ON THE EARTHQUAKE RESPONSE OF SUBMERGED TUNNELS

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SYNOPSIS

This paper investigates the earthquake responses of submerged tunnels through theoretical and experimental means. The former makes use of finite element method for the three-dimensional dynamic analysis involving the tunnel-soil layer interaction. The latter is the vibration tests carried out on the gelatin and rubber models. The results of these studies are examined and correlated to each other, and some useful conclusions are drawn.

INTRODUCTION

Recently in Japan, submerged tunnels have been increasingly adopted for constructing underwater tunnels. Therefore, considerable efforts have been made to clear the earthquake influence on these structures. In this study, both of analytical and experimental investigations are performed to estimate the earthquake response of these tunnels.

THE ANALYTICAL METHOD

The analytical model[(1)] of the tunnel-soil layer system is as follows;

1) The system is divided into a number of brocks in the transverse direction of the tunnel. (Fig.1)
2) The soil medium in each brock is divided into finite triangular elements each of which is treated as two dimensional plane strain problem. Mass of soil medium is concentrated on the neighboring nodes of the elements, and each node is considered to have two degrees of freedom.
3) The effects of longitudinal continuity between the adjacent sections are replaced by shear springs.
4) The tunnel is considered to be a bending and torsional beam in the longitudinal direction.

Concerning this model, the equations of motion are obtained through the matrix formulation, but the number of their unknowns becomes too large to be solved directly. Therefore, the following technique is adopted in this study to reduce the unknowns.

1) First, neglecting the effect of longitudinal continuity, the vibration

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modes in each section are divided into two groups, namely several influential modes which contribute the vibration of the tunnel and other uninfluential modes.

2) Second, considering the longitudinal continuity, the equations of the total system are transformed to the modal coordinates which are defined in the first step. And then the coordinates of uninfluential modes are reduced through Gaussian elimination technique by neglecting the inertia terms.
3) The earthquake response is obtained through the inverse transformation and direct integration of the reduced system.

It is assured from numerical investigations that the error is so small as 1% even if the 90% of unknowns are reduced.

The computer program developed by this analysis has flexible applicability. Spacial variations in the input earthquake wave are roughly simulated by the propagating motion of a single wave, travelling at a constant velocity without being modified.

THE EXPERIMENTAL STUDIES

The experimental model used in this studies is as follows:

1) The tunnel consists of 8x8cm square rod of rubber.
2) The model layer consists of gelatin of 0.4m thick in the 1.5m^{x}1.0m rigid box. (Fig.2)
3) Scale factors and boundary conditions are not examined in detail.

Random waves are introduced from the base of the model through the vibration table. Acceleration of the tunnel and surface displacement of the layer are recorded by electric and optical means. The response-frequency spectrum obtained from this experiment is shown by spots in Fig.3. The spectrum shows a remarkable dominance of the fundamental mode This means that the tunnel almost follows the fúndamental vibration of the layer.

The spectrum obtained analytically is also shown by curved line in Fig.3. The boundary conditions and the elastic constants of the model are set to coincide with that of the experiment. Note the good coincidence among these two spectrums which assures the analytical method.

SOME STUDIES ON THE ACTUAL TUNNEL

Some analytical studies are carried out on the 800m length reinforced concrete tunnel which has a large section as 30m^{x}9m and is submerged in the soft alluvium layer which is 50m in depth. The system is divided into 14 brocks, whose sections consist of finite elements as shown in Fig.4. The system is assumed to have 5%of critical damping. The earthquake record of El Centro 1940,NS is adjusted to be 100gal in maximum acceleration and is used as the input wave in the following investigations.

1) First, the layer is assumed to be uniform ($E=1.0x10^{4}ton/m^{2}$), but the one end section is assumed to be fixed. The earthquake waves act from both of the fixed section and the basis of other sections so that the wave propagates to the longitudinal direction in the layer. Maximum

bending moment Mp comes to 1.0×10^5ton.m due to this propagation. (shown in Fig.5) If the maximum acceleration is more than 250gal, Mp exceeds the crack moment Mcr.

2) Using the BART's ground displacement spectrum, the maximum moment Mb is also calculated and is shown in Fig.5 for being compared with Mp.

3) Second, the tunnel is supposed to be extended through two layers, namely from a soft deposit layer to a comparatively hard gravel layer. Fig.6 shows the distribution of the maximum bending moment of the tunnel induced by the earthquake in the case the rigidity ratio of the adjacent layers being 2. Maximum moments corresponding to various rigidity ratios are plotted with circular marks in Fig.5. The maximum moment exceeds Mcr under strong earthquakes even if the rigidity ratio is less than 2.0.

4) For the practical purpose to estimate these moment concentration, the following formula is proposed;

$$M = \frac{EI\cdot L^2\gamma^2 Q}{(1+\gamma)(1+\gamma^2)} \quad \text{in which} \quad L^2=\sqrt{\frac{\alpha Gs_1 B}{H\cdot EI}} \quad , \quad \gamma = \sqrt[4]{\frac{Gs_2}{Gs_1}}$$

Gs_2 ; Rigidity of the stiffer layer.
Gs_1 ; Rigidity of the softer layer.
Q ; Relative displacement of two layers estimated from response spectrum.

Triangle marks in Fig.5 are the results of this expression, and it is assured that the rough estimation can be made through this procedure.

5) The effect of a hinge joint is investigated and shown in Fig.6 with a dotted line. It is seen that the moment decreases only in the vicinity of the hinge.

6) The effect of the spacial variation in the input wave is investigated. The maximum bending moment of the tunnel increases as the phase lag of the input wave increases, but in the case of the reasonable phase lag 0.00025sec/m (4km/sec) the moment increases only 10~20%.

CONCLUSION

Based on the analytical studies on an actual tunnel, this paper points out the importance of the effects of longitudinally propagating waves and of spacial variations of the vibrational properties of layer. A simple approximation formula is proposed herein for estimating the effect of the spacial variations on the moment of the tunnel.

Longitudinal vibration of the system is not discussed in this study, but its importance has been mentioned in many papers. The advanced study should include the investigation of longitudinal vibration.

BIBLIOGRAPHY

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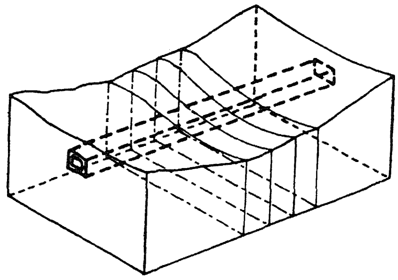

Fig.1 Analytical Model

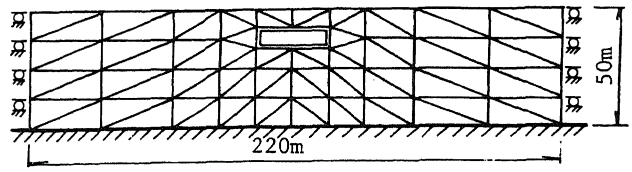

Fig.4 Finite Idealization

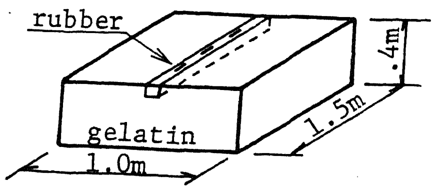

Fig.2 Experimental Model

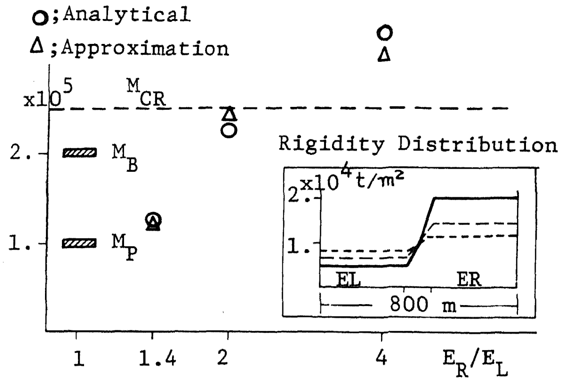

Fig.5 Maximum Bending Moment

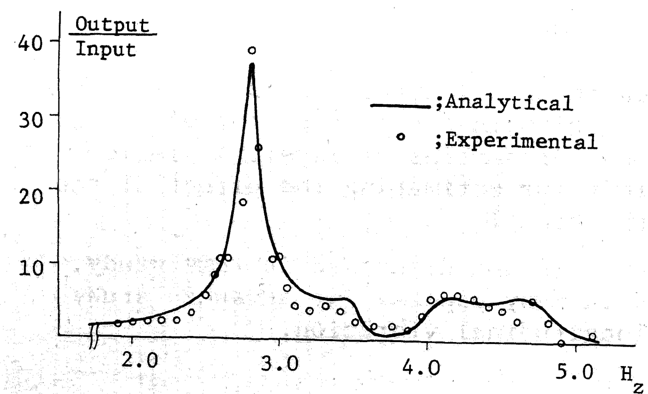

Fig.3 Frequency Response Spectrum

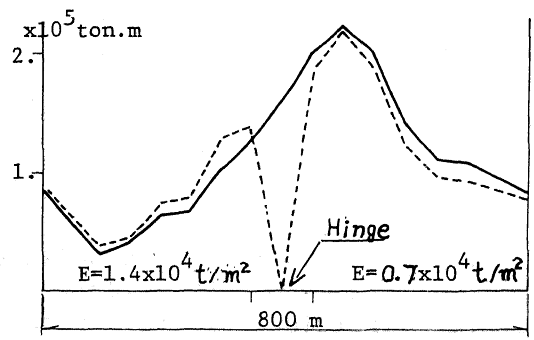

Fig.6 Distribution of Maximum Bending Moment