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SEISMIC PERFORMANCE ANALYSIS OF UNDERGROUND RAMP TUNNEL STRUCTURE USING 3-D MASSIVE NUMERICAL COMPUTATION

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Abstract. *There is increasing concern about the three-dimensional finite element analysis of large underground tunnels due to the threat of a nearby earthquake generating large strong motion on the tunnel with spatial variation. Using a new numerical analysis method based on massive numerical computation, we carried out a 3-D seismic response analysis of an underground ramp tunnel structure. Based on the finite element method, this method can analyze a large-scale computer model consisting of a nearby ground structure as well as the entire tunnel structure to be studied. As expected, the 3-D seismic response of the tunnel is complicated due to the complex configuration of the tunnel structure. While the intensity of response is smaller than the design criterion, the calculations show large deformation and stress for the part where the ramp tunnel passes through the interface between soft and hard ground layers, with stress and section force varied on the connection with the ramp tunnel. These results suggest that 3-D seismic response analyses should be performed for underground tunnels with complicated configuration which could be subjected to a nearby earthquake.*

1 INTRODUCTION

The working report of the International Tunneling Association (ITA) in 2001 [1] was a state-of-the-art review of earthquake-induced damages and researches on earthquake-resistant designs of tunnels, focusing on practice in the US. In order to perform rational earthquake-resistant design of large tunnels, the report suggested that appropriate aseismic investigations are needed which correctly evaluate the 3-D earthquake motions, response characteristics of the tunnel and dynamic interaction between the tunnel and ground. Since several subway stations were damaged during the Hyogoken-Nanbu Earthquake in 1995 [2], more attention has been paid to the aseismic capability of underground structures. Large-scale underground infrastructures are now being planned and constructed in many countries, and aseismic measures have been employed in many large-scale tunnels such as the Trans-Tokyo Bay Highway tunnel [3] and the Marmaray tunnel crossing the Bosphorus strait [4]. In order to perform rational earthquake-resistant design of large tunnels, we propose a 3-D numerical analysis.

We have developed a large-scale 3-D numerical analysis technique for practical design, and are researching application of the technique to the earthquake-resistant design of actual large tunnels having complicated structures [5, 6]. To make effective use of the expressway networks in metropolitan Tokyo efficiently, a circular route of highway network is being constructed to carry traffic away from the city center. The construction uses tunnels to help preserve the environment. In the case of a highway tunnel, a number of ramp tunnels are necessary for the main tunnel to access the ground surface. These ramp tunnels diverge from and merge into the main tunnel, and pass through several ground layers between the main tunnel and the ground surface. In addition, sections of the ramp tunnels vary in a complex manner and so their seismic response is very complicated. We have been investigating the seismic response of ramp tunnels and the dividing and merging parts between the ramp tunnels and main tunnel.

This paper outlines our large-scale 3-D dynamic FEM analysis technique, and the results of a full-scale 3-D seismic response analysis of a center-ramp-type road tunnel and the surrounding ground. The tunnel is being constructed as part of the Yamate tunnel of the Tokyo Metropolitan Expressway. In past studies [5, 6] the tunnel structure was simplified, but in the present study a very detailed model of the tunnel structure was used to quantitatively evaluate the seismic behavior for practical design. Based on the results, the deformation, displacement, stress and section force of the tunnel structure are evaluated, and the applicability of 3-D numerical analysis for the aseismic design of large tunnels is investigated.

2 3-D DYNAMIC FINITE ELEMENT ANALYSIS METHOD

The material is assumed to be linearly elastic. By reducing the continuous system to a discrete idealization and employing Newmark's β method in the time domain ($\delta=1/2$, $\beta=1/4$), the governing equation can be expressed as:

$$\left(K+\frac{2}{\Delta t}C+\frac{4}{\Delta t^2}M\right)u^{n+1}=\left(\frac{2}{\Delta t}C+\frac{4}{\Delta t^2}M\right)u^n+\left(C+\frac{4}{\Delta t}M\right)v^n+Ma^n, \tag{1}$$

where K, M, C and Δt are global stiffness matrix, lumped mass matrix, Rayleigh damping matrix and time increment. u, v, and a are displacement vector, velocity vector, and acceleration vector, respectively. Rayleigh damping is defined as $C = aK + bM$ using K and M, and parameters a and b are determined such that the damping can be appropriately set.

To solve the problem of many degrees of freedom, Ku is built by the element-by-element method [7], and the preconditioned conjugate gradient method [8], which is an iterative analysis method, is adopted. As stiffness matrix of element is evaluated step-by-step, K need not be kept in memory and therefore the problem of significantly many degrees of freedom is overcome. In addition, a combination of non-structure elements and structure elements is used to reduce the computation cost in evaluating stiffness matrix of element in the element-by-element method. Structure elements are used in the large region without approximation of geometrical shape, and non-structure elements are used in the narrow region with complicated shape close around the structure. As there is a single shape of structure element, the number of element stiffness matrixes needed to be kept in memory is the same as the number of materials, and thus the computational cost for the element stiffness matrix is significantly reduced. In this study, second-order tetrahedron elements are used for the non-structure elements, and hexahedron isoparametric elements (voxel elements) for the structure elements. As second-order tetrahedron elements are used for non-structure elements, the response variation in the complicated region close to the structure can be simulated with relatively few elements.

3 ANALYSIS METHOD

The numerical analysis was applied to the center-ramp type road tunnel of the Yamate Tunnel of the Tokyo Metropolitan Expressway, as shown in Fig. 1. The geological section of the ground around the tunnel is shown in Fig. 2. The two main tunnels (outside diameter 12.83 m), 7.25 m apart, employ steel segments. The RC divergence/confluence part and exit/entrance tunnel (called “ramp tunnel” hereafter) are constructed between the two main tunnels. As shown in the figure, the ramp tunnel extends to the surface with a complicated, and varied cross-section of structure. The ground between the main tunnel and ramp tunnel varies from a hard layer with Vs of 400 m/s or more to a soft sedimentary layer with Vs of around 150 m/s. Past studies [5, 6] have clarified that the local structure such as the transverse section depends on the response of the tunnel as a whole. Therefore, the external appearance of the tunnel and main internal structure are very finely modeled, except for some detailed structures that would not affect the main response characteristics.

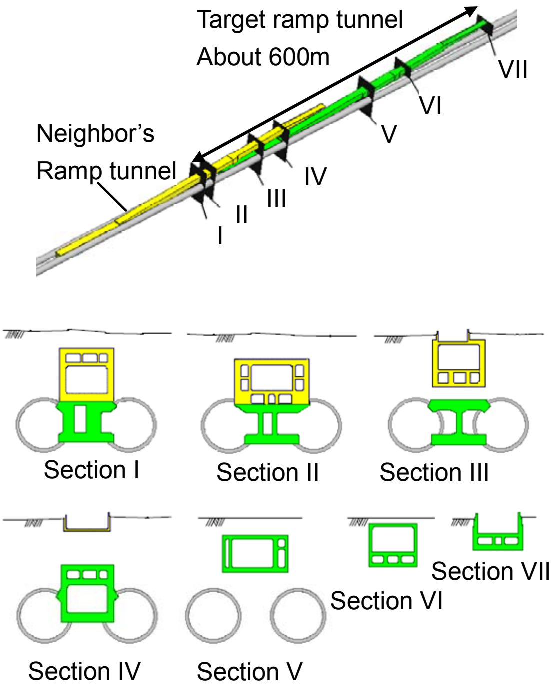
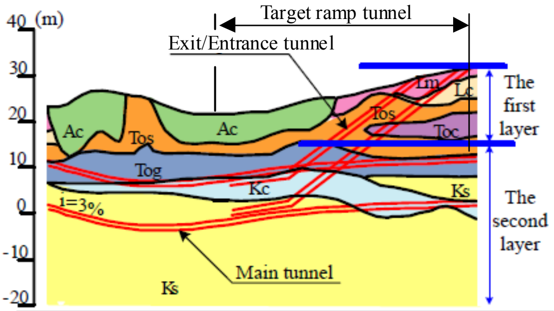


Figure 1: Overview of target ramp tunnel structure in the Tokyo Metropolitan Expressway Central Circular Route: the Yamate Tunnel.



Geological feature	Alluvium	Kanto Loam layer		Tokyo layer Group			Kazusa layer Group	
Symbol	Ac	Lm	Lc	Tos	Toc	Tog	Kc	Ks

Figure 2: Vertical section of geological profile.

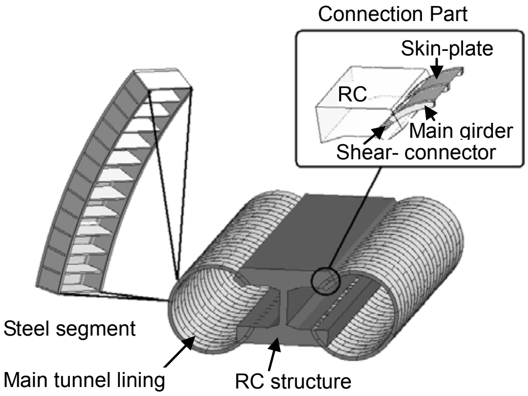
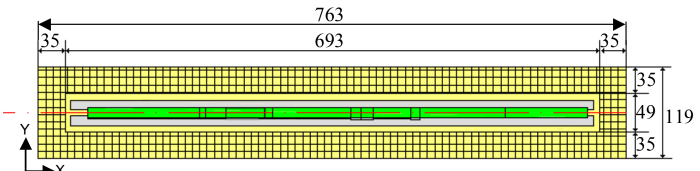
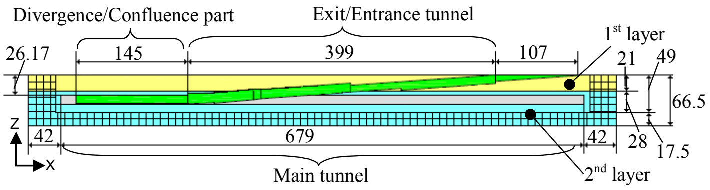


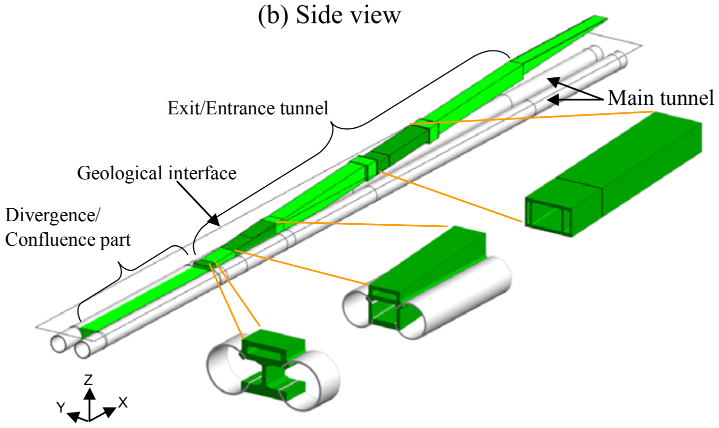
Figure 3: Connection part between main tunnel and RC structure.



(a) Plane view



(b) Side view



(c) Bird's-eye view for the tunnel structure

Figure 4: Overview of numerical model.

The connection part between the ramp tunnel and main tunnels is important in terms of transferring seismic loading, and therefore the new type of connection structure where a part of the steel shell is embedded in the RC structure is also modeled in detail as shown in Fig. 3. The numerical analysis model is generated as shown in Fig. 4, based on the results of studying the appropriate range for the numerical model used for dynamic analysis [5]. The design strength of concrete in the RC structure is 40 N/mm^2 (40 MN/m^2). As parameters used in the analysis, the elastic constants and Poisson's ratio corresponding to the design strength are employed. As shown in Fig. 3, the steel segment of the main tunnel consists of main girders and skin plates. For simplicity, the steel segment section is modeled as a solid with the lining being the same thickness as the height of the girders. The elastic constant is determined such that the in-plane bending stiffness of the solid section model is the same as that of the original steel segment. The mass of the solid section model is set such that the unit weight in the longitudinal direction of the tunnel remains the same as the original steel segment (see Table 1). As for Poisson's ratio, the value for steel (of which the segment is made) is used. As the shear-wave velocity impedance ratio is significantly different, the ground is set as a two-layer model with the upper boundary of the Tog layer as the geological interface between the two layers. A level 2 acceleration wave is used as input motion, as described later. An earthquake response analysis of the free field is performed first using SHAKE, and the converged stiffness and damping ratio are obtained. The parameters for 3-D analysis are determined based on the converged stiffness and damping ratio of the free field, so that the maximum response of the linear analysis matches that obtained through analysis by SHAKE. Therefore, the nonlinear behavior of the ground could be approximately simulated through linear analysis. The parameters for 3-D analysis are listed in Table 2.

Based on the fundamental frequency of ground (0.7 Hz) obtained by analysis using SHAKE, and the predominant frequency range of earthquake waves, the upper limit of the frequency range within which an accurate analysis is assured, is set as 2 Hz. Assuming that the analysis is accurate if the wavelength can cover 10 elements, the element size is set at

	Real structure	Model
Structure	Girders and skin plate	Isotropic solid body
Thickness of lining (mm)	530	530
Thickness of girder (mm)	43	-
Area of cross section (m^2)	0.0493	0.6360
Second moment of area (m^4)	0.001304	0.014888
Modulus of elasticity (N/m^2)	2.10x10^{11}	1.84x10^{10}
Flexural rigidity (Nm^2)	2.738x10^8	2.738x10^8
Mass density (kg/m^3)	7850	609
Mass per unit length (kg/m)	387	387

Table 1: Modelling of main tunnel lining.

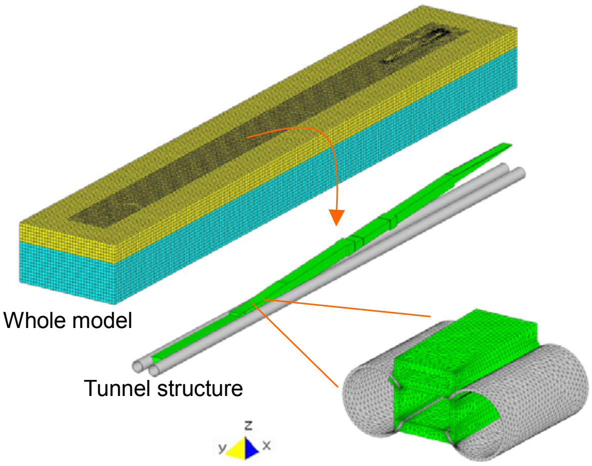


Figure 5: Finite element mesh.

	Mass density ρ (kg/m^3)	Shear wave velocity Vs (m/s)	Poisson's ration ν	Damping factor α* (1/sec)
Main tunnel	609	3372	0.30	2.0
Ramp tunnel	2500	2299	0.15	2.0
1st ground layer	1500	60	0.45	2.0
2nd ground layer	2000	400	0.45	2.0

*: Layleigh's mass damping factor

Table 2: Material properties for the analysis.

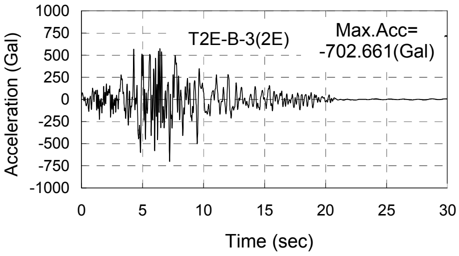


Figure 6: Maximum design earthquake: T2E-B-3.

3.5 m for second-order elements, and 1.75 m for first-order elements. In the meshing of the structure part, at least one element is placed in the cross-section direction to appropriately simulate the distribution of the stress and section force of the structure, and the mesh size is 1 m. It was confirmed that the accuracy of displacement is appropriate and the distributions of stress and section force are tolerable. Figure 5 shows the 3-D finite element model of the structure and ground. The total number of nodes and the total number of elements are 2,638,078 and 2,268,533, respectively. As for the input wave, the maximum design earthquake (T2E-B-3) with maximum acceleration of 702.7 Gal is employed, which is one of the largest earthquake ground motions assumed in current earthquake-resistant design in Japan (Fig. 6). The input wave is epicentral earthquake ground motion (directly underneath type), and the duration of main shaking is 10.23 seconds with a time interval of 0.01 second. The seismic response of free-field ground is performed first, and the input wave is applied at the depth of the bedrock in the actual earthquake-resistant design, which is 5 m below the bottom of the main tunnel. The seismic response at the depth corresponding to the bottom of the 3-D numerical model is computed, which is used as the input wave for the 3-D analysis. Two cases are analyzed: one with the input direction perpendicular to the tunnel longitudinal axis, and the other parallel with the tunnel longitudinal axis.

4 ANALYSIS RESULTS

Figure 7 shows the deformation and displacement of the tunnel when the response of the ground is large. The response of the entrance/exit part of the tunnel in the upper ground layer, where the response is remarkable, is large in the direction of the input wave. When the direction of the input wave is along the tunnel longitudinal axis, compressive stress and

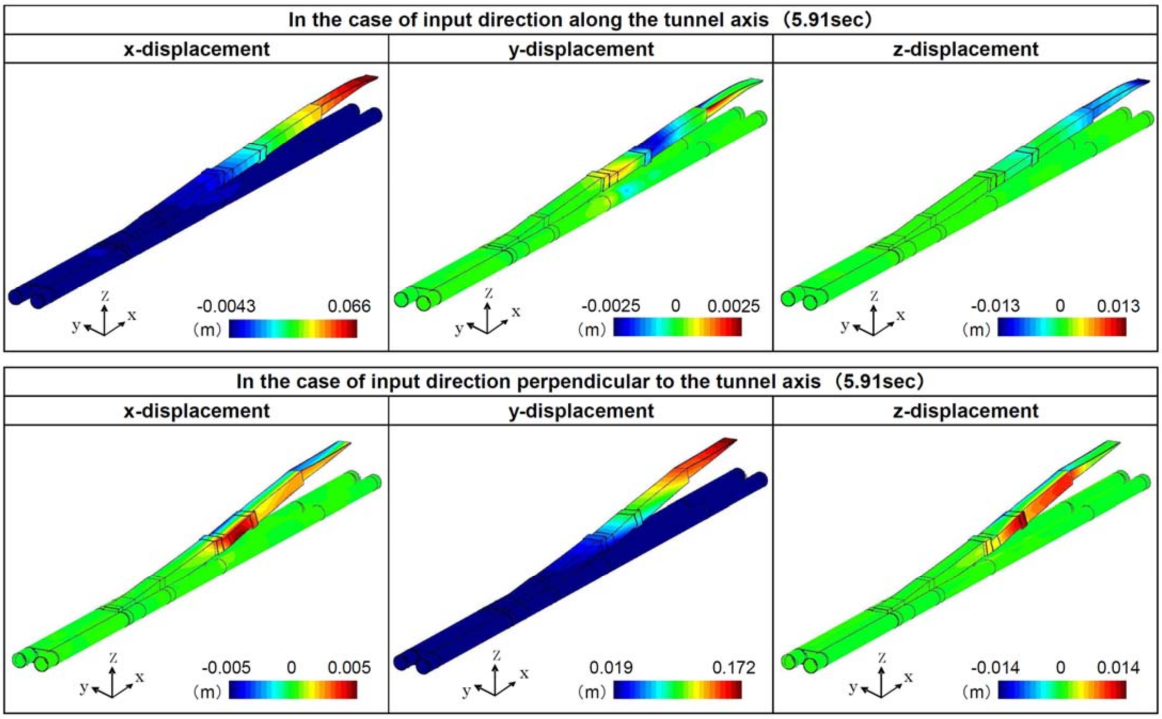


Figure 7: Deformation and displacement of the tunnel.

tensile stress are observed in the tunnel. When the input direction is perpendicular to the tunnel longitudinal axis, the tunnel deforms in the direction perpendicular to the tunnel longitudinal axis, and sectional shear deformation of the tunnel can be observed together with bending and rotating deformation. When the input direction coincides with the tunnel longitudinal axis, the displacement in the x-direction significantly varies at the location where the tunnel structure changes, and also in the area from the ground layer boundary to the middle depth of the upper layer. Due to the large stiffness of the tunnel in the longitudinal direction, the displacement of the tunnel is 0.09 m at the ground surface level, contradicting the larger displacement of the free field ground, which is 0.21m. On the other hand, when the input direction is perpendicular to the tunnel longitudinal axis, the displacement in the y-direction of the tunnel at the ground surface level is 0.17 m, indicating that the tunnel closely follows the ground deformation in the direction of the input wave. In comparison to 0.17 m which is the displacement of the tunnel in the y-direction, the perpendicular displacements in the x-direction and z-direction are 0.005 m and 0.014 m, respectively, and are symmetrically distributed about the central axis of the tunnel. When the input direction is perpendicular to the tunnel axis, a larger response concentrates in the part of the tunnel where the structure is varying, and in the part of the ground where the ground condition is changing.

Figure 8 shows the distribution of stress. The area subject to large stress is shown enlarged in Fig. 9. The main component of stress (with the maximum value shown in parentheses) is σ_{xx} (27 MN/m^2) when the input direction is along the tunnel axis, and the normal stresses are σ_{xx} (25 MN/m^2), σ_{yy} (34 MN/m^2), σ_{zz} (41 MN/m^2) and shear stress is σ_{yz} (29 MN/m^2) when the input direction is perpendicular to the tunnel axis. In each case, the stress in the RC structure is large, and the maximum value is 63–102% of the design strength of concrete. Though the response tends to be large on assumption of the conventional design earthquake assuming plane wave, the increase in stress due to earthquake should be taken into account in the design.

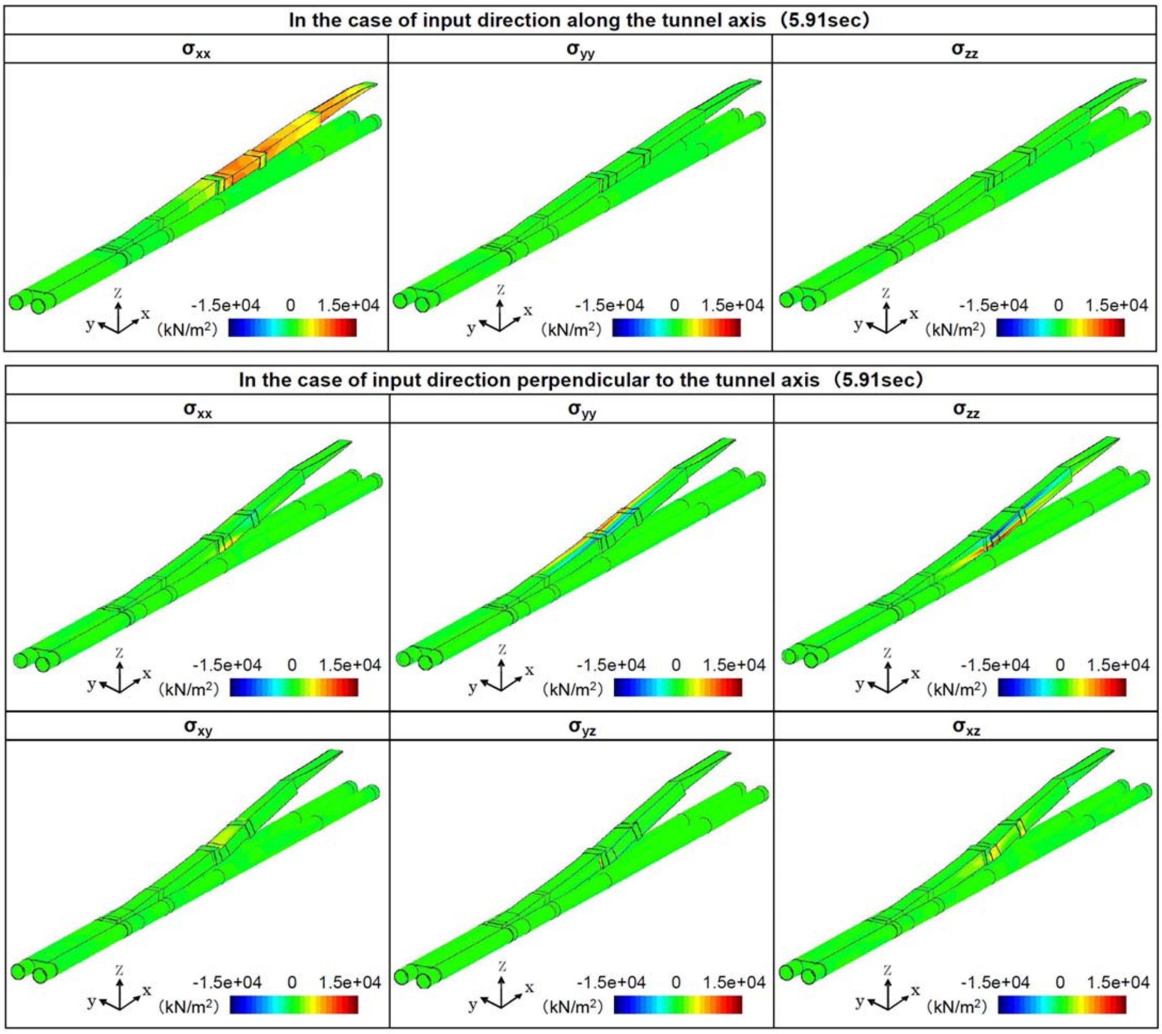


Figure 8: Stress of the tunnel.

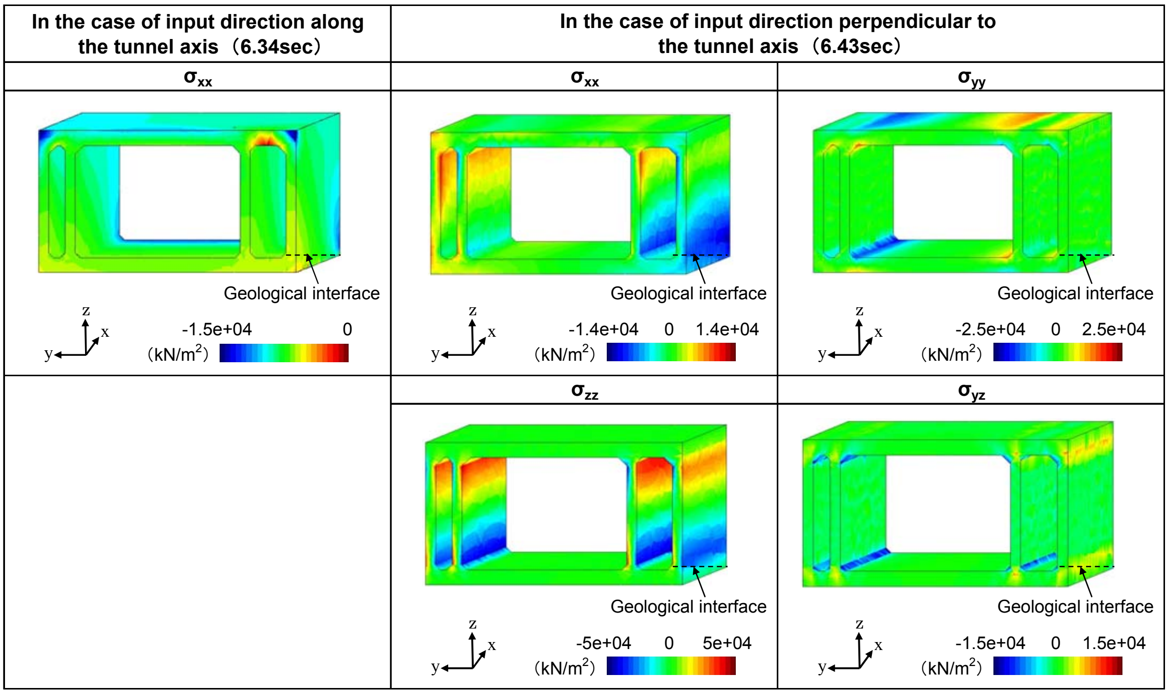


Figure 9: Stress of the tunnel around geological interface at the time when the maximum stress occurs

When the input direction is along the tunnel axis, as shown in Fig. 9, σ_{xx} is not evenly distributed in the transverse section, and becomes large at the corners in some sections. On the other hand, when the input direction is perpendicular to the tunnel axis, the sign of the stress on the left part of the tunnel section differs from that on the right part due to bending in the longitudinal direction of the tunnel, and large stress occurs in the lower part of the side wall of the tunnel above the ground layer boundary. In addition, bending moment is large at the end of the structure member due to the shear deformation of the transverse section of the tunnel, resulting in large fringe stress σ_{yy}, σ_{zz} in the slab and side wall. σ_{yz} is shear stress in the transverse section of the tunnel. In this analysis, although the distribution of stress is reasonably smooth, slight dispersion can be observed in the area with stress concentration due to the use of single elements in the direction of thickness of the tunnel. Therefore, the maximum value of stress may depend on the way of meshing; finer meshing could improve the accuracy of analyzing stress in the stress concentration area.

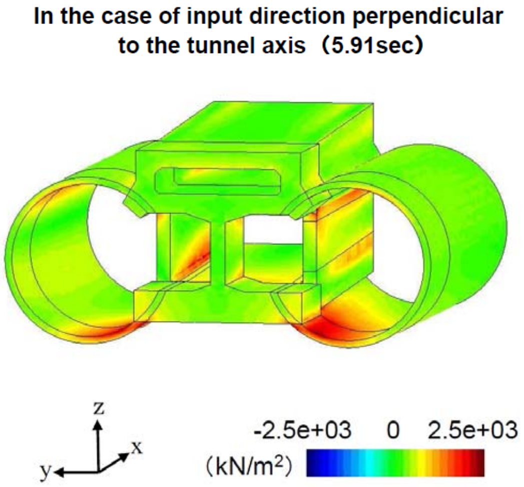


Figure 10: Mises stress around nose point

Figure 10 shows the distribution of Mises stress at the nose part which connects the divergence/confluence part and the exit/entrance tunnel. The distribution of section force in the connection part along the tunnel axis is shown in Fig. 11. It can be seen that the stress locally varies at the nose part where the tunnel section changes (Fig. 10). As for the distribution of section force in the connection part, the section force varies around the nose part and over the middle wall al-though the transverse section is constant (Fig. 11). By carrying out a 3-D analysis using a more detailed model for the local structure in the connection part, a structure with rational cross-section for the connection part to assure the capacity of the connection structure can be determined.

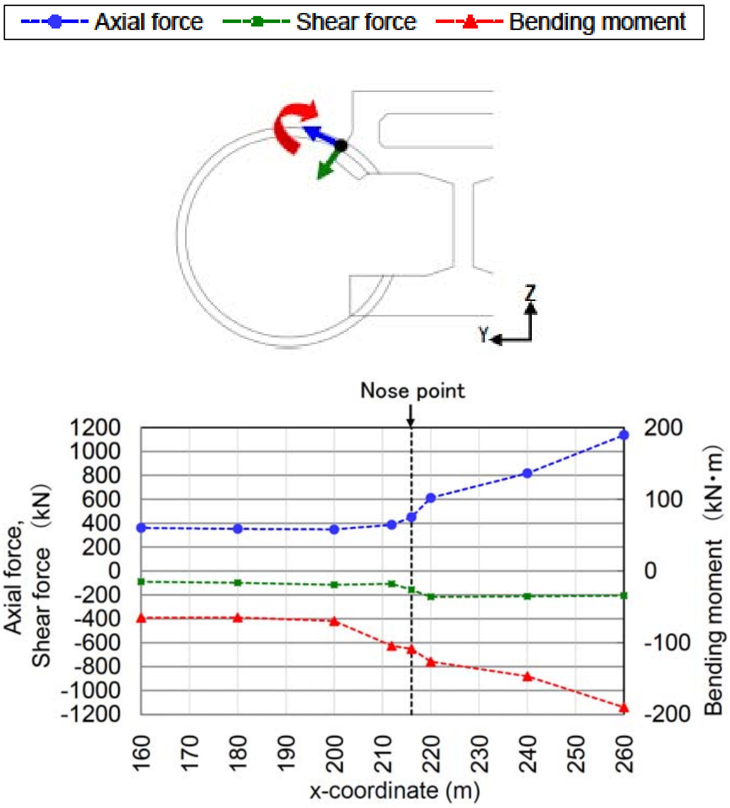


Figure 11: Section force at connection part around nose point

The above stress and section forces are induced due to 3-D interaction. Especially, the shear deformation of ground concentrates in the tunnel within the upper ground layer, and stress in the tunnel significantly increases in the part where the structure varies. It is difficult to rationally evaluate these kinds of behavior by the 2-D response-seismic-coefficient method, which is currently used in practical design, or by the response displacement method for investigating the behavior in the longitudinal direction, where the tunnel and ground are modeled using beam and spring elements. 3-D analysis could identify the location where the aseismic capacity needs to be clarified, and thus it is possible to evaluate their aseismic capability. In addition, the conventional aseismic design method using simplified models tends to overestimate the seismic response [1], and it is possible to perform a more rational design of tunnel structure and to reduce the construction cost by using 3-D analysis. In the actual design of the tunnel in this study, the structure joint is placed in the transverse section of the tunnel at the location of the ramp tunnel above the ground layer boundary to enhance the aseismic capacity of the ramp tunnel around the ground boundary, based on the results of 3-D analysis of the response.

5 CONCLUSIONS

We have developed a large-scale 3-D dynamic FEM analysis technique, and used it to analyze the earthquake response of a center-ramp type road tunnel (ramp tunnel of the Yamate Tunnel of the Tokyo Metropolitan Expressway) with a complicated structure. We clarified that the ramp tunnel with complicated structure displays complex 3-D behavior, and the 3-D analysis could quantitatively evaluate the seismic behavior. In addition, by carrying out seismic response analysis using a full-scale model of the tunnel and ground, it is possible to evaluate the displacement, stress, and section force of the tunnel more precisely, and to determine the location where displacement and stress significantly increase. In order to increase the evaluation accuracy, the forces in the tunnel computed by 3-D analysis could be used as external loading forces for a separately generated detailed model of the local part of the tunnel structure taking nonlinearity into consideration, and thus it is possible to optimally design the tunnel. Through 3-D numerical analysis, a more suitable aseismic design of large tunnel with complicated structure could be realized, and 3-D numerical analysis is an effective approach to rationalize the tunnel structure in the practical design.

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