ANALYSIS OF DYNAMIC BEHAVIOR OF SUBMERGED TUNNELS

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1. INTRODUCTION

According to Hamada et. al. several numerical methods for the estimation of dynamic strains of submerged tunnels were already proposed on the basis of concept of the response displacement method [(1)]. However, it is difficult for engineers to estimate the exact ground deformation which relays greatly on the geophysical condition which is a large area on the tunnel axis, along with the characteristics of the earthquake waves. Hamada et. al. [(1)] further explains the difficulties such as exact evaluation of the coefficient of the sub-grade reaction and the flexibility of the joints between the elements. Therefore it is important to use a simple model to calculate approximate values of the dynamic strains of tunnels and of relative displacement of joints.

2. THEORY OF DYNAMIC STRAINS OF TUNNELS AND THE RELATIVE DISPLACEMENT OF JOINTS

New analytical model of submerged tunnel which consists of elements and flexible joints between elements were developed. There are some assumptions to create the simple model. The tunnel is considered to be consisting of infinite chain of tunnel elements and joints as shown in Figure 1. Also only the axial strain is calculated since it is much more dominant than the bending strain. The normal strain of the ground in the axial direction is uniform along the tunnel axis.

The basic equation related to the tunnel axis' direction deformation, v_p(x) is shown below:

$$\frac{d^2 v_p}{dx^2} - \beta_x^2 \cdot v_p = -\beta_x^2 \cdot v_g \qquad (1)$$

General solution for Eq. (2) is:

$$v_p = c_1.\exp(-\beta_x x) + c_2.\exp(-\beta_x x) + \gamma_x x \qquad (2)$$

On Eq. (3) for the first boundary condition we assume x value as 0, and v_p as 0 concluding the values for c_1+c_2 to be 0.

$$\mathrm{x} = 0, \quad v_p = 0, \quad c_1 + c_2 = 0 \qquad (3)$$

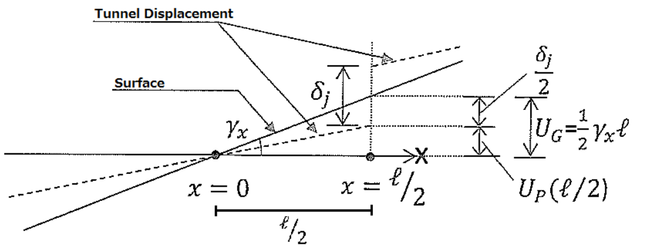

Fig. 2- Boundary Condition at $x = \ell/2$

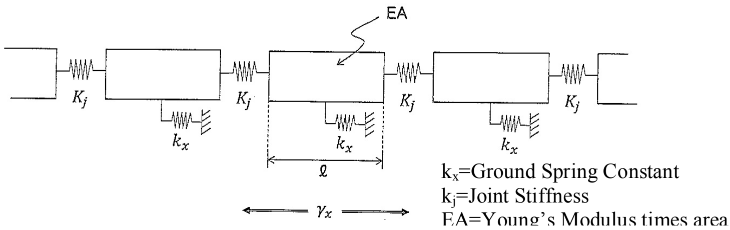

Fig. 1- Simplified Numerical Model

For the second boundary condition x is assumed to be in the middle of the box which is ℓ /2, and resulting values is displayed on Eq. (6):

at $x = \ell/2$

$$v_p\left(\frac{l}{2}\right) = c_1 exp\left(-\frac{\beta_x l}{2}\right) + c_2 exp\left(\frac{\beta_x l}{2}\right) + \frac{\gamma_x l}{2} \qquad (4)$$

$$EA\left(\frac{dv_p}{dx}\right) = -EAc_1\beta_x exp\left(-\frac{\beta_x l}{2}\right) + EAc_2\beta_x exp\left(\frac{\beta_x l}{2}\right) + EA\gamma_x \qquad (5)$$

$$c_1 exp\left(-\frac{\beta_x l}{2}\right) + c_2 exp\left(\frac{\beta_x l}{2}\right) + \frac{\gamma_x l}{2} + \frac{1}{2}\frac{1}{k_j}\left\{-EAc_1\beta_x exp\left(-\frac{\beta_x l}{2}\right) + EAc_2\beta_x exp\left(\frac{\beta_x l}{2}\right) + EA\gamma_x\right\} = \gamma_x \cdot \frac{l}{2} \qquad (6)$$

Including Eq. (3) and (6) to the Eq. (1), the result is Eq.(7):

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$$\varepsilon_x = \gamma_x \left\{ 1 - \frac{\cosh \beta_x}{\cosh \frac{\beta_x l}{2}} \left(1 - \frac{2 \cdot \frac{\tanh \frac{\beta_x l}{2}}{\beta_x l}}{\frac{EA}{k_j l} + \frac{2 \cdot \tanh \frac{\beta_x l}{2}}{\beta_x l}} \right) \right\} \tag{7}$$

$$k_j = 0 \quad EA => \infty \quad \beta_x => 0 \quad \delta_j = \gamma_x l$$

3. RESULTS AND DISCUSSION

3.1. The Dynamic strain and Non-Dimensional Relative Displacement of Joint

The dynamic strain of the tunnel ε_x and the relative displacement of flexible joint δ_s are obtained from Eq. (7) as follows:

$$\delta_j / l = \gamma_x \frac{\frac{2}{\beta_x l} \tanh \frac{\beta_x l}{2}}{1 + \frac{k_j l}{EA} \cdot \frac{2 \cdot \tanh \frac{\beta_x l}{2}}{\beta_x l}} \tag{8}$$

$$\beta_x = \sqrt{\frac{K_x}{EA}} \tag{9}$$

Where EA and ℓ are the stiffness of push-pull deformation and the length of the tunnel element, while k_j and k_x are the spring constant of the flexible joint and the coefficient of the subgrade reaction. γ_{xx} is the normal strain of the ground in the axial direction.

In the Fig. 3 (Strain Transfer Ratio) is showed the ratio of the maximum strain of the tunnel to the ground strain (strain transfer ratio) which is obtained by substituting x=0 into Eq. (8) and Fig. 4 (Non-Dimensional Relative Displacement of Joint) shows non-dimensional relative displacement of joints. From these figures it is clarified that the strain transfer ratio is always less than 1.0 and the relative displacement of the joint is smaller than $\gamma_{xx}{}^{l}$.

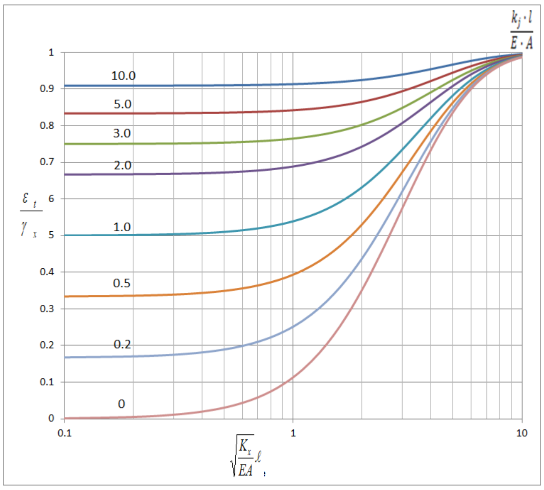

Fig. 3: Strain Transfer Ratio

3.2 Calculation of Non-dimensional Parameter

Knowing the Young Modulus, the Area, the Length of the box, the Joint stiffness (k_j) and the Spring coefficient of ground per unit length of tunnel (k_x), we could show the portable zones of the ratio of the joint spring k_j to the stiffness of tunnel elements EA/ ℓ, we have to calculate the values $\sqrt{\frac{k_x}{E \cdot A}} \cdot l$ and $\frac{k_j \cdot l}{E \cdot A}$ using the minimum and maximum values for k_j and k_x

For the tunnel that was analyzed, $\sqrt{\frac{k_x}{E \cdot A}} \cdot l$ gives the minimum value is: 0.354 and the maximum value of: 1.125. For the $\frac{k_j \cdot l}{E \cdot A}$ the minimum value is: 0.087 and the maximum is: 0.1

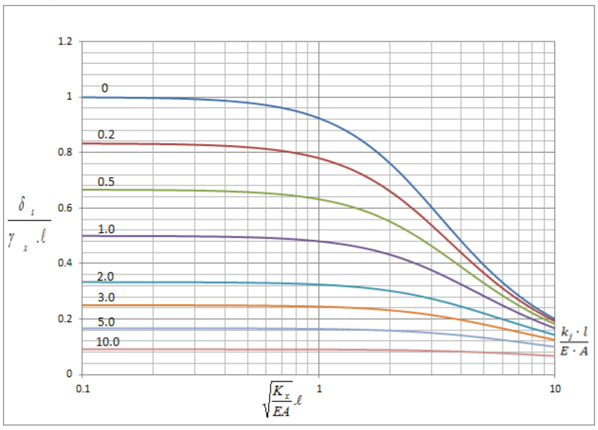

Fig. 4: Non-Dimensional Joint Disp.

4. Conclusions

The authors are going to examine the rational of the numerical model by comparing the tunnel strain and joint displacement observed in earthquake and the value calculated by the proposed theory. For the numerical analysis, authors use March 11th Great Tohoku Earthquake and the aftershocks.

5. References

Hamada, M. (1984) "Earthquake Observation of Two Submerged Tunnels and Numerical Analysis", Proceedings of Eight World Conference on Earthquake Engineering, San Francisco, California, 1984, vol. 3, pp. 673-680