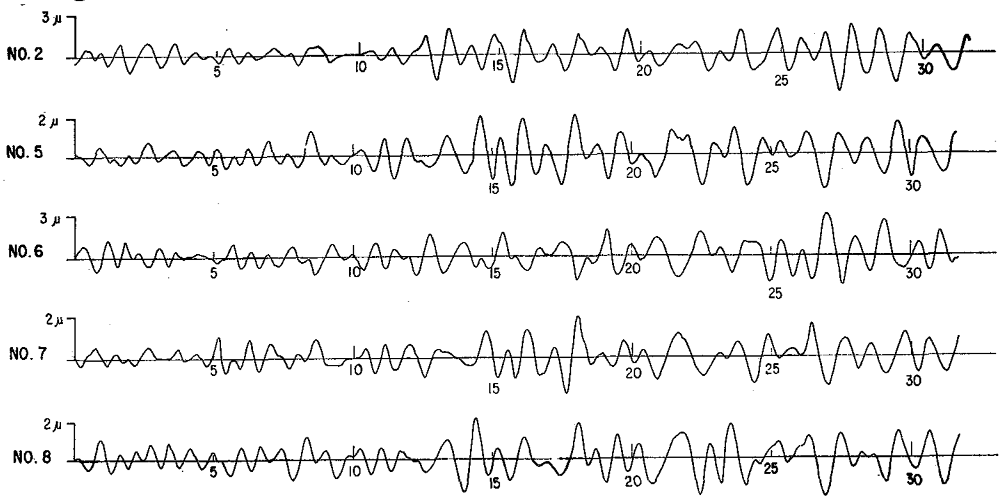

Fig. 4-(2) Records of the Earthquake (Aug. 31, 1972)

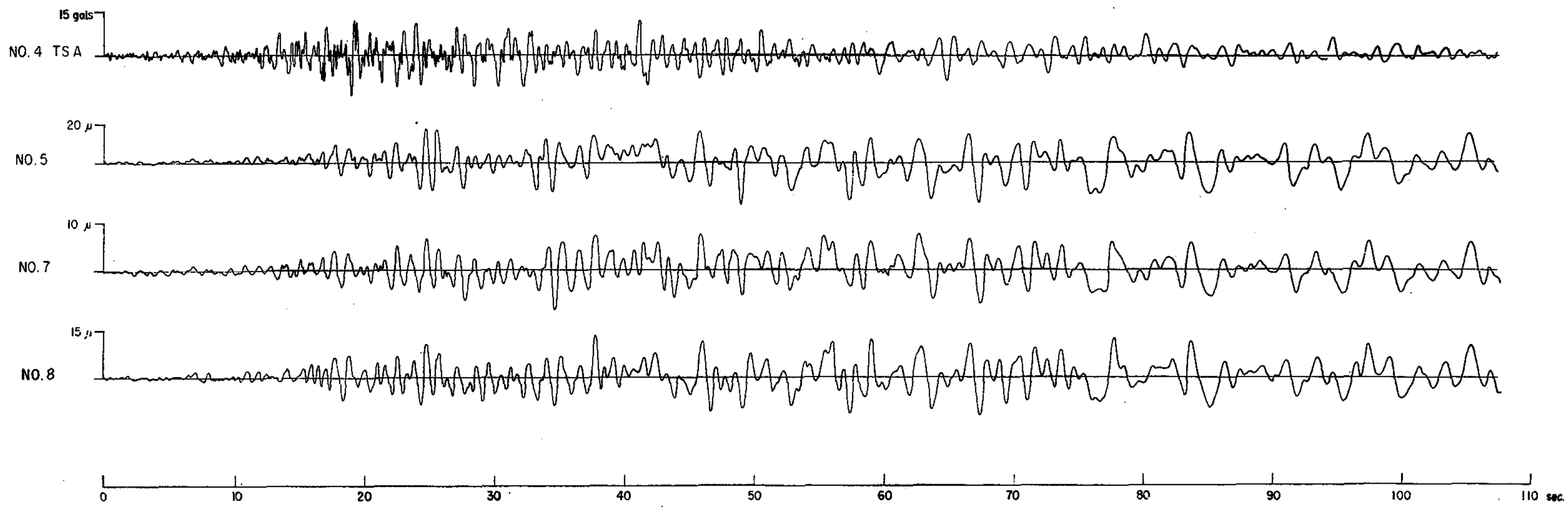

Fig. 5-(1) Records of the Earthquake (Dec. 4, 1972)

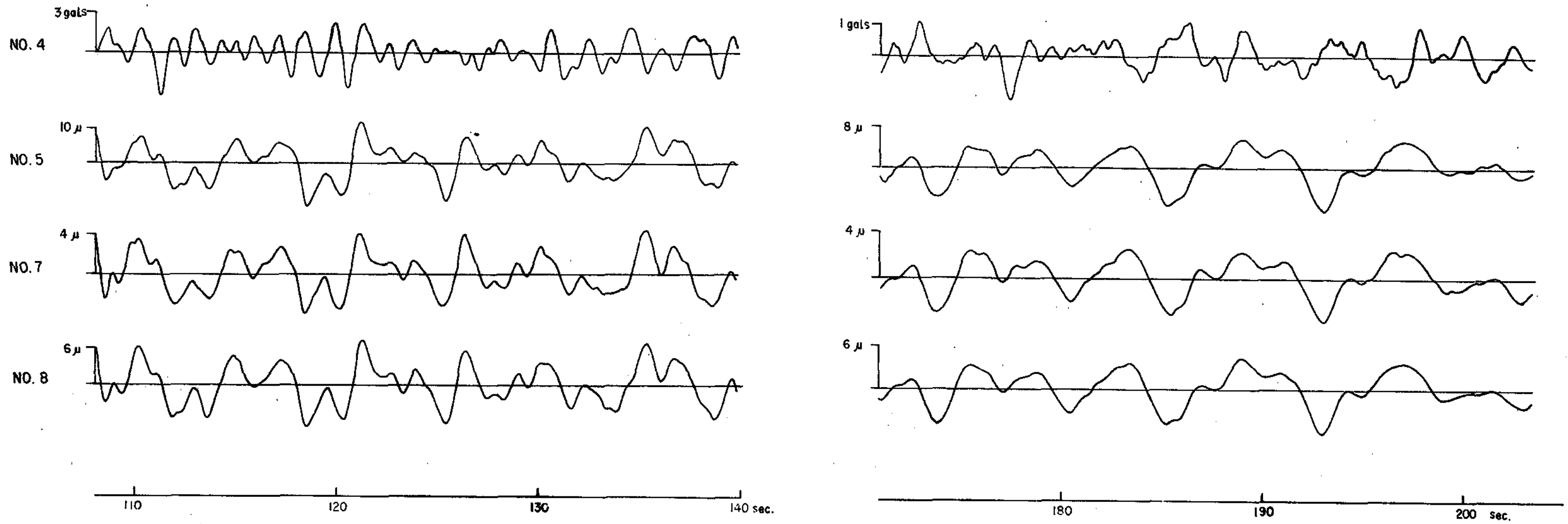

Fig. 5-(2) Records of the Earthquake (Dec. 4, 1972)

meters at Element No. 2 while No. 2 TSA and No. 4 TSA are the accelerations in the direction orthogonal to the tunnel axis at Element No. 2 and Element No. 4 respectively, and No. 2 TAA is the acceleration in the direction of the tunnel axis at Element No. 2.

Regarding Fig. 5, the notations are similar to those in Figs. 3 and 4, and continuous records from 0 sec to 107.8 sec have been taken, but from 107.8 sec until the time of starting of the next operation at 108 sec on the record and before the record for 171 ~ 203.4 sec, there are stoppages of several tens of seconds not indicated in the figure. As for the No. 5 strain record, the full amplitude of vibration could not be recorded due to shift of the zero-line.

IV. Analyses of Records

Although movements of ground surface have not been caught in these observations, it has been shown from results of underground observations of earthquakes that accelerations underground are about the same as at the ground surface or generally smaller.[1] As for displacement waveform, it can be surmised from experiments that there is not much difference between tunnel and ground.[1]

Several reports [3][4] have been made on the results of analyses records carried out up to this time, the major points being the following: 1) Deformations from bending and pull and push are produced in the tunnel, but generally the axial strains are larger and more easily produced than these from bending. 2) Vibration components of comparatively low frequencies are predominant at all times in the records of strain. There are almost no vibration components of high frequencies to be seen. Further, the periods of predominant vibration components are close to those of the self-vibrations of the surface layer. 3) When earthquake waves of short periods operate to the ground having a long natural period, there is little likelihood of strains occurring in the tunnel. 4) The maximum value of strain produced in the tunnel increases with increasing acceleration, but there is a considerable amount of scatter depending on the character of the earthquake motion.

Supplemental explanations are given centered around the analysis results of records of the earthquakes of August 31, 1972 and December 4, 1972.

1. Maximum Acceleration, Maximum Strain and Epicentral Distance

As indicated in Fig. 3, the strains produced in the earthquakes of Group A compared with extent of acceleration are exceedingly smaller than in the cases of the other two groups. Fig. 6 is an illustration of the maximum values of strain and acceleration for

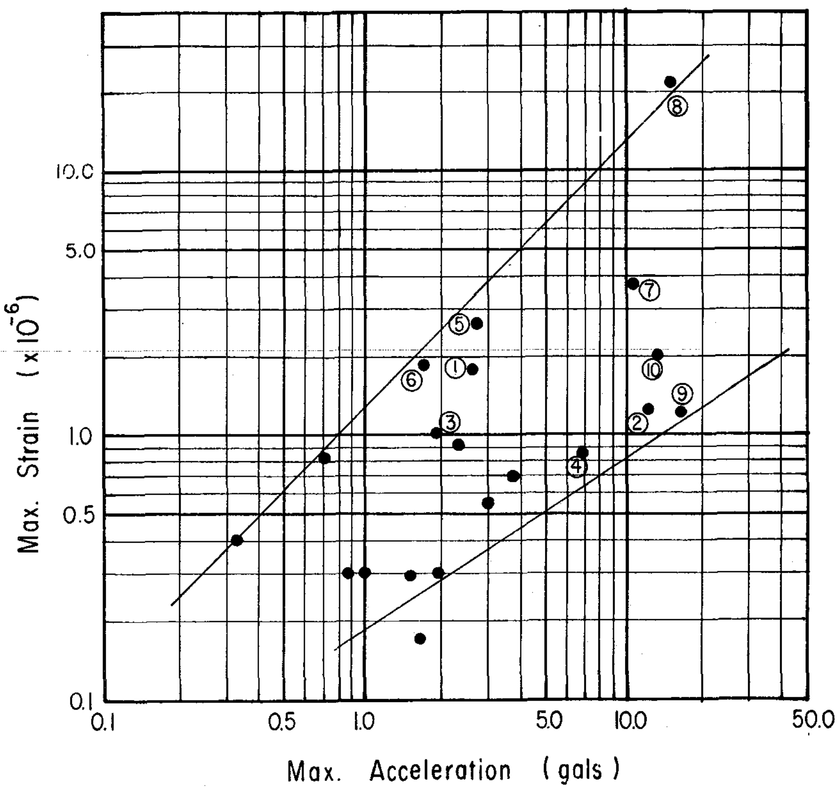

Fig. 6 Relations between max. acceleration and max. strain

each earthquake obtained as described in Chapter II. The maximum accelerations and maximum strains of earthquakes indicated by one point for each earthquake fall between the two straight lines shown in the figure, but earthquakes of Group A all have their points near the lower straight line demonstrating that occurrence of strain is small despite the large maximum value of acceleration.

Next, the values of Group B are between the upper straight line and the lower straight line but gathered towards the former, and with the earthquake of M = 7.2 it is seen that the point is close to the upper straight line. This shows that in regard to strain the maximum value of acceleration of earthquake motion is not necessarily a decisive factor for the size of strain, and that rather the frequency characteristics are of importance.

Fig. 7 shows the relations between magnitude, epicentral distance and maximum strain. On looking at this it is seen that with earthquakes of magnitude of 5.0 strains are recorded only for near earthquakes and that the values are comparatively scattered. However, with earthquakes of M = 5.5 ~ 6.2, the sizes of strains are not affected so much by epicentral distances and are gradually decreased with increase in distance. As for the earthquake of M = 7.2, there is occurrence of large strain compared with earthquakes of M = 5.5 ~ 6.2 and it may be assumed that the difference in earthquake scale has an influence.

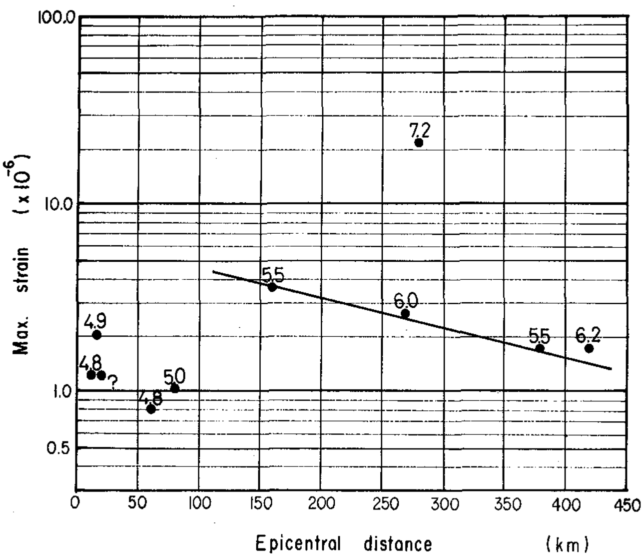

Fig. 7 Relations between magnitude, strain and epicentral distance

note: number attached black point shows magnitude of earthquake

2. Frequency Characteristics of Acceleration Records

i) Regarding the earthquakes in Group A, as seen in Fig. 3, the acceleration records are shown to be impact-type with large maximum acceleration having vibration components of several Hz prominent in the major vibrations while the durations are short and large strains corresponding to the maximum accelerations are not produced in the tunnel compared with the other groups.
In the earthquake of September 30, 1970, vibrations of $3 \sim 7$ Hz were the predominent vibration components in the major vibrations and the maximum acceleration was 12.1 gal. The maximum strain at this time was 1.2×10^{-6}. The results of Fourier analyses of strain and acceleration are shown in Fig. 8.

ii) Regarding the earthquakes in Group B, explanations are made based on the earthquake of August 31, 1972 which is typical of this group.
Power spectra of strains for the approximately 32 seconds of acceleration records in the direction of the tunnel axis and the direction orthogonal to the axis at Element No. 2 and in the direction orthogonal to the axis at Element No. 4 are shown in Fig. 9, (a), (b) and (c) respectively.

According to this figure, predominant frequencies are at 0.5 ~ 0.55 Hz, 0.77 ~ 0.87 Hz, 1.0 Hz, 1.13 ~ 1.17 Hz, 1.67 Hz, 1.73 Hz and 1.85 Hz.
On comparison of the records for the directions orthogonal to the tunnel axis at Element No. 2 and Element No. 4, it can be seen that the two are similar, but Element No. 2 has relatively more vibration components at parts of comparatively higher frequencies and Element No. 4 conversely at parts of lower frequencies.
This is presumably due to the difference in the natural period of the ground in which each element is submerged. 2)
Next, on comparison of the records of accelerations in the direction of the tunnel axis and the direction orthogonal to the axis, it can be seen that power spectra are more numerous in parts of lower frequencies in the former than in the latter. This difference is though to be due to the variations in thickness and topography of the soft layer of the ground in which the tunnel is submerged and to the direction of vibration. 2)

iii) The earthquake of December 4, 1972 was a medium-scale one of M = 7.2 and was recorded over a long period of time. Since the earthquake motion was unstationary with variations in amplitude and frequency characteristics, it was analyzed dividing it into 4 sections of 0 ~ 107.8 sec, 108 ~ 139.8 sec, 171 ~ 203.4 sec and the portion at which strain indicated maximum value (56 ~ 80 sec), naming these Section Cl, Section C2, Section C3 and Section C4 respectively.
Fig. 10, (a), (b), (c) and (d) show the power spectra of accelerations corresponding to these sections, Cl, C2, C3 and C4 respectively.

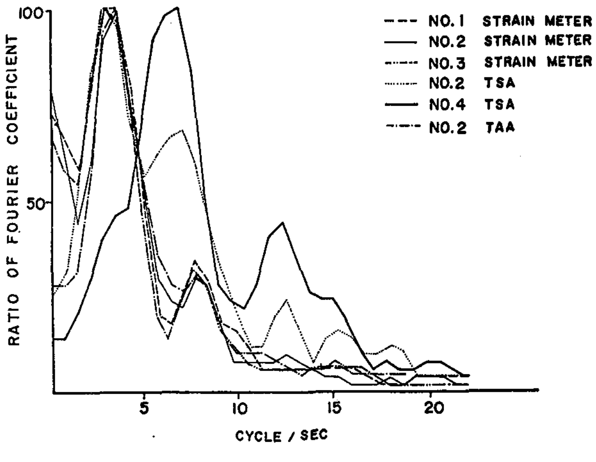

Fig. 8 Fourier Analysis of Earthquake Record-5-1

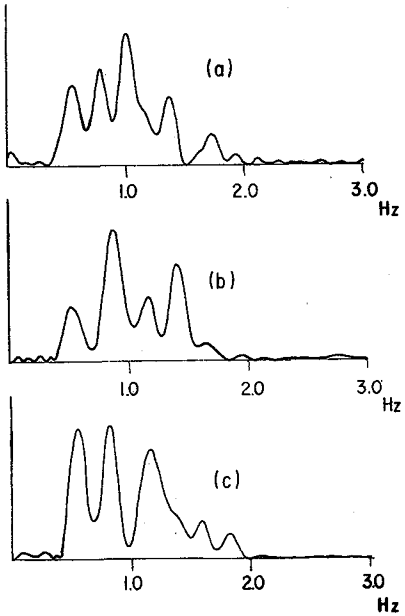

Fig. 9
Power Spectra of
Accelerations
during the Earthquake
(Aug. 31, 1972)

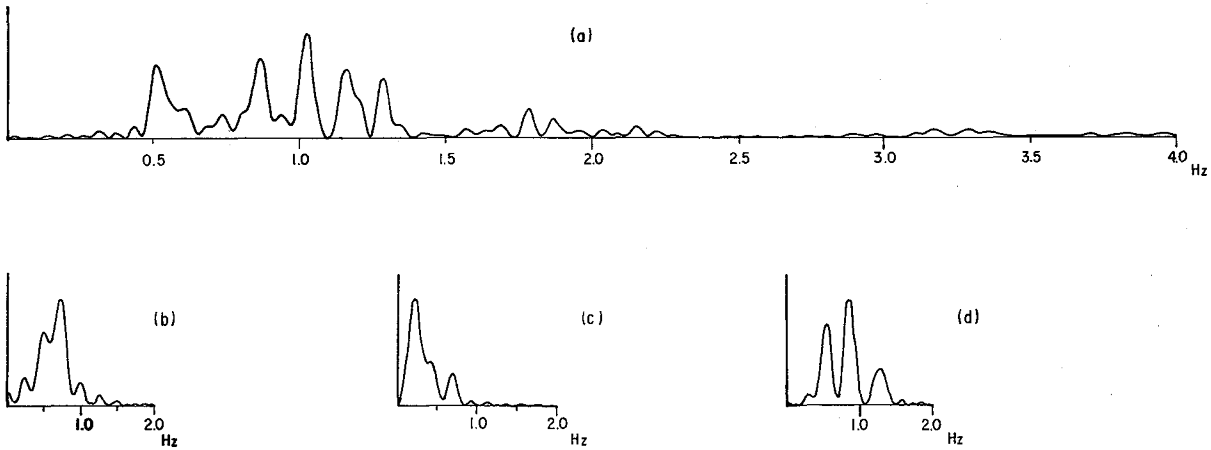

Fig. 10 Power Spectra of No. 4 TSA during the Earthquake (Dec. 4, 1972)

From Fig. 10, it is seen that vibration components of around 1 Hz are contained in greatest number in Section C1. However, after the major part of acceleration the frequencies of the most predominant vibration components are 0.76 ~ 0.88 Hz as seen in Sections C2, C3 and C4 and are in agreement with the predominant frequencies of Group B.
However, in Section C3, vibration components of 0.22 Hz are predominant, which may be said to be a peculiarity of this earthquake.
Further, the peak value of acceleration in Section C3 is about 3 gal.

3. Properties of Strains

The characteristics of strains produced in the tunnel due to earthquakes of Group B and Group C are described using power spectra calculated from strain records, strains in the direction of the tunnel axis, bending strains and cross-correlograms of strain records.

i) Group B

(a) Period Characteristics

Fig. 11, (a), (b) ..... (f) indicate the power spectra of the strain records No. 1, No. 2, No. 5 ..... No. 8 of the earthquake of August 31, 1972.

Comparing the records No. 1 and No. 2 from Element No. 2, it can be seen that the two are similar in waveform, and moreover that components of 1.04 Hz are extremely predominant.

Regarding the four strain records obtained at Element No. 4, these are all fairly similar and it is recognized that in comparison with the records of strains at Element No. 2, there are relative predominances at the comparatively low frequencies of 0.61 Hz and 0.86 ~ 0.89 Hz. The reason for this has been described in the section on acceleration.

(b) Phase

As is clear in Fig. 4, the strain waveforms are extremely alike and the period characteristics are similar. In order to investigate phase relationships, cross correlations between strain records were obtained and the time lags from zero-point time to the times of occurrences of maximum peak values were investigated.

Fig. 12, (a), (b) and (c) show the cross correlograms

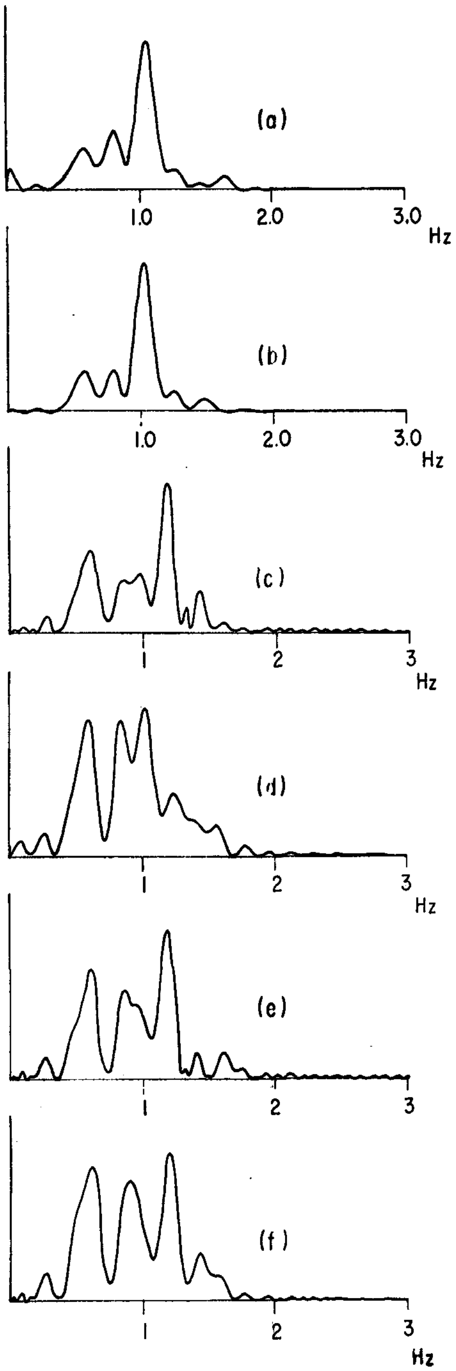

Fig. 11

Power Spectra of Strains during the Earthquake

(Aug. 31, 1972)

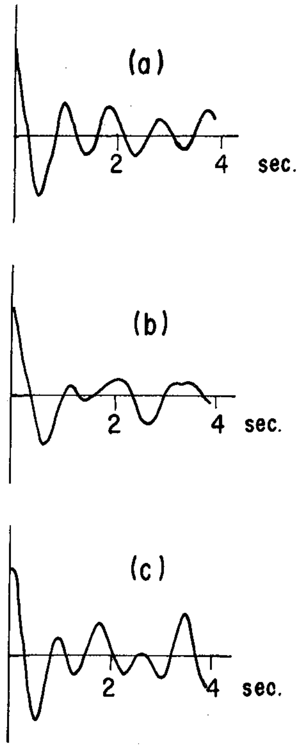

Fig. 12

Cross-Correlogams between Strains during Earthquake

(Aug. 31, 1972)

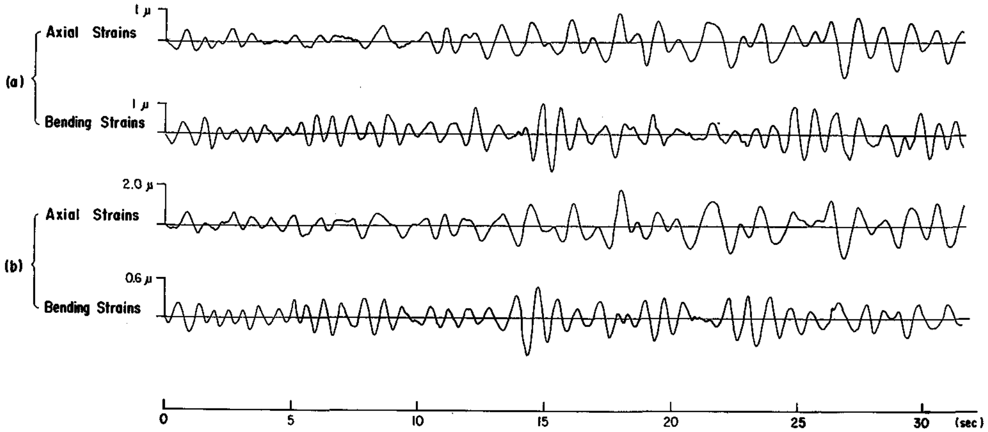

Fig. 13 **Axial and Bending** Strains in the Earthquake (Aug. 31, 1972)

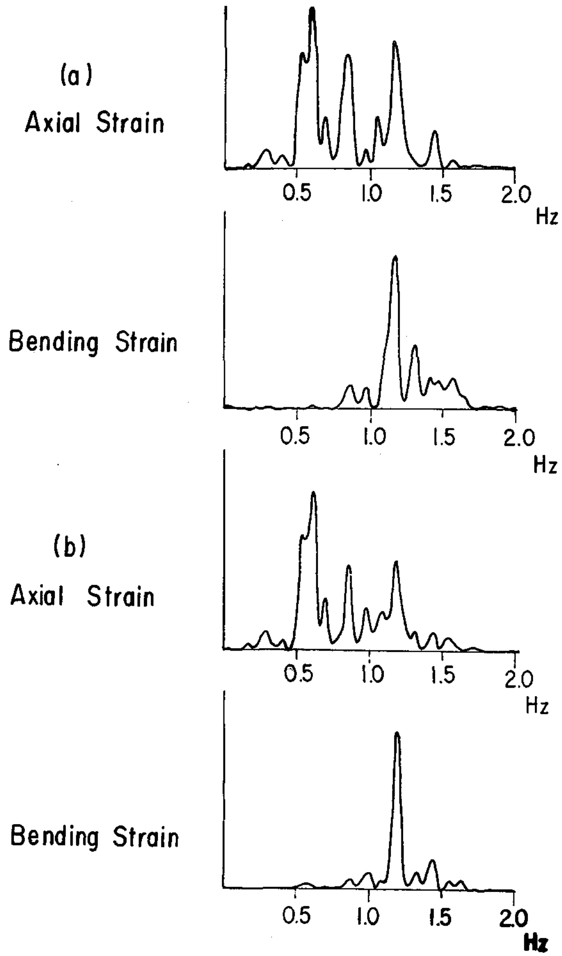

Fig. 14 **Fourier Spectra of Axial** and Bending **Strains in the Earthquake** (Aug. 31, 1972)

between the strain records No. 1 and No. 2, No. 6 and No. 7, and No. 5 and No. 8 respectively. According to these, it is found that there is a possibility of time lag of 0 ~ 1/30 sec in (c) and that there are no differences seen in the cases of (a) and (b).

Further, in case of comparison of the No. 1 and No. 8 strain records, although there are partial phase differences (14 ~ 16 sec), it is seen that the greater part is in good agreement.

(c) Axial Strains and Bending Strains

Axial strains and bending strains were isolated from the strain records of opposing side walls of Element No. 4. Fig. 13 (a) and (b) are strains computed from No. 5 - No. 6 and No. 7 - No. 8. Seen overall, it is recognized that bending strains are conspicuous in the two sections of 14 ~ 16 sec and 22 ~ 24 sec where phase differences are relatively apparent during the 32 seconds. Fig. 14, (a) and (b) are power spectra computed from Fourier analyses of Fig. 13, (a) and (b).

Regarding axial strain, the three vibration components of 0. 6 ~ 0. 69 Hz, 0. 84 ~ 0. 85 Hz and 0. 97 ~ 1. 18 Hz are prominent among the number of predominant periods of which those at 0. 6 ~ 0. 69 Hz and 0. 97 ~ 1. 18 Hz are especially marked.

As for bending strain, it is worthy of note that unlike axial strain, only vibration components of 1. 18 Hz are extremely predominant. Further, in case of comparison of waveforms of bending strains at two points 50 meters apart, phases do not agree at the three sections of 10 ~ 12 sec. 19 ~ 21 sec and 27 ~ 29 sec, while considered for the total length, a phase difference of about 0. 1 sec can be recognized.

ii) Group C --- December 4, 1972 Earthquake

(a) Period Characteristics

Fig. 15, (a)... (d) are power spectra of strains with (a), (b), (c) and (d) being the analysis results for the sections Cl, C2, C3 and C4 respectively. In each of these figures (i), (ii) and (iii) indicate the strain records, No. 5, No. 7 and No. 8 respectively.

Viewed as a whole the absolute value of strain in the three strain waveforms in larger in No. 5 compared with No. 7 and No. 8, but the wave forms are much alike through the durations of recording (0 ~ 203. 4 sec) and there are almost no phase differences to be noted.

Fig. 16 is the cross correlogram between No. 5 and No. 8 according to which the phase difference is practically zero. In Fig. 15, (i), (ii) and (iii) are much alike in power spectra at all sections. However, compared with No. 7 and No. 8, there are somewhat more components of low frequencies in No. 5.

According to Fig. 15, only specific cycles are predominant when it comes to Sections C2 and C3 while other components are decreased. Moreover, the predominant frequencies are 0.172 Hz in Section C2 and 0.135 Hz in Section C3 to become vibrations of extremely long periods.

Section C4 is a section in which strains become large with peaks indicated at 0.26, 0.53, 0.84 and 1.04 Hz. It is seen from wave forms that peak values of strain waveforms are produced mainly by vibration components of $0.53 \sim 1.04$ Hz.

(b) Axial Strains and Bending Strains

Axial strains and bending strains were computed for $0 \sim 107.8$ sec from No. 7 and No. 8.

Fig. 17, (a) and (b) are axial and bending strains and (c) and (d) are power spectra determined by Fourier analyses of these strains respectively.

It may be said that waveforms of axial strains are almost in exact agreement with the strain curves of No. 7 and No. 8 throughout the duration of $0 \sim 107.8$ sec.

In case of comparison between axial strain waveform and bending strain waveform, a fair amount of difference may be seen.

In bending waveforms, vibration components of around 1 Hz are predominant throughout all sections. That is, with axial strains, after the 50-sec point in the records, components of long periods appear prominently while vibration components of around 1 Hz are decreased, but with bending strains, it may be noted from visual inspection that vibration components of around 1 Hz are contained in relatively larger numbers.

Power spectra obtained by Fourier analyses of bending strain waveforms also show that components of around 1 Hz are predominant.

Further, in case of comparison of strain sizes, the value of maximum axial strain is approximately 4 times that of maximum bending strain.

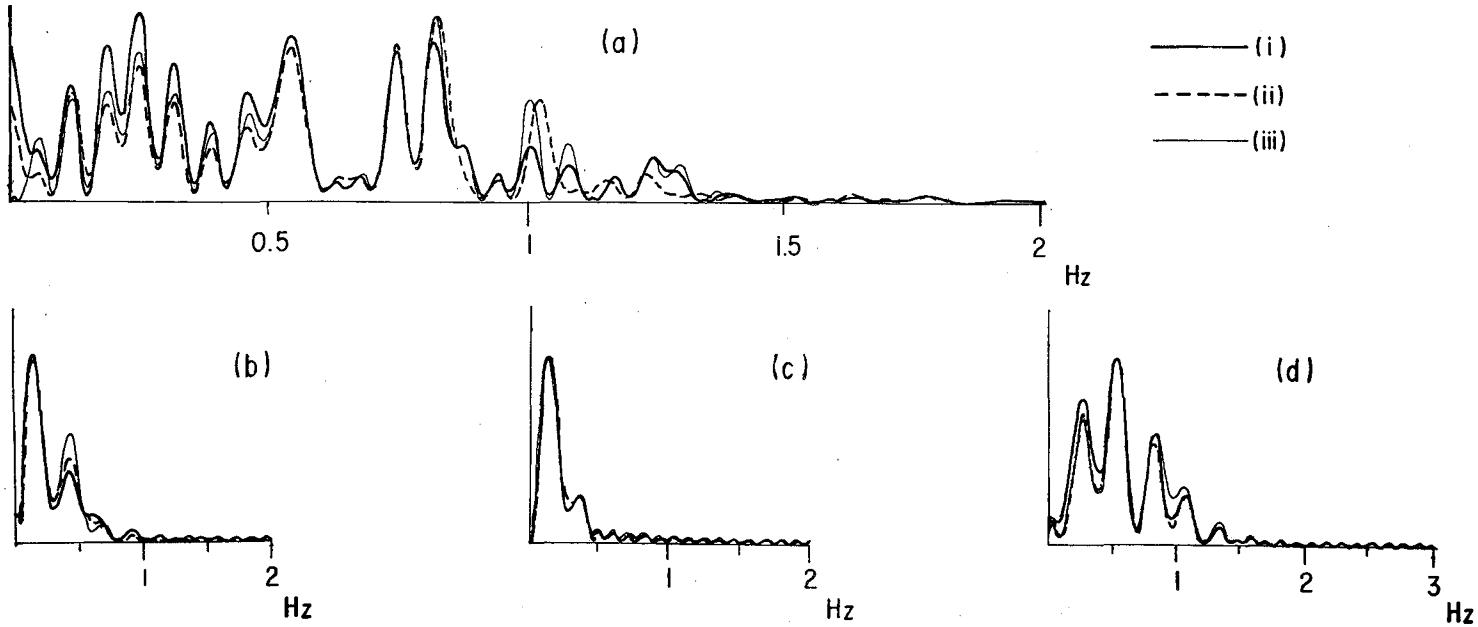

Fig. 15 Power Spectra of Strains in the Earthquake (Dec. 4, 1972)

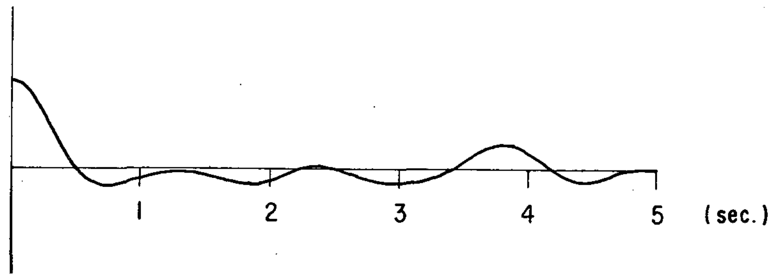

Fig. 16 A Cross-Correlogram between Strains in the Earthquake (Dec. 4, 1972)

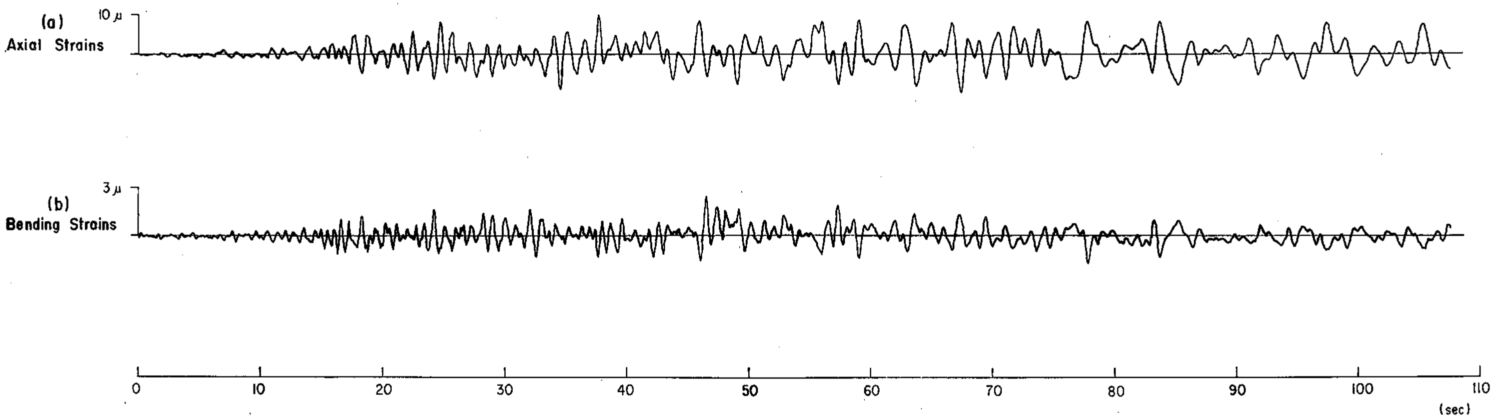

Fig. 17-(1) Axial and Bending Strains in the Earthquake (Dec. 4, 1972)

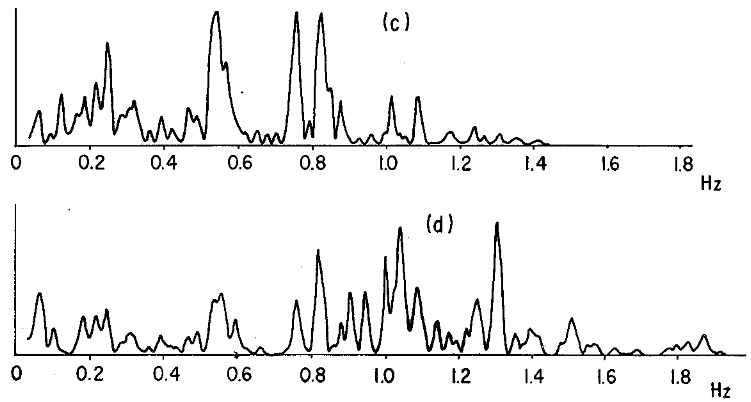

Fig. 17-(2) Power Spectra of Axial and Bending Strains in the Earthquake (Dec. 4, 1972)

V. Summary

Considering that the tunnel lies in ground of the condition indicated in Fig. 1 and that the fundamental vibration frequency at the Element No. 4 point is around 1 sec, the present study may be boldly summarized as follows:

a) Strains produced in the tunnel increase with increasing earthquake acceleration. The sizes are greatly affected by the frequency characteristics of earthquake motion with coefficient of variation exceeding 10 and are scattered.

b) Almost no strain is produced by earthquake motion of the impact-type (approximately 2 Hz or more in terms of acceleration waveform).

c) With earthquakes of magnitudes around 6, strain size is not greatly affected by epicentral distance in 100 km or more.

d) Regarding waveforms of strains measured at various points in the length of 205 meters, waveforms are quite similar although sizes differ and there are almost no phase differences.

e) Axial strains are larger compared with bending strains.

f) Axial strain is predominantly seen at frequencies of 1 Hz or lower. This is particularly noticeable in case of an earthquake of magnitude of 7. 2.

g) In bending strains, components of around 1 Hz are always greatly predominant in earthquakes of $M = 5.5 \sim 7.2$.

Acknowledgements

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