THE AXISYMMETRIC FINITE ELEMENT MODEL DEVELOPED AS A MEASURE TO EVALUATE EARTHQUAKE RESPONSES OF SEISMICALLY ISOLATED TUNNELS

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SUMMARY

A seismically isolated tunnel is the tunnel structure in which a thin layer with elastic soft material is formed between a tunnel body and surrounding soil, for the purpose of isolating the transmission of seismic ground strain to a tunnel body. The interaction among a tunnel body, an isolation layer and surrounding soil, therefore, should be treated appropriately in the seismic design of those structures. This paper proposes a simplified numerical model based on an axisymmetric finite element procedure. The formulation of the model is presented, in order to make computer programming of the proposed model possible. An example of numerical simulations using the model is also presented, demonstrating effectiveness of the proposed model.

INTRODUCTION

It is known that the application of seismic isolation to the tunnel section where geological conditions change abruptly and a junction with different structures, such as vertical shafts, is highly effective [Tanaka and Suzuki, 1998]. In order to evaluate appropriately the behavior of the tunnel employing a seismic isolation system, it is ideal that three-dimensional finite element model should be applied to modeling a shaft, surrounding ground and a tunnel. However, three-dimensional modeling for not only irregular formation of surface deposits, but discretization for a finite element mesh, taking into account of tunnel structures, are extremely troublesome works. In addition, a computer with high performance and large main memory is necessary for such an analysis. Thus, the adoption of three-dimensional models to the practical design is not a matter-of-fact.

Then, the author proposed the axisymmetric finite element model [Suzuki, 1997] as a simplified model, treating the interaction between a tunnel body, an isolation layer and surrounding soil without any complexity experienced in three-dimensional modeling. This model was adopted as a standard model in the manual for seismic isolation design for underground structures [PWRI et. al., 1998]. This paper presents a theory and numerical processing on the axisymmetric finite element model first. Then, the effectiveness of the model is demonstrated through simulations with respect to seismically isolated tunnel at a junction with a vertical shaft.

CONCEPT AND NUMERICAL PROCESSING

Outline Of The Proposed Model

Fig.1 illustrates a schematic diagram of the axisymmetric finite element model. As shown in the figure, a tunnel is passing through the boundary between a soft soil deposit in the left and a stiff soil deposit in the right. The lower part of the figure represents the application of axisymmeteric modeling to the ground and tunnel condition shown in the upper part. It is essential, therefore, that special consideration should be taken in dealing with the effect of ground surface and lateral boundary condition in the axisymmeteric model. Nevertheless, the

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interaction between a tunnel body and surrounding soil can be rigorously evaluated by finite elements with a specified stress-strain relationship. Thus, if a method to convert seismic load in the axisymmeteric model to make ground displacement around a tunnel equal in both the upper and lower figures is defined, a simplified procedure, evaluating three-dimensional interaction around a tunnel, can be established.

Method To Convert Seismic Load

The fundamental theory on the method to determine seismic load in the axisymmetric model will be described, under ground and loading conditions shown in Fig.2. In the figure, H denotes the thickness of surface deposit, z the coordinate taking from bedrock and h_c the height from bedrock to tunnel center under actual tunnel and ground condition. In the axisymmetric model, a symmetric axis locates at a height of the upper outer surface of actual tunnel and outer radius R denotes the distance from the axis to bedrock. The inner surface of the axisymmetric model, which corresponds to the inner surface of tunnel lining, is located at radius $r = r_0$, in which r_0 denotes the outer radius of a tunnel lining. Then, h_c and R can be related by $h_c = R - r_0$. The seismic load considered here is enertial force originated from ground acceleration due to earthquake excitations distributed in a sine shape and with a maximum value of a_0 on ground surface as shown in the figure. Static loading method is employed, in which force of inertia due to an earthquake is loaded statically, ignoring a dumping term of equation of motion.

Fig.3 illustrates a schematic diagram to describe the method of loading inertial force of surface ground. In the proposed model, seismic load is divided into two types: a force of inertia acting on the ground lower than the tunnel, $p^*(z)$ given in equation (1) ; and concentrated force S^*, acting on the outer surface of tunnel body given in equation (2).

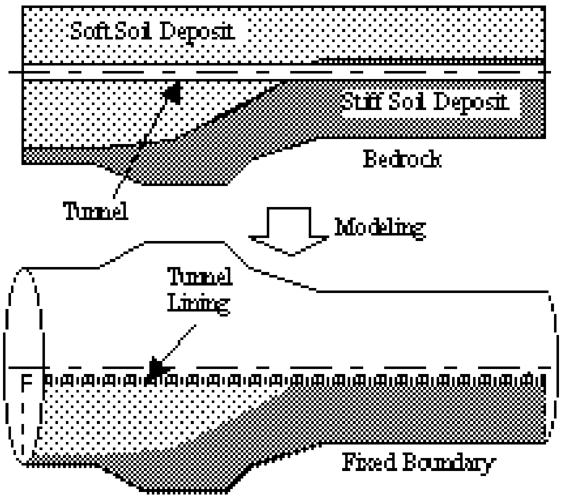


Figure 1: Schematic representation of the axisymmetric model

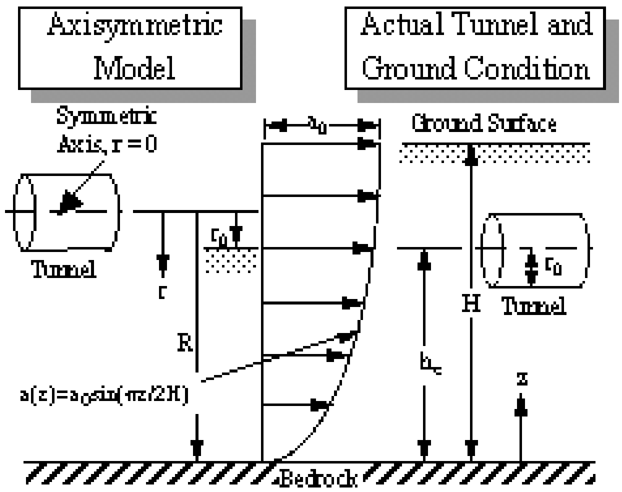


Figure 2: Coordinate of the axisymmetric model in comparison with actual condition

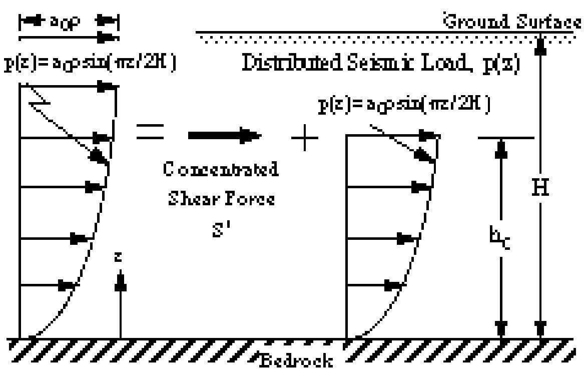


Figure 3: Method to apply seismic load

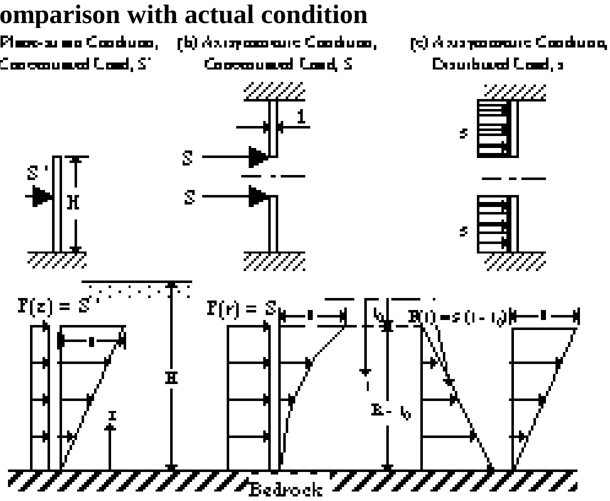


Figure 4: Conversion for concentrated load S*

$$p^*(z) = a_0 \rho \sin\left(\frac{\pi z}{2H}\right) \tag{1}$$

$$S^* = \rho a_0 \int_{h_0}^{H} \sin\left(\frac{\pi z}{2H}\right) dz = \frac{2\rho a_0 H}{\pi} \cos\left(\frac{\pi h_0}{2H}\right) \tag{2}$$

The conversion of seismic load in the axisymmetric model is conducted in the following manner. The displacement at r (= R – z) of a hollow cylindrical disk with unit thickness, the outer surface of which is constrained, is defined as u, when horizontal force P acts at r. The displacement of surface ground at z with unit width is also defined as u^*, when horizontal force P^* acts at z. Placing both displacements u and u^* equally, P can be expressed using P^*, R and r in the following:

$$P = \frac{2\pi(R-r)}{\ln(R/r)} P^* \tag{3}$$

Therefore, force of inertia lower than tunnel center, $p^*(z)$ in equation (1) can be replaced by p(z ; R - r) in eqation (4).

$$p(z; R-r) = a_0 \rho \sin\left(\frac{\pi(R-r)}{2H}\right) \frac{2\pi(R-r)}{\ln(R/r)} \tag{4}$$

Concentrated force S* in equation (2) also can be replaced by S in the following:

$$S = \frac{2\pi(R-r_0)}{\ln(R/r_0)} S^* \tag{5}$$

Fig.4 shows schematic representation of the relation between concentrated force and ground shear deformation, comparing cases of a hollow cylindrical disk in figure (a) and a soil column with surface in figure (b). Values of shear displacement at location r = r_0 in figure (a) and in figure (b) are coincident with each other. However, the vertical distribution in the hollow cylindrical disk in figure (b) is not straight, and it is widely different from that in figure (a). Thus, it is necessary that distributed force, s given in equation (6) is loaded uniformly in the vertical direction, in order to make the vertical distribution of shear displacement in the proposed model equal to that in actual ground.

$$s = \frac{\ln(R/r_0)}{R - r_0 - r\ln(R/r_0)} S \tag{6}$$

Substituting equation (5) into equation (6), distributed load s is given by equation (7).

$$s = \frac{4a_0 H(R-r_0)\cos\left(\frac{\pi h_c}{2H}\right)}{R - r_0 - r\ln(R/r_0)} \tag{7}$$

In a process of numerical analyses, earthquake loads acted at z = R - r is calculated by multiplying mass matrix with the ground acceleration at z. Thus, the acceleration at z used in such calculation can be given by equation (8), derived from equation (4) and (7). The acceleration is defined as a modified acceleration coefficient and noted by ma(z) in this paper.

$$ma(z; R-r) = a_0 \sin\left(\frac{\pi(R-r)}{2H}\right) \frac{2\pi(R-r)}{\ln(R/r)} + \frac{4a_0 H(R-r_0)\cos\left(\frac{\pi h_c}{2H}\right)}{R - r_0 - r\ln(R/r_0)} \tag{8}$$

Numerical Processing For Modified Acceleration Coefficients

Under actual ground condition, soil profile is not uniform and vertical distribution of ground acceleration is not so simple as shown in Fig. 2. Fig. 5 shows the process to calculate modified acceleration coefficients for the axisymmetric finite element model. Surface ground is sliced into N soil layers with different layer thickness H_i and density ρ_i, as shown in Fig.5(a). When the location at z = h_c exists within the n-th layer from ground surface, S^* can be given as described in the figure. In the axisymmetric finite element mesh, vertical discretization is conducted, dividing into M layers as shown in Fig.5(b).

Ground acceleration at the inner l-th nodal point in the axisymmetric model, a_l also can be given as described in the figure, when the nodal point exists within the m-th layer in Fig.5(a). Thus, modified acceleration coefficient, ma_l at the inner l-th nodal point can be obtained as shown in Fig.5(c) and it is given by equation (9).

$$ma_l = \frac{2\pi(R-r)}{\ln(R/r)} a_l + \frac{2\pi(R-r_0))}{R-r_0-r_0\ln(R/r_0)} \frac{S^*}{\rho_m} \qquad (9)$$

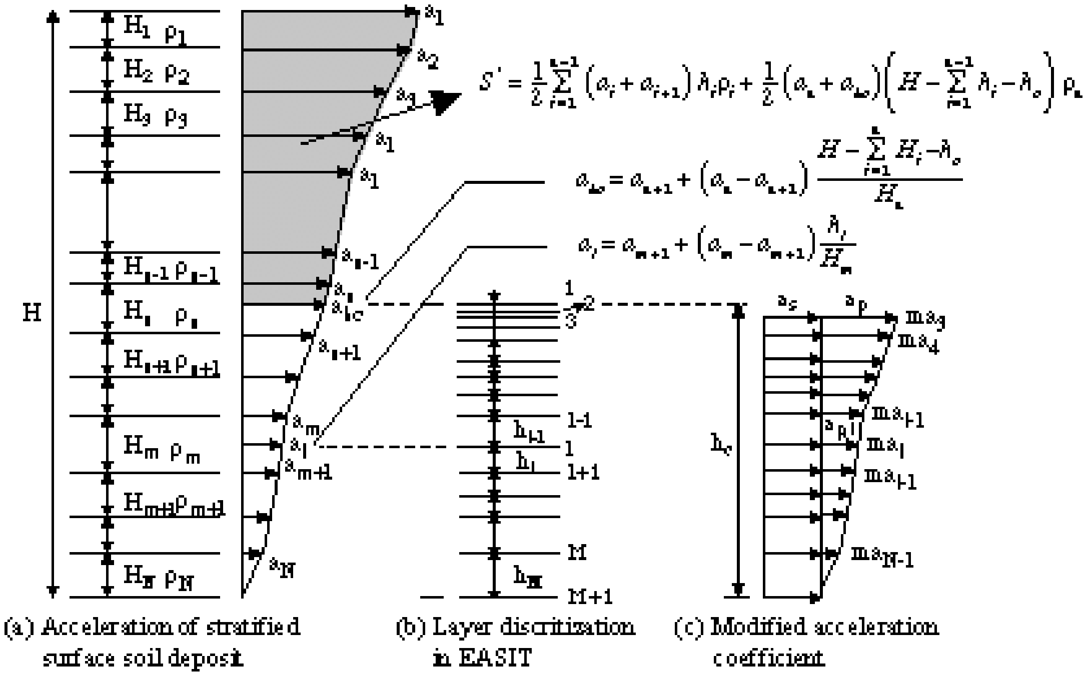


Figure 5: Process of acceleration conversion from stratified surface soil deposit to the axisymmetric model

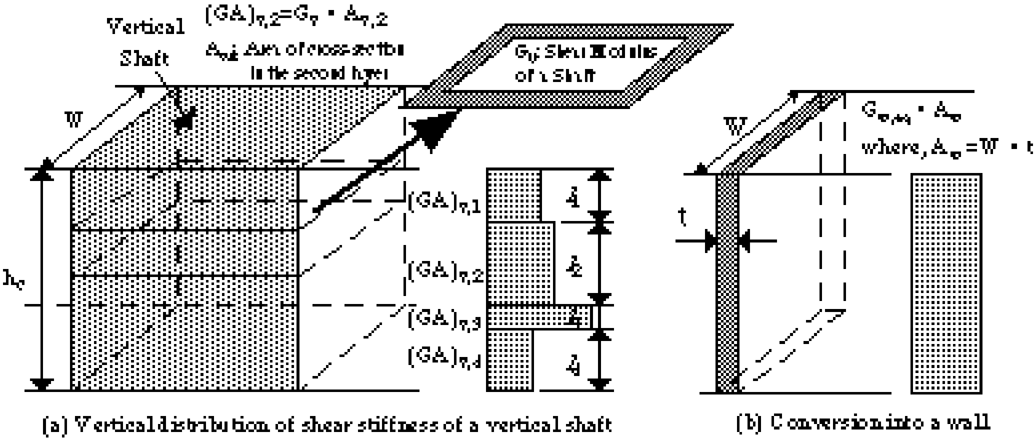


Figure 6: A schematic diagram to illustrate the conversion of a vertical shaft into a wall consistsing of equivalent shear stiffness

Treatment For A Vertical Shaft

The application of seismic isolation to the tunnel section at a junction with a vertical shaft is considered most effective in both cost and seismic performance. A special consideration should be made in modeling a vertical shaft, since it is structurally three-dimensional. The region from the inner wall of a shaft to a certain distance underground is taken into consideration here.

Fig.6 illustrates a schematic diagram to explain how to convert a three-dimensional structure of a vertical shaft into a wall. The conversion is conducted focussing on equivalence of shear stiffness. The shear stiffness of a vertical shaft is distributed, changing its values vertically as shown in Fig.6(b). In the proposed model, a vertical shaft is converted into a wall with a thickness of t and a width of W, which are coincident with those of actual shaft. When such a wall is consisted of uniform shear stiffness vertically, the shear modulus of the wall,

$G_{W,eq.}$ can be given as the average value in the vertical direction under a condition that shear stiffness of both the shaft and the wall are equivalent. Thus, a shaft is converted into a wall and can be modeled by axisymmetric procedure described hitherto.

$$G_{W,eq.} = \frac{\frac{1}{2}\sum_{i=1}^{n}(GA)_{v,i} l_i}{W \cdot t \cdot h_c} \tag{10}$$

SIMULATIONS USING AXISYMMETRIC FINITE ELEMENT MODEL (EASIT)

Computer program 'EASIT" based on the axisymmeteric finite element model was developed, using numerical processing described above. Its validity was verified by comparing results of three-dimensional finite element analyses on seismic behavior of a shield-driven tunnel buried both at a ground section where geological condition changes abruptly and at a junction with a vertical shaft [Suzuki and Maruyama, 1998]. In this chapter, an example of numerical simulations is demonstrated in order to explain how to use this model and to show its effectiveness , with respect to a seismically isolated shield-driven tunnel at a junction with a vertical shaft.

Ground And Structure Conditions

Fig.7 illustrates ground and structure conditions considered in numerical simulations. The tunnel considered in the analysis is a shield-driven tunnel, the outer diameter of which is 5.05 meters, consisted of reinforced concrete lining with a thickness of 25 cm. It is connected with a vertical shaft as shown in the figure at a depth of about

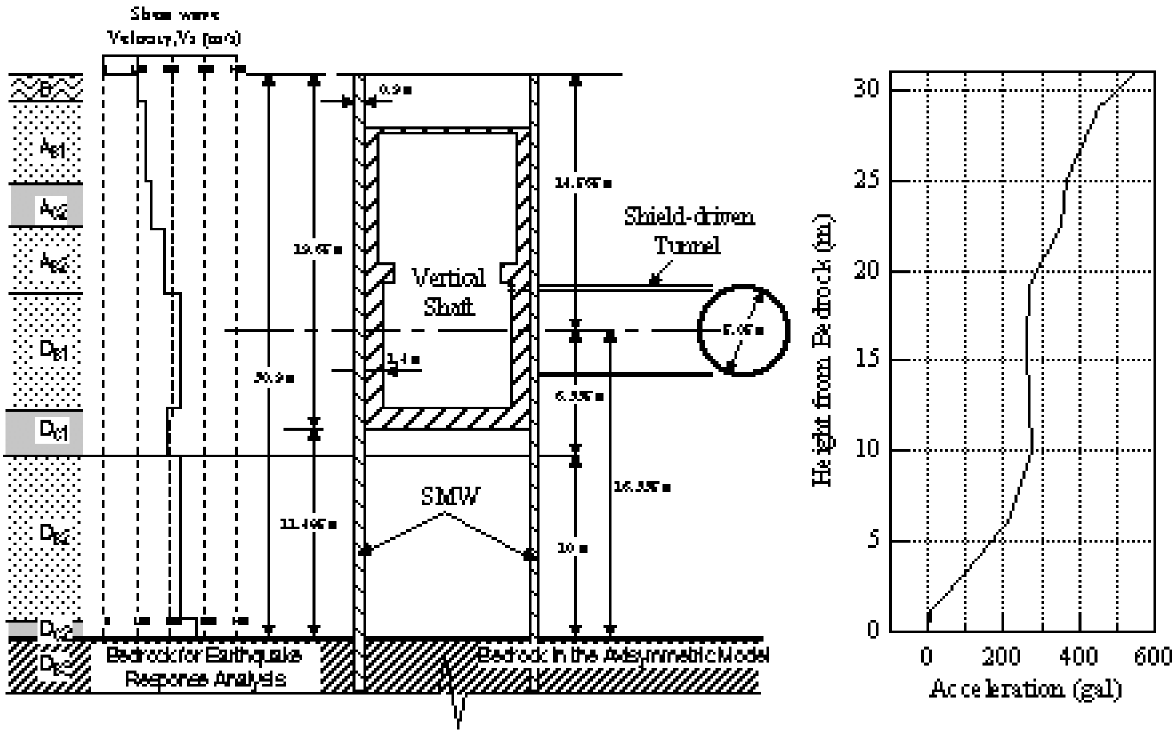
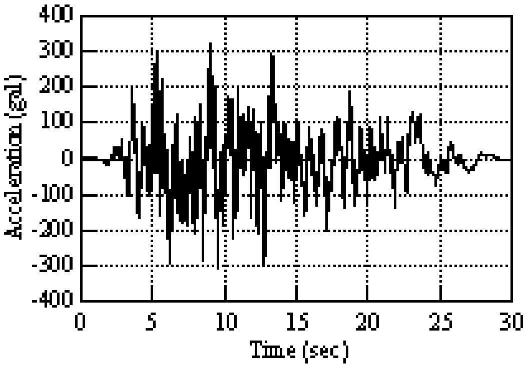


Figure 7: Ground and structure condition and loaded ground acceleration in numerical simulations



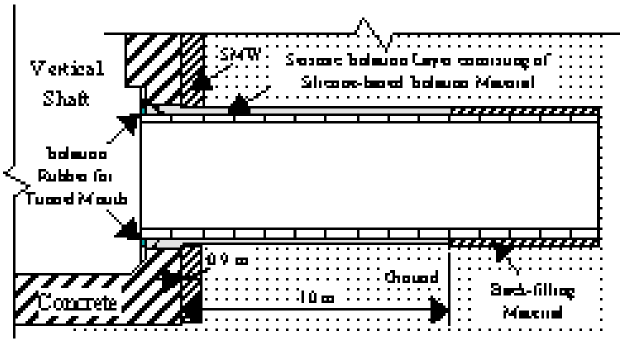


Figure 8: Accelerogram of Input wave **Figure 9: Seismically isolated structure considered**

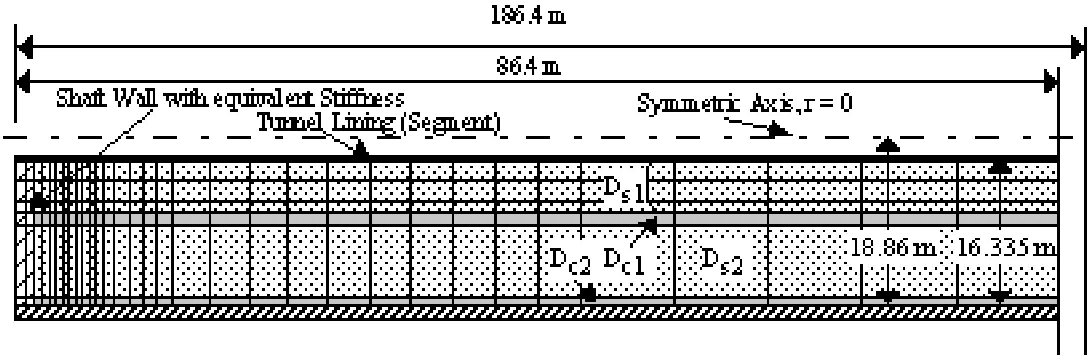


Figure 10: Discretization of axisymmetric finite element mesh

14.5 m. Diluvial sand layer D_{s3} shown at the bottom of the figure is defined as bedrock. The thickness of surface soil deposit above D_{s3} is about 30 meters. Most part of the tunnel is located within D_{s1} layer, while the tunnel crown locates in alluvial sand layer A_{s2}. A vertical shaft is constructed, laying its bottom on D_{c1} , at a depth of about 20 m.

Seismic Load And Modeling By Axisymmetric Finite Element Model

One-dimensional earthquake response analysis based on multiple reflection theory of surface deposit was carried out first, using equivalent linear procedure, with an input motion illustrated in Fig.8. Ground acceleration used in the axisymmeteric model was given, as the acceleration at a time when shear strain energy in the deposit reached its maximum. Such acceleration distribution computed is shown on the right hand side in Fig.7.

Fig.10 illustrates finite element mesh for numerical simulations. As shown in the figure, R equals to 18.86 meters and soil layers lower than A_{s2} are modeled. Fixed boundary is placed at the boundary surface between D_{c2} and D_{s3}. Tunnel lining (segments) and surface soil layers are divided into only 9 layers in the vertical direction. In the horizontal direction, on the contrary, total length of the model is 186.4 meters and discretization in this direction is also made roughly except for the region close to the shaft wall where discretization with a short interval of 0.5 m is conducted. The shaft wall was divided into two walls with a thickness of 0.7 m. The shear modulus of which was calculated as 8560 N/mm^2 by equation (10) using shear stiffness of the vertical shaft including soil stiffness after reduction due to earthquake response analyses.

Three cases of analyses were conducted: (1) the connection between shaft body and tunnel lining is made rigidly; (2) a flexible segment with a width of 1.0 m and with elastic modus of 0.1 N/mm^2 is instrumented at the location adjacent to the shaft wall; and (3) the seismic isolation layer with a thickness of 7 cm and with shear modulus of 0.5 N/mm^2 is applied to the region from the inner surface of the shaft wall of a vertical shaft through the distance 10 m from an outer surface of the wall as shown in Fig.9. This isolation layer can be easily constructed by injecting the silicone-rubber based isolation material during shield-driving [Suzuki and Tanaka, 1998].

Results Of Numerical Simulations

Numerical simulations were carried out both on compressive and tensile tunnel deformations. The compressive deformation is given by loading ground acceleration toward the left side and with tunnel compressive stiffness. The tensile deformation is, on the other hand, is given by loading toward the right side and with tunnel tensile stiffness which is determined from the stiffness of tunnel lining itself and that of a ring joint.

Figs.11 and 12 illustrate results of analyses on tunnel compressive deformation. Horizontal displacement of tunnel lining shown in Fig.11 shows that the change in the lateral direction is sharp in case of rigid connection, while it is rather moderate in both cases of flexible segment and seismic isolation application. Therefore, compressive force generated in tunnel lining is reduced remarkably by applying such seismic devices.

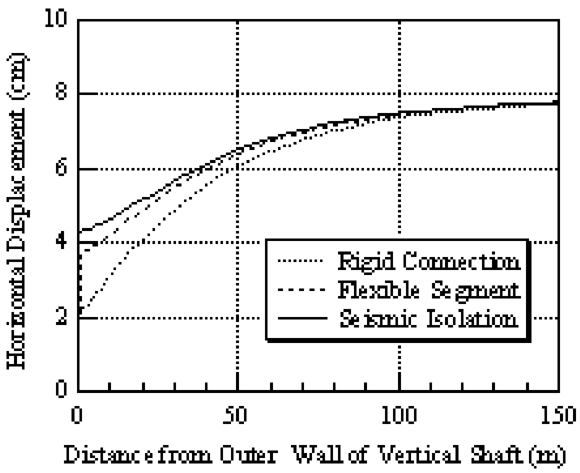


Figure 11: Horizontal Displacement of tunnel lining during compressive deformation

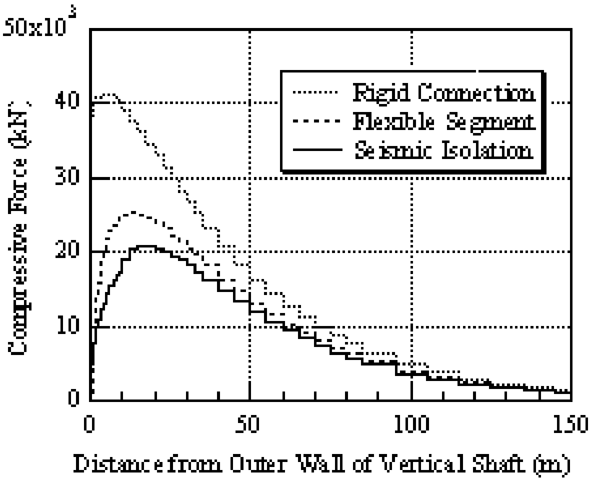


Figure 12: Comparison of compressive force among three different cases

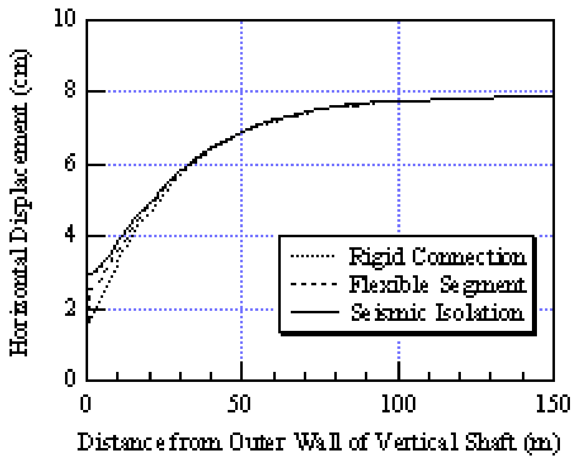


Figure 13: Horizontal Displacement of tunnel lining during tensile deformation

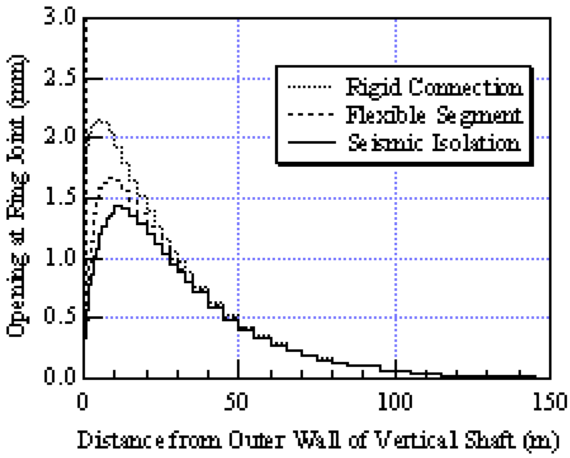


Figure 14: Comparison in opening of ring joints among three different cases

Figs.13 and 14 illustrate results of analyses on tunnel tensile deformation. Results on opening of ring joints are summarized in Fig.14 instead of tensile force of tunnel lining. A clear difference was obtained in Figs.11 through 14 between results of two cases in which seismic devices were applied. However, the previous technique, using beams and springs for modeling tunnel and interaction between tunnel and surrounding ground respectively, could not give any clear differences, because there is no appropriate method defining spring constants evaluating interaction between tunnel lining and surrounding soil or structures. Thus, the axisymmeteric finite element model is effective for interaction analyses with respect to underground tunnels.

CONCLUSING REMARKS

A simplified numerical model based on an axisymmetric finite element procedure was proposed in this papar. The formulation and numerical processing for the proposed model was presented concretely, which is helpful to computer programming for the proposed model. The computer program “EASIT” was developed and it was applied to numerical simulations with respect to the tunnel at a junction with a vertical shaft. The simulations proved that the proposed model was effective, since a clear difference in tunnel behavior was obtained between the application of flexible segment and the application of seismic isolation.

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