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Diagonal expansion and contraction of a circular tunnel with isolation material during earthquakes

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1.Introduction The dynamic behavior of a circular tunnel in the transverse direction is investigated when the tunnel is covered with an isolation material. Earthquake observations at different tunnel sites within a variety of alluvial soil deposits have demonstrated that a circular tunnel is liable to deform in such a way that its two diagonal diameters crossing each other expand and contract alternately. Therefore it is worthwhile checking the isolation effect under this particular vibration mode. The soil and the isolation material covering up a tunnel are assumed to be homogeneous media. The compatibility of displacements and continuity of stresses are assumed at the interfaces.

2.Derivation of stiffness of soil and isolation material

The soil deposit discussed in this paper is a two dimensional medium of an infinite extent (Fig.1). The governing equations of a visco-elastic medium undergoing harmonic motion are expressed in the cylindrical coordinates as;

$$(\lambda_{s,i}+2\mu_{s,i})\cdot\frac{\partial\Delta e^{i\omega t}}{\partial r}-\frac{2\mu_{s,i}}{r}\cdot\frac{\partial\Omega_z e^{i\omega t}}{\partial\theta}=\rho_{s,i}\cdot\frac{\partial^2 u_r e^{i\omega t}}{\partial t^2}\quad,\quad(\lambda_{s,i}+2\mu_{s,i})\cdot\frac{\partial\Delta e^{i\omega t}}{r\partial\theta}+2\mu_{s,i}\cdot\frac{\partial\Omega_z e^{i\omega t}}{\partial r}=\rho_{s,i}\cdot\frac{\partial^2 u_\theta e^{i\omega t}}{\partial t^2}$$

where, $\Delta=\frac{1}{r}\cdot\frac{\partial}{\partial r}\cdot(ru_r)+\frac{1}{r}\cdot\frac{\partial u_\theta}{\partial\theta}$, $\Omega_z=\frac{1}{2r}\cdot(\frac{\partial}{\partial r}\cdot(ru_\theta)-\frac{\partial u_r}{\partial\theta})$

The displacements and reaction to the motion of the cylindrical hollow can be expressed in terms of the following two potential functions: $\phi=\sum_{m=0,1,\dots}^{\infty}\phi_m$ and $\psi=\sum_{m=0,1,\dots}^{\infty}\psi_m$ .It is assumed that a circular cross-section of a circular hollow of radius 'r' deforms in such a way that its two diagonal diameters orthogonal to each other $(\theta=\pm45^\circ)$ alternately expand and contract. Thus normal and shear stress components are found to be:

$$\begin{Bmatrix}u_r\\u_\theta\end{Bmatrix}=\begin{Bmatrix}\hat{u}_r\sin 2\theta\\\hat{u}_\theta\cos 2\theta\end{Bmatrix},\quad\begin{Bmatrix}\sigma_{rr}\\\tau_{r\theta}\end{Bmatrix}=\begin{Bmatrix}\hat{\sigma}_{rr}\sin 2\theta\\\hat{\tau}_{r\theta}\cos 2\theta\end{Bmatrix}$$

By assuming the compatibility of displacements and continuity of stresses on the soil and the isolation material and tunnel lining interfaces, we can obtain the following relationship:

$$\begin{Bmatrix}\hat{\sigma}_{rr}\\\hat{\tau}_{r\theta}\end{Bmatrix}=\frac{\mu_i}{r}\begin{bmatrix}S_{rr}&S_{r\theta}\\S_{\theta r}&S_{\theta\theta}\end{bmatrix}\begin{Bmatrix}\hat{u}_r\\\hat{u}_\theta\end{Bmatrix}$$

3.Isolation effects The concept of a multi-step method is employed to evaluate the isolation effect. Radial

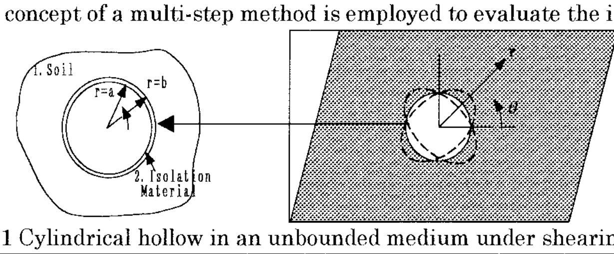

Fig.1 Cylindrical hollow in an unbounded medium under shearing

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and tangential displacements of soil $u_{r,soil}$ and $u_{\theta,soil}$ are tentatively approximated by the static solutions for a cylindrical cavity inclusion in an unbounded medium under alternate shearing.(Fig.1) The tunnel lining is then assumed to have a perfect bond with the isolation material and the soil, and to be stiff enough in its tangential direction for the tangential strain $\varepsilon_{\theta\theta,lining}$ to be kept zero at the wall of the lining. Assuming that the tunnel lining is a circular Bernoulli-Euler beam, its displacement parameter $\hat{u}_{lining}$ is expressed in terms of $\hat{\sigma}_{rr}$ and $\hat{\tau}_{r\theta}$ as: $\hat{u}_{lining} = \frac{r_a^4}{18EI}[2 \quad 1][\hat{\sigma}_{rr} \quad \hat{\tau}_{r\theta}]^T$ where, EI=bending stiffness of the lining. , the following equation is finally obtained:

$$\frac{\hat{u}_{lining}}{\hat{u}_{soil}} = \frac{-\xi \cdot A \cdot \frac{r_b}{r_a} \cdot (2S_{rr} + 2S_{r\theta} + S_{\theta r} + S_{\theta\theta})}{1 - \xi \cdot A \cdot \frac{r_b}{r_a} \cdot (2S_{rr} + S_{r\theta} + S_{r\theta} + \frac{S_{\theta\theta}}{2})} \qquad \text{where, } \xi = \frac{\mu_s r_a^3}{18EI}, A = \frac{\mu_i}{\mu_s}$$

Fig.2($\upsilon = 0.4$) and Fig.3($\upsilon = 0.49$) show the lining displacement ratio $|U_{linI.}/U_{linnoI.}|$ changing with the shear modulus ratio and relative soil stiffness. Here, U_{linI} and U_{linnoI} denote lining displacements with and without the isolation effect taken into account, respectively. As Poisson's ratio of the isolation material becomes smaller, the isolation effect is more pronounced.

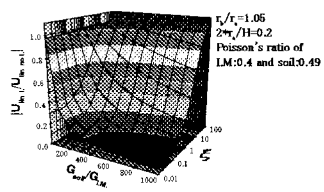

Fig.2 Isolation effects for the case of Poisson's ratio of the I.M 0.4

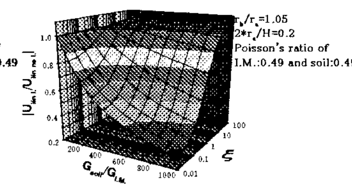

Fig.3 Isolation effects for the case of Poisson's ratio of the I.M 0.49

Fig.4(r_b/r_a=1.05) and Fig.5(r_b/r_a=1.2) show isolation effects depending on the change of thickness of isolation material. These figures show that the isolation effect increases as the thickness of isolation material increases. Fig.6 shows the change of the isolation effect when the shear modulus of soil is being decreased. The shear stiffness of the soil is changed while the bending stiffness of the tunnel is fixed in the practical range of ξ. If an earthquake occurs and the shear modulus of the soil decreases, this figure shows that the isolation effect decreases at the same time.

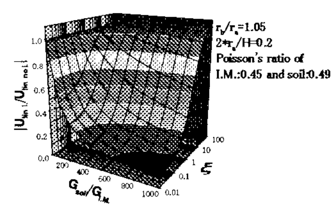

Fig.4 Isolation effects changing with the thickness of I.M, r_b/r_a=1.05

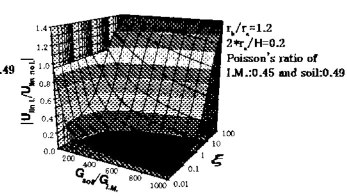

Fig.5 Isolation effects changing with the thickness of I.M, $r_b/r_{a=1.2}$

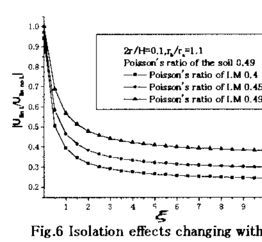

Fig.6 Isolation effects changing with the shear modulus of the soil

4.Conclusion By introducing the isolation material between soil and tunnel lining, three results have been obtained as follows. Firstly, as Poisson's ratio of the isolation material decreases, the isolation effect increases. Secondly, the isolation effect increases as the thickness of isolation material increases. Lastly, in the case of the shear modulus of the soil decreasing, the isolation effect also decreases.

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