EFFECTS OF SOIL DEPOSITS ON SEISMIC BEHAVIOR OF PREFABRICATED HIGHWAY TUNNELS

by

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SYNOPSIS

This paper deals with a comprehensive study on earthquake-resistance of prefabricated highway tunnels embedded into soft soil deposits undersea. The principal purpose of the study is to establish design methodology in providing adequate structural resistance to seismic disturbances. For evaluating dynamic behavior of soft soil deposits during earthquakes, measurements of seismic motions are carried out employing downhole accelerometers at three sites around Tokyo Bay, and dynamic analyses are conducted by utilizing seismic records obtained and applying the multi-reflection theory. Furthermore, model experiments and dynamic analyses on dynamic response of a highway tunnel embedded into soft soil deposits are conducted.

INTRODUCTION

Shirley Gut Siphon, which was constructed in 1894 as a part of the drainage system in Boston, U.S.A., is the first tunnel of prefabricated subaqueous tubes. A portion with length of 96 m among the total 457 m of the Siphon, was built by prefabricated work. The portion was made of elements with length of 14.6 m and 20.0 m, and with circular cross section of diameter of 2.6 m. The number of submerged tunnels (or prefabricated subaqueous tunnels) completed afterward or under construction at the present registers fifty one in the world for some eighty years.

It is expected that construction of tunnels of this type will become more frequent in Japan for the future, in view of considerable extension of demands for social investment as transportation facilities and sewage systems. A typical example of the demands is prefabricated undersea tunnels across the Tokyo Bay, proposed as a portion of the Tokyo Bay Loop Highways.

The land of Japan belongs to one of the most active seismic zones in the world. Particularly, major earthquakes have occurred frequently in the past around the Tokyo Bay. Accordingly, specific attention shall be given to the design and the construction of the submerged tunnels, for providing adequate structural resistance to seismic disturbances.

In order to make up a reasonable earthquake regulation by summarizing the various investigations, PWRI has requested to JSCE to establish "Committee on Earthquake-Resistant Design of Submerged Tunnels." The committee (chairman is Professor Shunzo Okamoto) was organized in July, 1971 by participants from universities and govern-

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mental institutions concerned. The committee presented the first interim report[1] in March, 1972, as a result of the activities in the beginning year.

Also, comprehensive studies on earthquake resistance of submerged tunnels have been conducted at the Public Works Research Institute (PWRI), Ministry of Construction. In the present report interim results of the investigations at PWRI are briefly described[2]-[4].

MEASUREMENTS OF SEISMIC RESPONSE OF SOIL DEPOSITS USING DOWNHOLE SEISMOMETERS

Downhole seismometers are installed at three sites around the Tokyo Bay, as shown in Fig. 1. These were set up in 1970 and 1971 by the Ministry of Construction, to measure dynamic behavior of the surface soil layers during actual earthquakes.[3]

At the site of the Futtsu Cape, indicating a comparatively uniform sand layer, three-component downhole seismometers (acceleration transducers) are equipped at three levels; surface, -70 m and -110 m. At the Ukishima Park, consisting of reclaimed soils, silts and sands from the surface, four seismometers are installed at surface, -27 m, -67 m and -127 m. At Kannonzaki, indicating a rocky layer with a surface soil layer of 2 m deep, three seismometers are set up at surface, -80 m and -120 m. Furthermore, a SMAC-type strong-motion accelerograph is also equipped on the ground surface at each of these sites, in order to surely obtain ground acceleration records during strong earthquakes.

Fig. 2 shows a set of seismic records obtained at the Ukishima Park during a moderate earthquake (Richter magnitude of 4.8 and hypocenter at 40 km directly underneath the observation site) on September 30, 1970. Fig. 3 indicates relations between maximum accelerations measured at various levels underground and depth, taking accelerations at the surface as units. It seems obvious that the results from the measurements will give valuable information in evaluating seismic effects on underground structures like prefabricated subaqueous tunnels.

ANALYSIS ON SEISMIC RESPONSES OF SUBSOILS

To analytically evaluate seismic motions in soil layers, dynamic responses of surface layers were computed by means of the Kanai's multi-reflection method, which is to numerically analyze seismic response of grounds considering the propagation of shear waves in multi-layered deposits.

Analysis was conducted for the ground at the Ukishima Park, where meaningful seismic records are available as mentioned above. Since shear velocities at the site are not clarified, twelve models with various shear moduli, shown in Fig. 4, were analyzed. Fig. 5 shows some of the results obtained. Fig. 5 (a) indicates the results for Model 1 subjected to an incident wave measured at the ground surface, and (b) is those for Model 1 subjected to an incident wave measured at the lowest

(-127 m). Fig. 6 compares the results analyzed with measured ones. From these the degree of discrepancies between analyses and measurements may be known for the case. It seems essential to adequately estimate analytical models in these analyses.

DYNAMIC ANALYSIS OF A SUBMERGED TUNNEL

Dynamic analysis was conducted for a submerged tunnel proposed across the Yokohama Bay, shown in Fig. 7. Dynamic behavior of sections of grounds and of sections of tunnel together with the surrounding soils was analyzed at three various transverse sections. Fig. 8 indicates finite element models for the three sections, A, B and C.

The following briefly describes the results for Section B (tunnel and surrounding soils). Assuming that the section is in plane strain and has a damping ratio of 10%, and that a shear wave velocity is 50 m/sec for the surrounding soil, the fundamental period of about 2.6 seconds is obtained. Fig. 9 indicates the maximum responses of displacements, and accelerations obtained for Section B subjected to the average response spectra proposed in 1964 by PWRI, when considered the maximum incident acceleration of 200 gals.

MODEL EXPERIMENTS ON DYNAMIC BEHAVIOR OF A SUBMERGED TUNNEL

Model experiments on dynamic behavior of a prefabricated submerged tunnel were performed.[3] The prototype is shown in Fig. 7. Three models consisting of soil layers and a tunnel were fabricated on a larger-size shaking table. In the experiments similarity relations between the prototype and the models were considered. To statisfy the similitude gelatin was employed as ground soils, and rubber as the tunnel which will be actually made of reinforced concrete.

It is noted that gelatin can be advantageously used for soft soil layers in model experiments, due to the fact that its Young's modulus varies from about 0.04 to 2 kg/cm^2 according to the content of gelatin in water and the temperature. Prior to the dynamic experiments, elastic properties of gelatin were examined through static compression tests. It is noted that Young's modulus changes considerably with the temperature. Therefore it is essential in the experiments to control the temperature of the gelatin models.

Three models (shown in Fig. 10) were fabricated in consideration of model to prototype ratios of 1/500 in length and 1/5 in time. Model 1 is a model of two-layered ground with the upper layer with shear velocity of 100 m/sec and uniform depth of 25 m, and the lower layer with 300 m/sec and uniform depth of 95 m. Model 2 is of two-layered ground with varying depths. Model 3 includes a tunnel in the ground of Model 2. Table 1 summarizes the outline of the prototype and the models.

Dynamic experiments were conducted using a large-size shaking

table possessed by the National Research Center for Disaster Prevention, Science and Technology Agency. The following three steps of experiments were performed, respectively, for the three models in two horizontal directions.

a) Harmonic Excitation
b) Free Damped Vibration
c) Seismic Excitation

Deformation of the models was measured using an optical displacement meter unbonded to the models, and two 16-mm moving cameras.

Fig. 11 illustrates mode shapes during resonant states. From these it is found that the fundamental mode shapes are of shear deformation of the ground and that for Model 2 and Model 3 there are two predominant natural periods which are corresponding to the resonances of the two different sections. It is found that the corners tend to vibrate with greater amplitudes than other portions. Since this seems different from actual behavior for the prototype without any particular corners, it is advised that the effects of the corners are removed.

For Model 1 that has uniform soil layers, damping ratio seems almost constant regardless of amplitude, but for Model 2 and Model 3 that have varying soil layers, damping ratio varies slightly with amplitude. The damping ratio was generally found to be 1% of critical for the most cases, the damping ratio, however, for longitudinal oscillation of the sections with the deeper soft layer, was about 2.5%.

Fig. 12 shows typical examples of responses of Model 3 when subjected to seismic excitation in the longitudinal directions. Time-acceleration records employed for the model are adjusted from seismic acceleration records obtained at El Centro during the Imperial Valley Earthquake of 1940 and at Hachinoe during the Tokachi-oki Earthquake of 1968. White noise oscillations that are roughly flat between 5 and 25 for the models, was also employed. In adjusting the seismic records and the white noise, a model-to-prototype ratio of 1/5 was taken for time from the similarity requirements, and maximum table accelerations were decided about 50 gals and 100 gals, in consideration of accuracy of measuring instruments and model strength.

For the three models, displacement responses to the Tokachi-oki record are greater than those to the El Centro record. This seems due to the fact that response spectra of the Tokachi-oki record are more predominant for structures with longer periods, than those of the El Centro record.

CONCLUSIONS

From the extensive studies through the field measurements, the laboratory dynamic experiments and the analyses described above briefly, the following conclusions can be drawn.

(1) Accelerations at deeper locations of soft soil deposits are small comparison with the surface accelerations. Shapes of vertical

distribution of maximum accelerations are different among various earthquakes.

(2) The multi-reflection theory may be employed satisfactorily in estimating seismic response of multi-layered subsoils, provided that soils properties, primarily elastic moduli, are appropriately evaluated.

(3) For estimating three-dimensional behavior of long structures embedded into soft subsoils during earthquakes, model experiments would be an effective way. In model experiments gelatin can be advantageously used as soft soils.

(4) Dynamic analyses by means of the finite element method would be also effective in obtaining seismic response of underground structures.

(5) It is found that deformation of soft soil deposits has significant effects on the dynamic behavior of the embedded structures, and that soil deposits in resonance to seismic motions might exert the structures into critical state. Furthermore, the structures would be affected extensively in the vicinity of a site where depth of soft soil deposits varies steeply. This seems due to the fact that the deformation of deeper soil deposits is larger than that of the other section.

(6) It is expected in the near future to complete resonable specifications for the earthquake-resistant design of prefabricated subaqueous tunnels, through continuing research activities and summarizing various results. It is obvious, however, that liquefaction and failure of soils during earthquakes is a crucial factor affecting the aseismic stability of underground structures. Although the topic is not discussed in the present report, investigations on the effects on submerged tunnels have been carried out at PWRI and the other institutions concerned.

REFERENCES

1) S. Okamoto, et al.: Report on Studies on Earthquake-Resistance of Submerged Tunnels (1971), JSCE, March, 1972.

2) E. Kuribayashi, T. Iwasaki, K. Tuji: Measurement and Analysis on Seismic Accelerations under the Ground, Proceedings of the 11th Meeting on Earthquake Engineering, JSCE, July, 1971.

3) E. Kuribayashi, T. Iwasaki, K. Tuji: An Experimental Study on Dynamic Characteristics of Prefabricated Tunnels, Technical Memorandum of PWRI, No. 747, March, 1972.

4) S. Ibukiyama, E. Kuribayashi, T. Iwasaki: Earthquake Resistibility of Submerged Tunnels, Fourth Joint Meeting of U.S. - Japan Panel on Wind and Seismic Effects, UJNR, Washington, D.C., May 17 - 19, 1972.

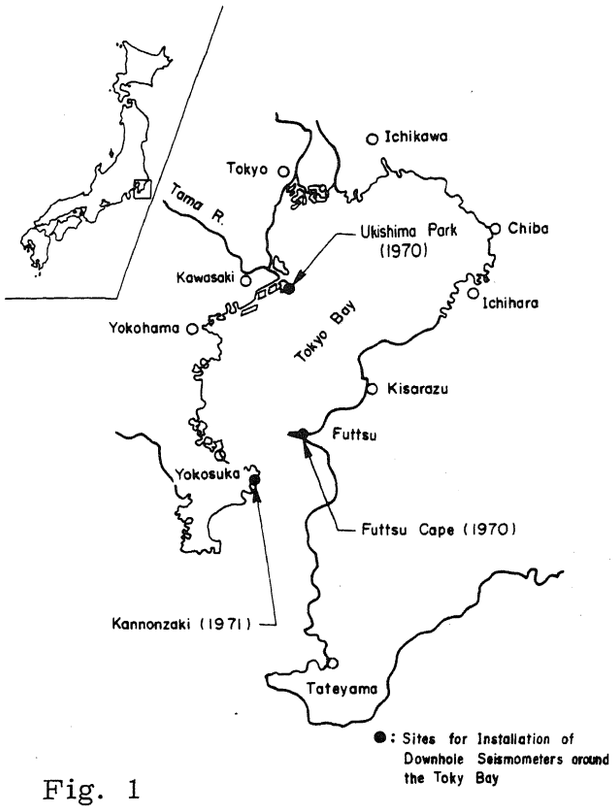


Fig. 1
Sites of Downhole Accelerometer Installation.

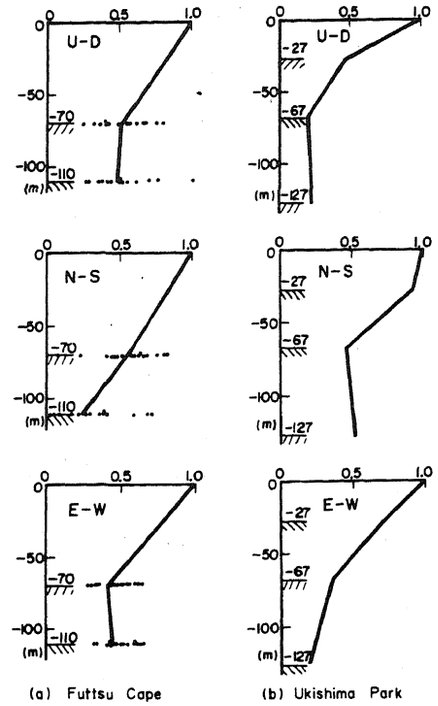


Fig. 3 Distribution of Maximum Accelerations with Respect to Depth

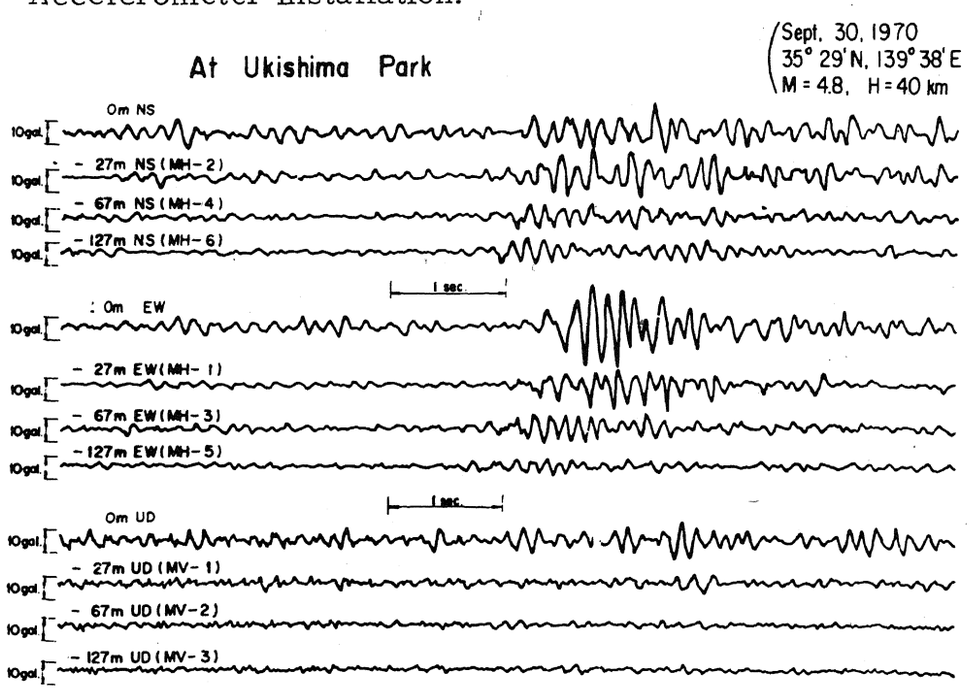


Fig. 2 Seismic Records from Downhole Accelerometers.

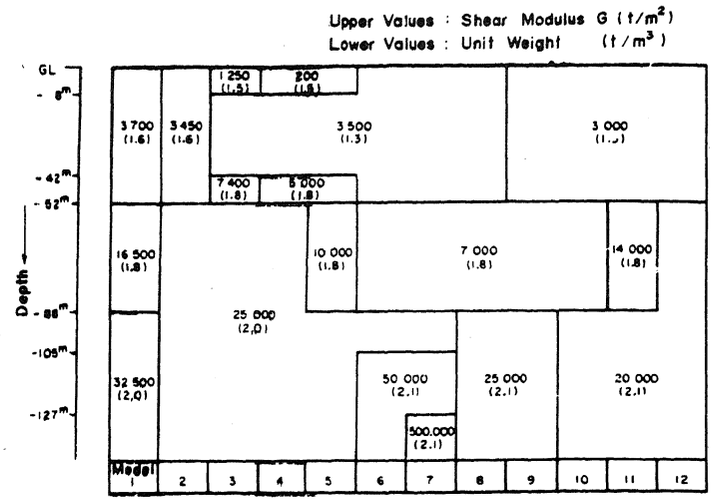
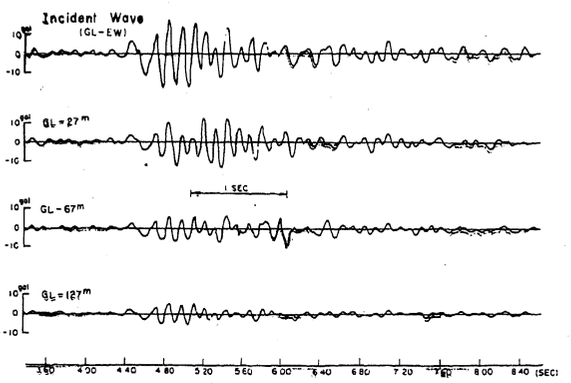
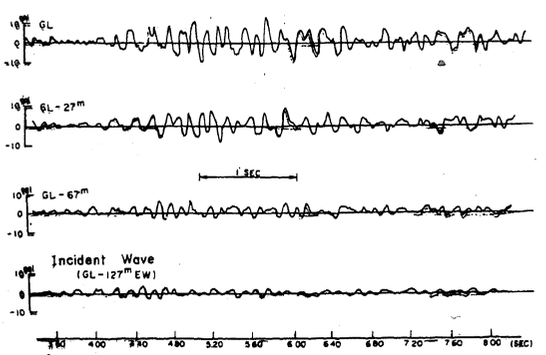


Fig. 4 Various Models of Surface Soil Layers at the Ukishima Park for Analyses by Multi-Reflection Theory.

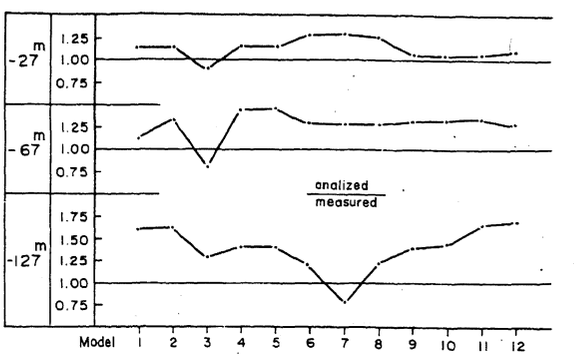


(a) Case where the Record at the ground Surface Considered as the Incident Wave (for Model 1)

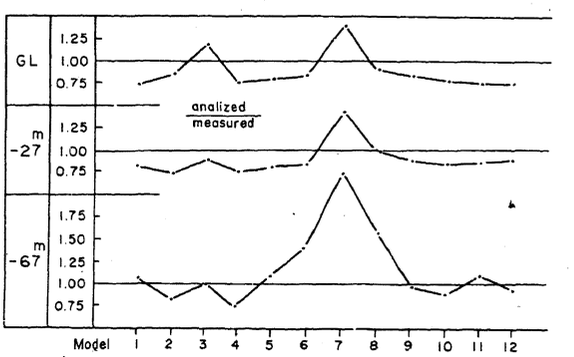


(b) Case wher the Record at -127m Wave Considered as the Incident Wave (for Model 1)

Fig. 5 Examples of Analyses by the Multi-Reflection Theory.



(a) Case where the Record at the ground Surface Considered as the Incident Wave (for Model 1)



(b) Case where the Record at -127m Wave Considered as the Incident Wave (for Model 1)

Fig. 6 Ratios of Analysed Accelerations to Measured Ones.

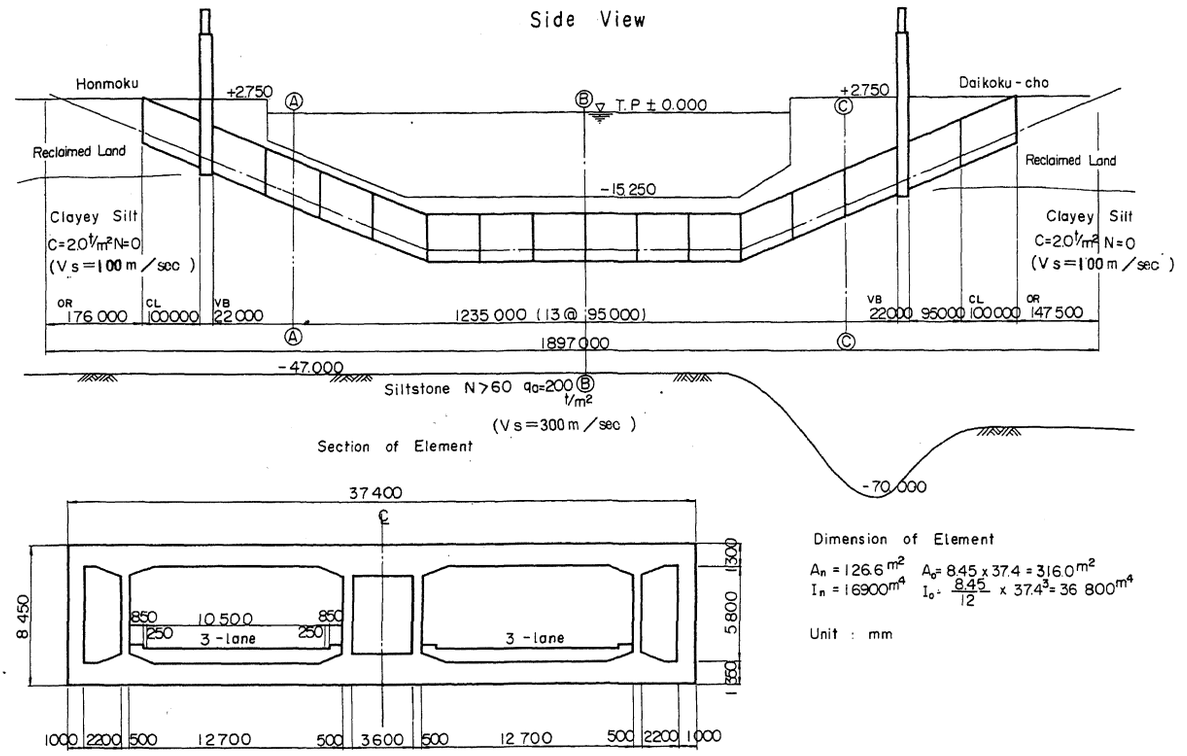


Fig. 7 Yokohama Bay Undercrossing Tunnel (Proposed)

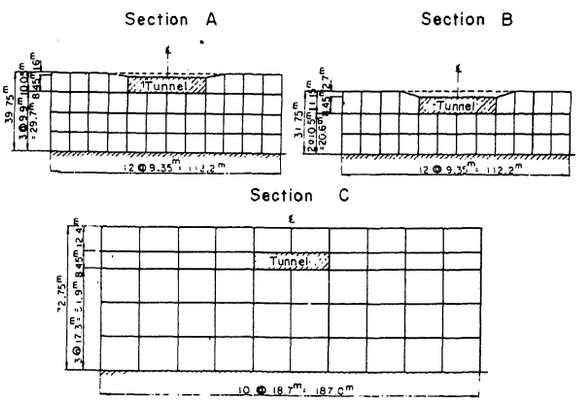


Fig. 8
FEM Models for Three Sections.

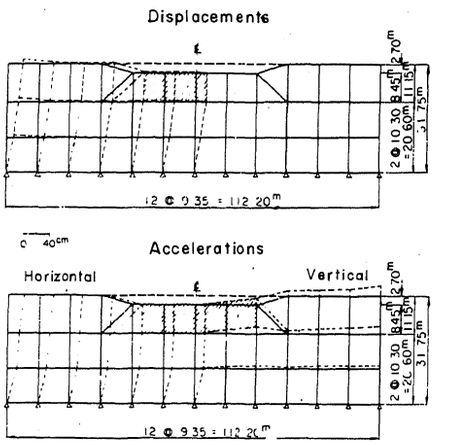


Fig. 9 Results of A Dynamic Analysis for Section B.

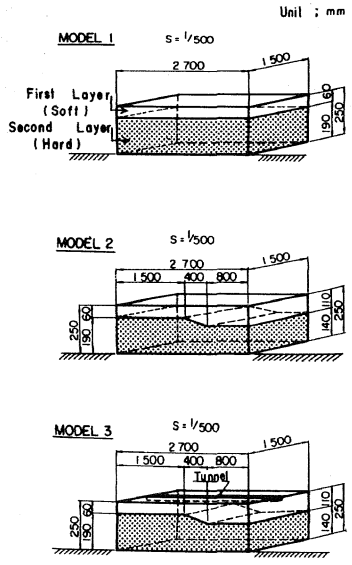
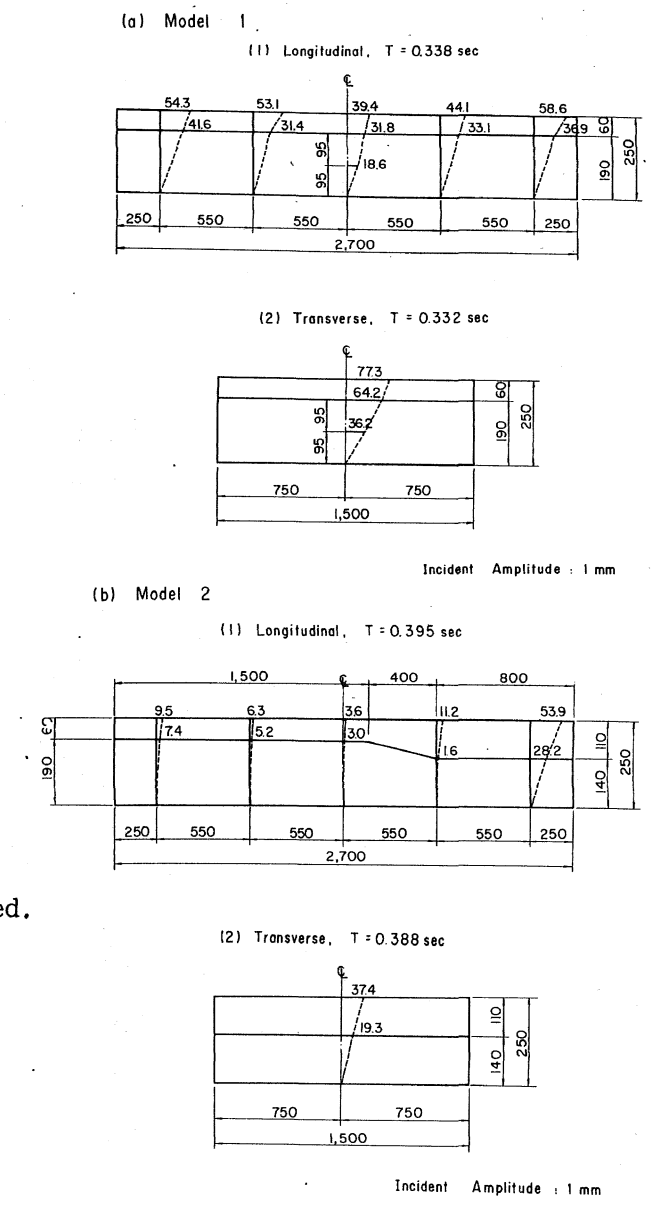


Fig. 10
Three Models Experimented.



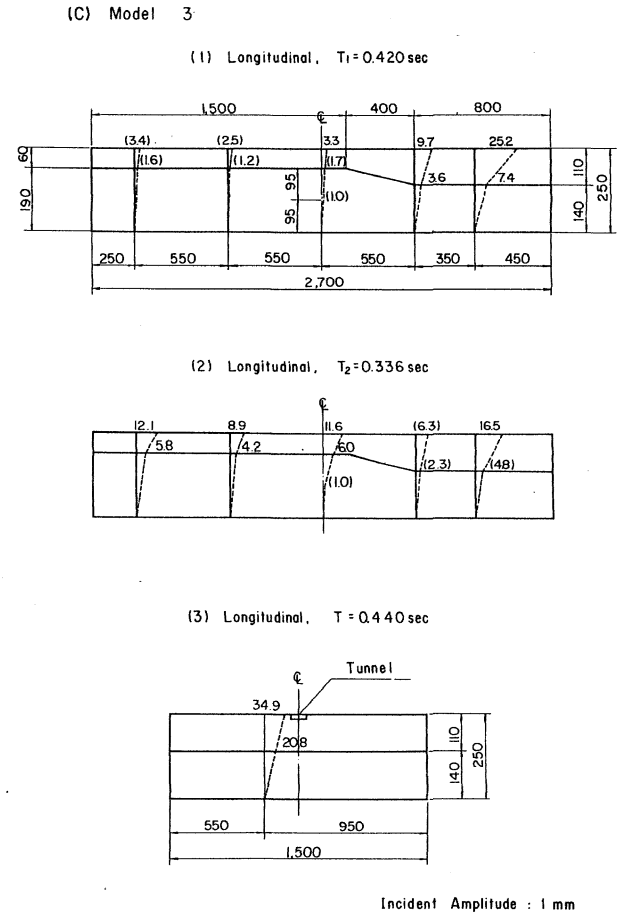


Fig. 11 Mode Shapes (Measured by An Optical Displacement Meter)

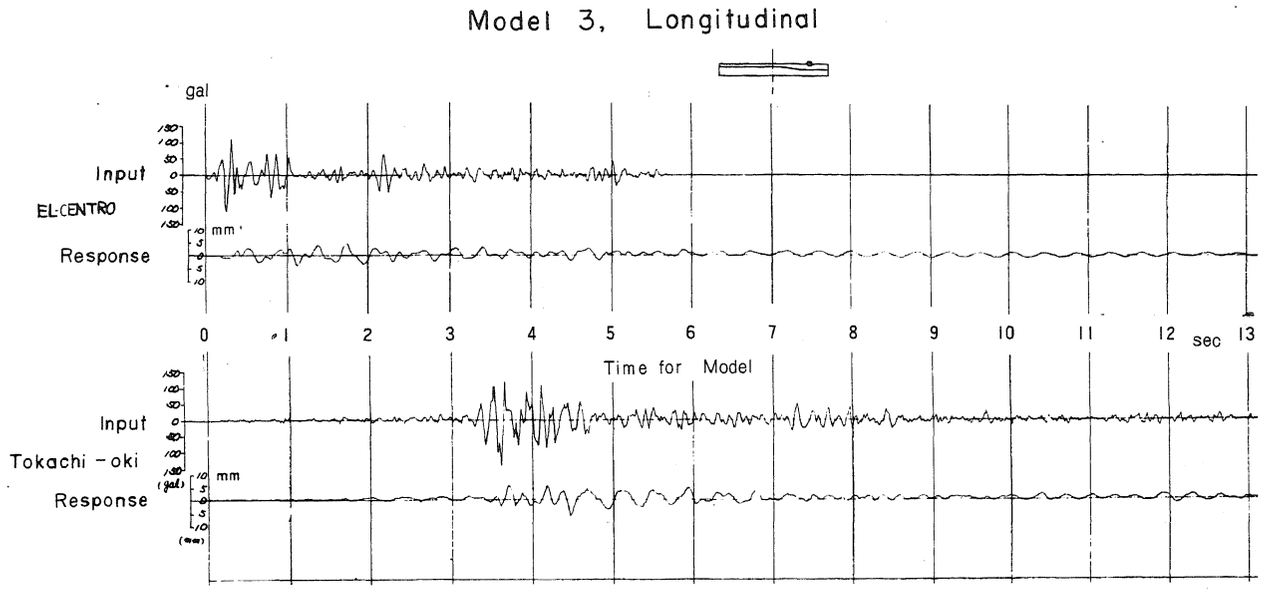


Fig. 12 Response to Seismic Excitation

Table 1 Comparison of Prototype and Model

Prototype or Model		Prototype		Model (Required from Similitude)		Model (Actual)	
Layer		First Layer	Second Layer	First Layer	Second Layer	First Layer	Second Layer
Ground	Material	Clayey silt	Siltstone	Gelatin	Gelatin	Gelatin	Gelatin
	Dimension (plan)	750 m × 1, 350 m		1. 50 m × 2. 70 m		1. 50 m × 2. 70 m	
	Depth	30 - 55 m	95 - 70 m	0. 06 - 0. 11 m	0. 19 - 0. 14 m	0. 06 - 0. 11 m	0. 19 - 0. 14 m
	Shear Wave Velocity	100 m/sec	300 m/sec	1. 0 m/sec	3. 0 m/sec	1. 1 m/sec	3. 0 m/sec
	Shear Modulus	153 kg/cm^2	1, 830 kg/cm^2	0. 0102 kg/cm^2	0. 0917 kg/cm^2	0. 013 kg/cm^2	0. 09 kg/cm^2
	Young's Modulus	459 kg/cm^2	5, 320 kg/cm^2	0. 0306 kg/cm^2	0. 266 kg/cm^2	0. 040 kg/cm^2	0. 27 kg/cm^2
	Unit Weight	1. 5 t/m^3	2. 0 t/m^3	1. 0 t/m^3	1. 0 t/m^3	1. 0 t/m^3	1. 0 t/m^3
	Poisson's Ratio	0. 5	0 0. 45	0. 5	0. 45	0. 495	0. 495
	Fundamental Period	2. 0 sec		0. 4 sec		0. 37 sec	
Tunnel	Material	Reinforced Concrete		Rubber		Rubber	
	Dimension (plan)	37. 4 m × 1, 350 m		0. 075 m × 2. 7 m		0. 075 m × 2. 7 m	
	Depth	8. 45 m		0. 017 m		0. 017 m	
	Young's Modulus	270, 000 kg/cm^2		15 kg/cm^2		12 kg/cm^2	
	Unit Weight	2. 5 t/m^3 (Net 1. 0 t/m^3)		1. 25 t/m^3 (Net 1. 0 t/m^3)		1. 35 t/m^3 (Net 1. 0 t/m^3)	

Similitude

Length $n = L_p / L_m = 50$

Density $m = \rho_p / \rho_m = 1.53$ (first layer)
$= 2.04$ (second layer)

Time $t = T_p / T_m = 5$

Velocity $v = V_p / V_m = n/t = 10$

Acceleration $a = A_p / A_m = n/t^2 = 20$

Young's Modulus $e = E_p / E_m = mn^2/t^2 = 1.5 \times 10^4$ (first layer)
$= 2.0 \times 10^4$ (second layer)

Poisson's Ratio $\nu = N_p / N_m = 1$