EARTHQUAKE RESISTANT DESIGN OF AN IMMERSED TUNNEL CONSIDERING THE EFFECTS OF TRAVELING WAVES

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SUMMARY

An immersed tunnel has some dynamic characteristics different from the ordinary structures constructed on the ground. Since the immersed tunnel usually has a length of 1-5 km, the effects of traveling seismic waves and the inhomogeneity of the ground must be considered in the design. This paper presents a result of investigation on the apparent traveling velocities of seismic waves along the ground surface which are to be used in the design, and the example of application to the design of the immersed tunnel of the proposed Tokyo Bay Crossing Bridge-Tunnel.

INTRODUCTION

An immersed tunnel is the general term for tunnels constructed on the bottom of water by a special construction method in which a trench along the planed tunnel axis is opened on the bottom to accomodate tunnel sections (elements) conveniently divided, built separately on shore, floated, towed then sunk into the trench followed by jointing of elements subsequently to form the tunnel proper and by covering up. Thus, an immersed tunnel is a long underground structure normally with smaller density than the surrounding soil. Therefore its dynamic characteristics are different from those of the structures above ground, and the earthquake reponse analysis considered the effects of traveling waves is necessary for design.

DESIGN OF IMMERSED TUNNELS IN ACTIVE SEISMIC AREA

A cross section of immersed tunnels is designed fundamentaly in the same manner as ordinary structures with box section. There are however some special conditions such as the high and continuous water pressure, the positive buoyancy necessary during the tugging to the site from the dock and the negative buoyancy quite contrary needed after submergence. Usually these conditions will influence the design of cross section of immersed tunnels more strongly than earthquakes. On the other hand, the influence of earthquakes is the major facter of the design of longitudinal tunnel section. Therefore it is required for the design to consider its influence when an immersed tunnel is in active seismic area. One of the reasons is that the sea bed in ports and harbors where immersed tunnels are planed, is quite often relatively soft. Another reason can be tracted to the discontinuities of topography, geology and the differ-

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ences of ground motion at each section of the tunnels since they are usually very long. Therefore, this paper presents, if not so mentioned the earthquake resistant design of the longitudinal tunnel section.

The fundamental dynamic characteristic of an immersed tunnel is that the deformation taking place in the langitudinal tunnel section is governed by the displacement of soil layers surrounding it. The current designing methods based on this characteristic can be classified into following two groups. One is called a seismic deformation method. The other is called the earthquake reponse analysis recommended by Dr. Okamoto & Dr. Tamura particularly for the design of immersed tunnel. The model to be used in this should take acount of the discontinuties of topography, geology and the elastic joints. Nowadays, the latter method is more often applied domesticaly as well as internationally. In Japan, Public Warks Research Institute of Ministry of Construction, Port and Harbour Research Institute of Ministry of Transport and several civil engineering consultants made programmes of the improved version of earthquake response analysis. These programes have been improved, and the effects of traveling waves can be considered in them now. The antiseismicity of Tokyo Bay Crossing Tunnel in Japan has been under study in which the effects of traveling waves are taken into acount positively.

It is considered in the design of a long structure such as immersed tunnels and of a large structure, that the earthquake motions to be taken into acount are different at each locations on the surface of technical seismic base ground under the structure. There considered to be following two reasons to describe the earthquake motions being defferent depending on the location. One of them is that the surface waves travel along the ground surface. The other is that the arival times and/or directions of body waves are transformed according to the structual conditions of soil layers between the seismic center and the tunnel site. It should he quite necessary to consider these phenomena into the earthquake resistant design of immersed tunnels, because they tend to increase both the strain of ground surrounding the tunnel and consequently the stresses of tunnel itself.

TRAVELING VELOCITY FOR DESIGN

Velocities of traveling waves have become major interests as the result of increasing designs and constructions of long and/or large structures. Several research institutes and constractors in Japan have started the earthquake observations employing the dense array observation method at more than ten spots targetting on ground, tunnels, pipe, etc. The result of those observations have also been reported already. The authors picked the matters concerning with traveling velocities from those reports, and suggested the traveling velocity for design as follows.

(1) K. Kawashima et al. (Ref.1) are observing ground motions at the 3-dimensional dense instrument array in their yard. It is considered that the traveling velocity in the horizontal direction is infinitely high. However, when a harmonic displacement wave was assumed to travele with

the velocity of 500m/s in the horizontal direction, the calculated strain of ground became closer to the observed one.

(2) Y. Nakamura et al. (Ref.2) are observing the ground motions at the array stations along some railways on soft ground. The ground motions with periods of about 1 sec predominated in records, and the traveling velocity was a little higher than 500m/s.

(3) S. Noda et al. (Ref.3) are observing at the 1-3 dimentional dense instrument array at 5 places around the Tokyo Bay. The traveling velocity in the horizontal direction observed at some place by the dense observation was very high. And the traveling velocity obtained through the analysis of relation between the distance of each stations to the epicentre and the time of the maxima amplitude wave arrival to each was about 4km/s.

(4) K. Yahagi et al. (Ref.4) are observing earthquakes at the Tokyo Port Tunnel which is about 1.0km long. They reported the traveling velocity in the horizontal direction was about 1km/s.

(5) M. Hamada et al. (Ref.5) are observing earthquake motions of an underground cylindrical shaped tank. The traveling velocity is considered to be 800- 1100m/s.

(6) K. Kato et al. (Ref.6) are observing earthquakes at some railway tunnels in Tokyo. The maximum longitudinal strain of the tunnel was caused by the waves predominating in the period range of 5-8sec. These strain values were similar to the calculated strain of the case that the earthquake wave traveled with the velocity of 1km/s. These phenomina were regarded as the characteristics of a surface wave.

In some of the above reports, the type (Body wave, Surface wave) of the observed waves is not stated clearly. Therefore, the authors assumed simply a classification of body wave and surface wave as in table-1.

Table-1 Classification of Body Wave and Surface Wave.

No.	Item	Body Wave	Surface Wave
1	Predominant period	Short	Long
2	Distribution of Velocity	No.	Exist
3	Velocity detection method	Time Lag of waves	Cross-correlation Func. of Whole Wave Form.

The autors adoptied a detection method as one of the items of classification, because it is generally believed that the predominating motion after the first several S-wave peaks should be interpreted as surface waves (for example, Ref.7). Thus, traveling waves are classificated as shown in table-2. Besides, concerning with the traveling velocity of body wave, one of the authors repoted (Ref.8) the result of a simple study using the model suggested to be the crust structure of Kanto district in Japan (Ref.9). The report showed that traveling velocity of body waves decreased to about 1.5km/s in case the seismic center located at the shallowest possible level which can be considered proper in the firld of seismology.

Table-2 Traveling Velocities

Author's Name	Velocity of Body Wave	Velocity of Surface Wave
K. Kawashima et al.	∞	500m/s
Y. Nakamura et al.	-	500m/s for T=1sec
S. Noda et al.	4km/s	-
K. Yahagi et al.	(1km/s)	(1km/s)
M. Hamada et al.	-	800-1100m/s
K. Kato et al.	-	1km/s

The traveling velocities in table-2 are distributed widely, but slower velocity among them should be adopted for design, because when the traveling velocity becomes slow, the ground strain consequently becomes large. The velocities of surface waves also varies depending on the periods, however it is sufficient to pay altention to the range of the predominant period of the object ground during earthquakes. The surface ground generally is very soft in and around ports and harbors of Japan, and the soil rigidity decreases during strong earthquakes. The predominant period of ground therefore can be concidered to be 1-2 sec. Based on these views, it is considered from table-2, that the traveling velocities of about 2km/s for body wave (particularly SH-wave) and about 1km/s for surface wave for a period range of 1-2 sec should be used in design.

STRESS INCREASE CAUSED BY TRAVELING WAVES

As mentioned earlier in this paper, the underground structures such as immersed tunnels and pipelines are considered to be deformed during earthquakes in accordance with the deformation of surrounding ground. Therefore the magnitude of stress and strain of these structures fundamentaly depends on the strain of ground. When the ground is deformed like a wave during earthquakes, the bigger amplitude of displacement and /or the shorter wave length of deformation will make the larger ground strain. Furthermore the more the inhomogeneity of the ground is conspicuous horizontally and/or the slower the seismic wave travels, the shorter the wave length will be. Hence, when the effects of traveling waves are not considered, the stress of the underground structures such as immersed tunnels is certain to be underestimated. This is the most remarkable in case that the horizontal ground condition is relatively homogeneous.

The results of earthquake response analyses for immersed tunnels and pipelines showed that the stress of these structures increased when the traveling waves were considered. The authors carried out some earthquake response analyses for Tokyo Bay Crossing Immersed Tunnel, in both cases of considering and neglecting the effects of traveling waves. The relationship between the traveling velocity used and the consequent ratio of maximum longitudinal stress is obtained from those analyses calculating the two cases and is shown in figure-1. The authors oftained the ratios from the results of the similar analyses carried out by P.W.R.I. M.C. and P.H.R.I.M.T. (Ref.10.11), and showed them in the figure-1, too. Though the extent of increase depended on the ground condition and the inputted earthquake motion, the increase of stress can be as much as 2-3 times.

NUMERICAL EXAMPLE

In this section, some results of earthquake response analyses for the longitudical direction of an immersed tunnel, a part of the proposed Tokyo Bay Crossing Bridge-Tunnel, are explained briefly. This crossing, as shown in figures 2 and 3 will span across the center of Tokyo Bay, and about 15km in length. It consists of an immersed tunnel, bridges and two artificial islands. The tunnel proposed at the time of analyses was about 3km in length and the section was about 44m wide, about 13m high. The authors calculated the earthquake response of tunnel for both cases of body wave and surface wave. The calculated sectional forces of tunnel caused by surface waves were smaller than those caused by body waves, and also the authors are improving the model for surface wave response. Hence the results of earthquake response analyses with body waves are described hereinafter.

The earthquake response analyses of two cases, considering and neglecting the effects of traveling waves (traveling velocity ; 2km/s, an incidence angle ; 45 degree), were carried out. The distributions of maximum axial force of each tunnel element were shown in figure-4. From this, it is clear that the traveling wave makes an axial force of each element larger. The maximum amplitude of ground acceleration and displacement were similar in those two cases, so that the increase of axial force might be caused by the increase of relative displacement of ground between any two points. The earthquake waves which were used in these analyses have for instance characteristic such as response spectora shown in figure-5, and they can be regarded as the worst ever expected earthquake mortion for the surrounding ground.

Generally the axial force of underground structure such as immersed tunnels is the largest of all the forces during earthquakes. Therefore the amount of longitudinal reinfocement is usualy decided by the design for the maximum axial force. The reinforcement which was needed in case of considering both the result of these earthquake response analyses and the effects of temperature change is shown in table-3.

Table-3 Reinforcement in the Longitudinal Direction

Accelerogram's Name	Traveling Wave	
	Neglected	Considered
Hachinohe	D22	D29
Kannonzaki	D25	D35

Note : Reinforcement pich is 200mm, Steps are 1+1/4

CONCLUSION REMARKS

The following matters were obtained as the conclusion remarks through the close examination of the observed apparent traveling velocities in the horizontal direction and the earthquake response analyses for the tunnel part of the proposed Tokyo Bay Crossing Bridge-Tunnel.

(1) The response of immersed tunnels during earthquakes is influenced considerably by the horizontal inhomogenities of ground condition and

the differences of the base ground motions depending on the location.
(2) From the results of earthquake observation, the apparent traveling velocities of 1-4 km/s for the body (SH) wave and about 1 km/s for the surface wave obtained for a period range of 1-2 sec. predominating in the immersed tunnels.
(3) For body wave, the lower the apparent velocity is, the larger the sectional force becomes, and the values are 2-3 times as compared with the case where the infinitely high velocity is assumed.
Therefore in the earthquake resistant design of immersed tunnels, it is sufficient to take the body (SH) wave traveling with a velocity of about 2 km/s into consideration.
(4) The immersed tunnel which is planed in the proposed Tokyo Bay Crossing Bridge-Tunnel is of the reinforced concrete construction. The axial tensile force is the most significant in the design among the sectional forces and, in this model, the force was approximately 2 times larger than that obtained in case of neglecting the effects of traveling waves. Thus, the more amount of longitudinal reinforcement is required.

The matters mentioned above are tentative conclusions, because the observed records of apparent traveling velocity are not so sufficient, and because the difference of the base ground motion depending on the location can not be described by only the traveling waves. At the present time, however, the earthquake response analysis considering the effects of traveling waves must be the most useful in the earthquake resistant design of immersed tunnels.

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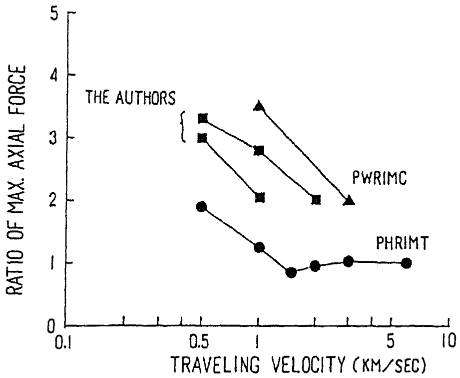

FIG-1 RELATIONSHIP BETWEEN THE VELOCITY AND THE FORCE RATIO

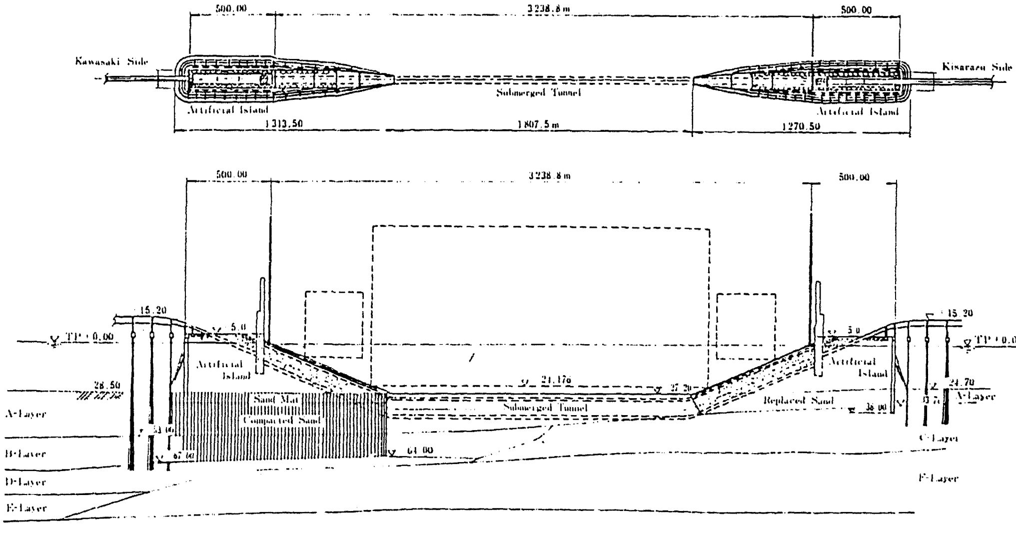

FIG-2 PROPOSED TOKYO BAY CROSSING TUNNEL (REF.12)

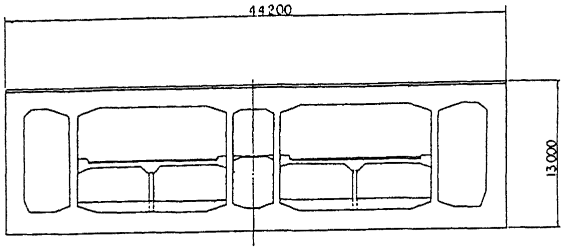

FIG-3 SECTION OF THE TUNNEL

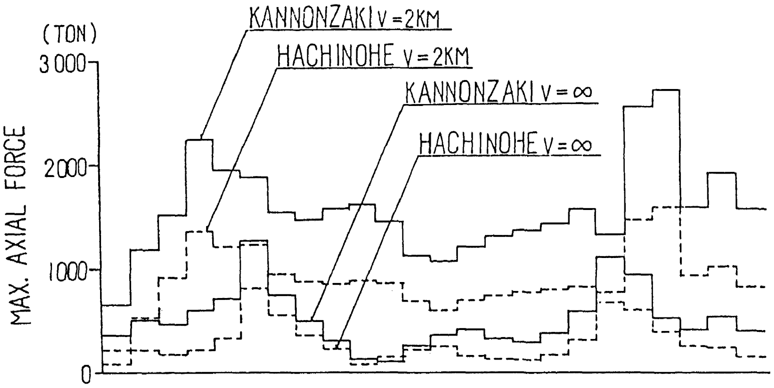

FIG.-4 DISTRIBUTION OF MAX. AXIAL FORCE

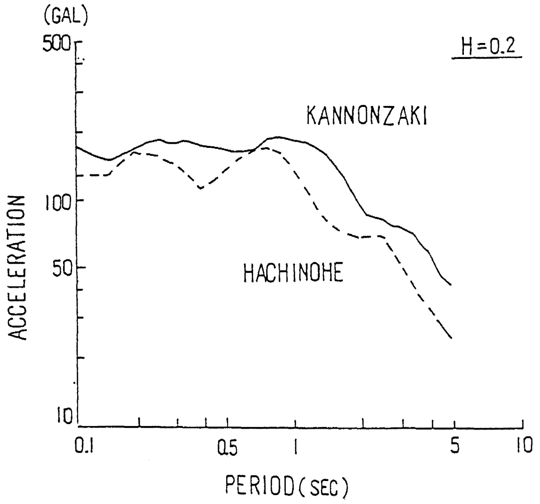

FIG-5 RESPONSE SPECTRA