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DYNAMIC BEHAVIOR OF A UNDERGROUND MOTORWAY JUNCTION DUE TO LARGE EARTHQUAKE

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SUMMARY

The Hansin-Awaji Earthquake of January 17, 1995 cause severe damage to various structures. Damage to the underground infrastructures was one of the amazing events, since underground structures had been considered to be relatively safe from earthquake effects compared to structures above ground. Recently, there is a great demand for a development of super-deep underground urban space in Tokyo Metropolitan area. However a seismic response behavior of a complicated structure, such as connection part of vertical shaft and tunnel, junction of a highway tunnel, ramp way, is not clear so far. Moreover, the seismic design procedure of complicate parts of underground infrastructure is not established. In this paper, the results of a large-scale three-dimensional dynamic analysis by using a workstation cluster of 16 nodes are described. It was clarified of the generation of a large axial stress to the ramp way due to axial input. Moreover, it was result that the shearing stress was not able to be disregarded due to axial and parallel input.

INTRODUCTION

It has been pointed out that underground structures suffer damages easily in the cross section with sudden change in ground condition and topography, and with sudden change in structure (for example, joint part with vertical shaft), for example Kawashima [1]. Failures have been found in the part of underground structure with sudden structure change in the Hanshin-Awaji Earthquake in 1995[2]. It has been pointed out that, in order to make reasonable aseismic design of this kind of underground structure under the special condition with sudden change in ground and structure, it is essential to conduct aseismic investigation considering the dynamic behavior of sudden change area in ground and structure. The dynamic behavior of underground structure with sudden change in ground and structure conditions has been studied through earthquake observation, for example Ohbo [3,4].

Since the Hansin-Awaji Earthquake, the design standard for excavated-tunnel and shield-tunnel have been revised. The level 2 earthquake motion should be taken into consideration. The aseismic design of these kinds of tunnels usually adopts soil-spring type response displacement method. For those tunnels (except

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for circular tunnel under simple ground condition) which this method is not suitable for, according to the importance of structures, aseismic design using FEM type response displacement method (or response seismic coefficient method), and design check based on earthquake response analysis are being conducted. As the conventional countermeasures against level 2 earthquake, the elastic washer is adopted in the common part, while in the connecting part to the vertical shaft, the flexible segment ring is adopted.

Recently, the countermeasure using isolation system around tunnel has been receiving more attentions. However, the aseismic design method as well as the necessary countermeasure technology for the junction part of the tunnel have not been clarified. The plan of the construction of the highway and railway in the deep ground in the Tokyo metropolitan area has been put into concrete shape. Such issues have been under discussion, as the labor-saving construction, the environment-consideration construction and the earthquake resistant evaluation of the junction in the design. Especially, there is a plan of constructing the side-ramp type tunnel as entrance part from ground surface to very deep underground main line of highway. It is very urgent task to evaluate the aseismic behavior of structures with sudden change in structure such as junction part during large earthquakes (level 2 earthquake). In this paper, 3D dynamic analysis has been performed using parallel structural analysis code. The analysis model is an underground structure with tunnel junction part of side-ramp type, which is the entrance from ground surface to the underground main line. The evaluation results of the response characteristics of the underground structure under large earthquakes are presented.

OUTLINE OF ANALYSIS MODEL

In this study, 3D analysis has been performed to evaluate the seismic behavior of the underground structure with junction part under large earthquakes. The analysis model is an underground structure with junction part, where the main line tunnel is connected with the side-ramp type tunnel, which is used as entrance from the ground surface. The ground with length of 550m, width of 150m, and depth of 50m, is considered as three-layer soil structure in which the underground structure is embedded. In the analysis model, it is assumed that, the main line tunnel (outer diameter 13m) in depth of 20m is connected to the ramp tunnel (outer diameter 9m), which is used as the access to the ground surface.

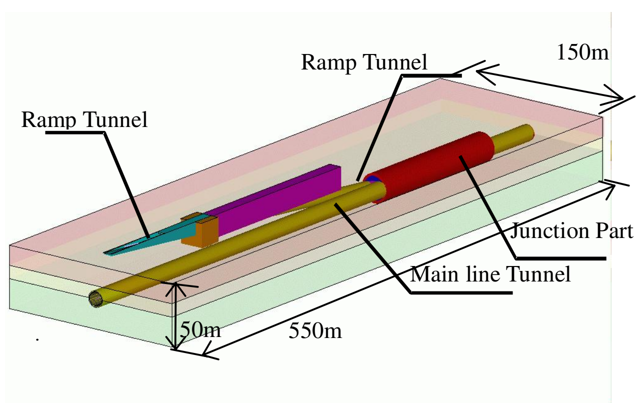


Fig.1 General view of objective structure

Figure 1 shows the analysis model. The slope of the access tunnel to the ground surface is set as 6%. The model consists of main line tunnel, junction part and ramp tunnel to the ground surface. The ramp tunnel near the ground surface is considered as a ditch structure.

OUTLINE OF ANALYSIS

FEM model

The 3D dynamic FEM analysis is performed to study the behavior of the junction part of the underground structure as shown in Figure 1 due to the earthquakes.

As an example, the FEM analysis mesh of the tunnel part is shown in Figure 2. The analysis object is a tunnel ramp, in which a two-line main line is connected by a one-line ramp through the side-ramp method. The case where the junction part is constructed by enlargement method after the completion of main line and ramp line, is assumed, and the objective structure is so modeled that the construction conditions could be taken into account.

In the modeling of objective structure, the aseismic capability is considered. Furthermore, to obtain the in-depth evaluation with high accuracy, the meshes in the areas from steel shell to the mid-wall of the tunnel are set small enough so that the dynamic components of results up to 10Hz could be well simulated. The number of elements is about 1,700,000, and the number of nodes is about 380,000.

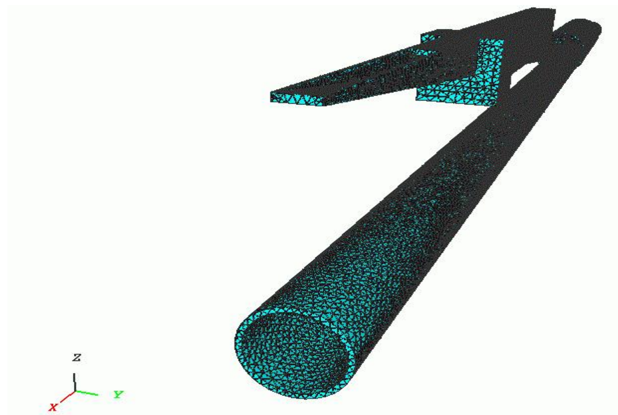


Fig. 2 FEM mesh

Analysis conditions

The boundary conditions adopted in the analysis are assumed such that the nodes on the left and right side boundaries are fixed in the vertical direction, and free in the horizontal direction. The nodes on bottom boundary are fixed. The analysis model shown in Figure 1 is meshed as groups so that the material properties can be changed. In this analysis, the stiffness of the main line tunnel and the ramp tunnel are set to be the same. The ground is treated as a three layer soil structures, and the soil improvement around the upper ramp tunnel is considered. The properties of the materials are listed in Table 1.

Table 1 Material Properties

	Shear Wave Velocity(m/s)	Modulus of Elasticity(Pa)	Density (g/cm^3)	Poisson Ratio	Damping Factor(%)
Surface Layer	180	1.74E+08	1.8	0.49	5.0
Middle Layer	350	7.20E+08	2.0	0.47	5.0
Bottom Layer	400	9.34E+08	2.0	0.46	5.0
Soil Improvement	507	1.50E+09	2.0	0.46	5.0
Tunnel		3.43E+10	2.6	0.17	3.0

The earthquake wave, which was observed under the ground in the Port Island during the Hansin-Awaji Earthquake which is applied to the bottom boundary of the analysis model (refer to Figure 3: the PGA of NS component is set to 600gal), in the parallel and orthogonal directions of the tunnel axis, respectively.

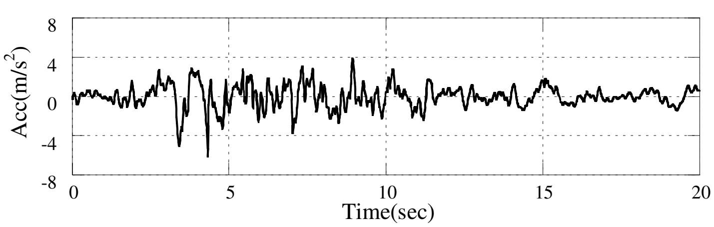


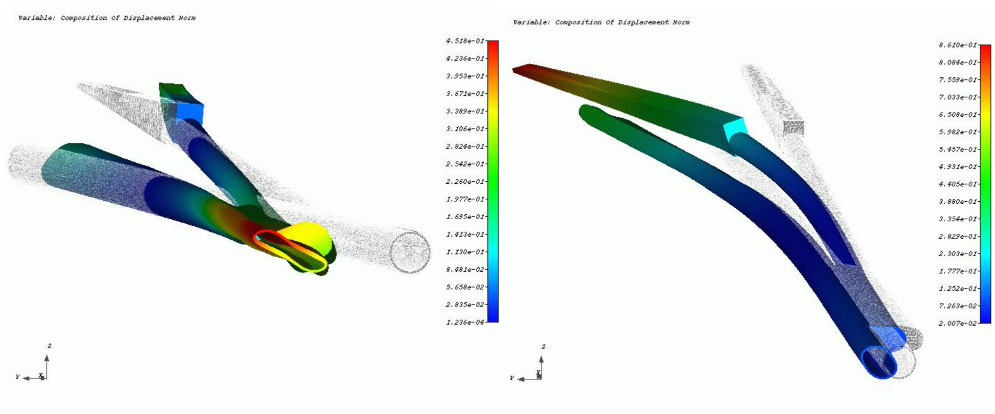
Fig. 3 Input Wave

Parallel structural analysis code ADVC is used in this seismic response analysis on an Itanium2-workstation-cluster of 16 nodes.

RESULTS OF ANALYSIS

Vibration Mode of Tunnel

The first natural frequency of the ground is important for the aseismic design of underground structures. In order to evaluate the response of 3D complex underground structure due to earthquakes, however, the deformation modes of both the underground structure and the ground should be verified.



(a) Mode 1 (b) Mode 2

Fig.4 1st and 2nd vibration modes of tunnel

Figure 4 shows the deformation mode of tunnel part of the first and second vibration modes obtained from the 3D eigen value analysis. So far, the natural vibration characteristics of underground structure have not been taken into account in the aseismic design of the underground structure. However, further study is necessary to clarify the behavior of the complex underground structure during the aseismic design.
The dynamic behaviors of the ground, the main line tunnel and the ramp tunnel are investigated in the following.

Table 2 Node number and depth of 3 Sections

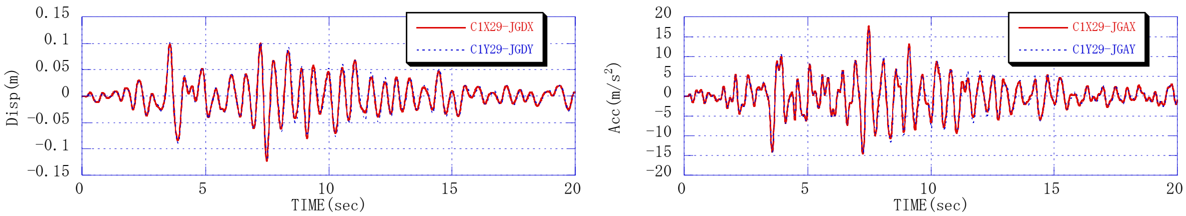
Ramp Part			Junction Part			Main Line Part		
	Node Number	Depth(m)		Node Number	Depth(m)		Node Number	Depth(m)
Ground	0	0.00	Ground	29	0.00	Ground	49	0.00
	1	-5.25		30	-5.50		50	-5.25
	2	-11.12		31	-11.12		51	-11.87
	3	-16.00		32	-16.00		52	-16.00
	4	-18.66		33	-18.66		53	-18.36
	5	-18.98		34	-21.65		54	-18.66
	6	-26.50		35	-26.50		55	-26.50
	7	-30.71		36	-33.40		56	-32.90
	8	-40.79		37	-40.29		57	-42.79
	9	-50.00		38	-50.00		58	-50.00
Main Tunnel	10	0.00	Main Tunnel	39	0.00	Main Tunnel	59	0.00
	11	-5.75		40	-5.75		60	-5.25
	12	-10.18		41	-9.43		61	-11.37
	13	-16.00		42	-16.00		62	-16.00
	14	-18.45		43	-18.13		63	-18.14
	15	-20.02		44	-20.01		64	-20.01
	16	-26.50		45	-26.50		65	-26.55
	17	-32.99		46	-32.99		66	-32.99
	18	-41.43		47	-40.77		67	-40.34
	19	-50.00		48	-50.00		68	-50.00
Ramp Tunnel	20	-5.43						
	21	-11.12						
	22	-16.00						
	23	-18.36						
	24	-19.63						
	25	-26.50						
	26	-33.01						
	27	-42.29						
	28	-50.00						

Response Wave

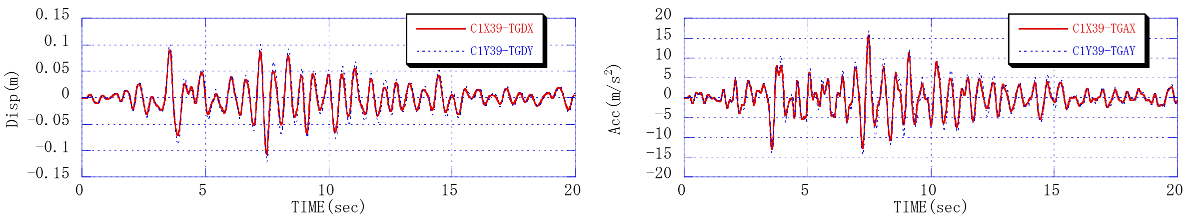
Because the number of nodes of the model is large enough, the response behaviors of following three sections are clarified, i.e. the section with the tunnel and the ground (called main line part), the junction section of main line tunnel and ramp tunnel (called junction part), and the section of ramp tunnel near the ground surface which is a ditch structure (called ramp part). The node number and the depth of three sections are shown in Table 2. At each section, 9 depths are considered. The location is about 40m from the center of tunnel for ground part, and about 10m from tunnel for ramp tunnel part. Because of the difference in mesh size of ground, tunnel and ramp, it is possible that the depth levels set at three sections may have different depth.

The displacement and acceleration responses at the ground around the junction and the surface of the upper tunnel when earthquake motion is applied in X direction (solid line) and Y direction (dotted line), are shown in Fig.5, respectively. At the ground part, the same displacement responses and acceleration responses are obtained regardless of the input directions, i.e. X direction and Y direction, while at the surface of the upper tunnel, the responses of displacement and acceleration in the X direction (direction of the tunnel) are smaller than those in the Y direction. The same input motion is used for both X direction analysis and Y direction analysis, but the responses at the surface of the ground part and those at the surface of tunnel part show different characteristics.

Figure 6 shows the displacement and acceleration responses at upper tunnel and lower tunnel under the input with the different directions. The responses of displacement and acceleration at the lower tunnel part are the same regardless of the input direction, while at the upper tunnel part, the smaller responses of displacement and acceleration are obtained when input is applied in the X direction. This trend is the same as that observed in the responses of surface ground part.

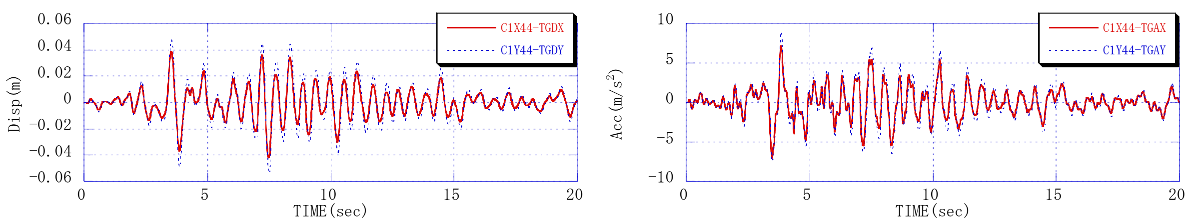


(a) Ground surface

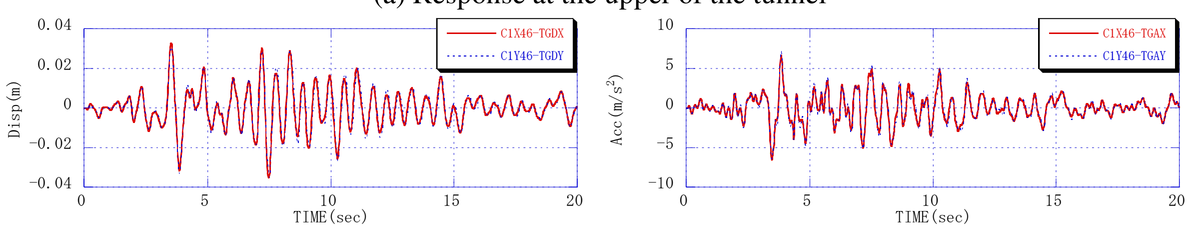


(b) Surface of the tunnel

Fig. 5 Comparison of displacement and acceleration response at the surface



(a) Response at the upper of the tunnel



(b) Response at the lower of the tunnel

Fig. 6 Comparison of displacement and acceleration response at the upper and lower of main line tunnel

Amplitude distribution along the depth

The response displacement distribution of ground and tunnel along the depth is very important for the aseismic design of the underground structure. The vertical distributions of the maximum and minimum displacement of the ground (40m depart from the center of the tunnel, indicated white circle) at three sections (main line part, junction part and ramp part), vertical distributions of the maximum and minimum displacement at the center of the main line tunnel (indicated black square) and the ramp tunnel (indicated black diamond), which are obtained from the analysis with the inputs in the different directions, are shown in Figure 7 and Figure 8, respectively.

In the case of X-direction input, the response behaviors of the ground and tunnel are similar until the depth of the lower part of the tunnel (depth -33m). However, in the tunnel region (-20m~-33m), the response of the tunnel turns to be smaller. In addition, the displacement amplitude of the ground above the tunnel is smaller than that of surrounding ground. Furthermore, the response in ramp region shows the same tendency. This result implies the possibility that tunnel surface suffers large load when earthquake motion acts in the axial direction of the tunnel. More detailed investigation is necessary in the future to judge whether the existence of the ramp leads to this phenomenon.

The results under the Y-direction input indicate that the amplification characteristics of the displacement response of the ground, main line tunnel and ramp tunnel are almost the same, which are different from those under X-direction input. It is likely that the 3D effect is small for the input in the orthogonal direction of the tunnel axis.

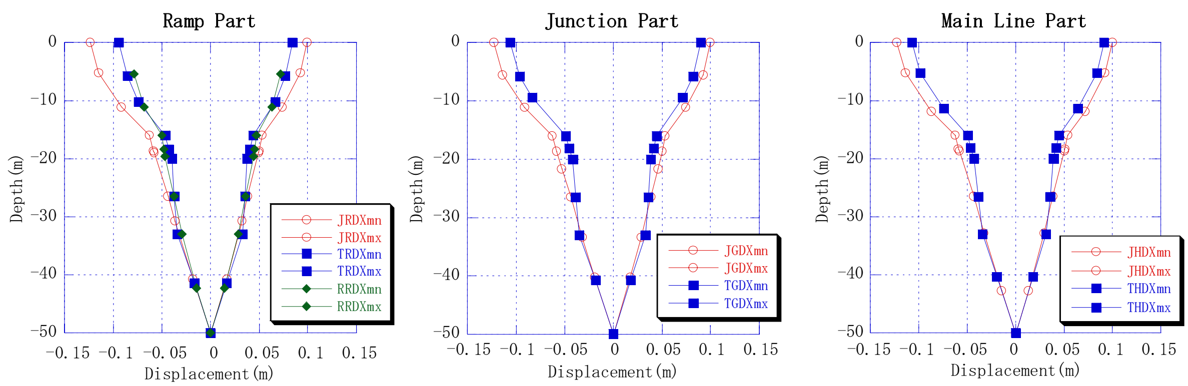


Fig.7 Comparison of displacement responses in ramp, junction and main line due to X-direction input

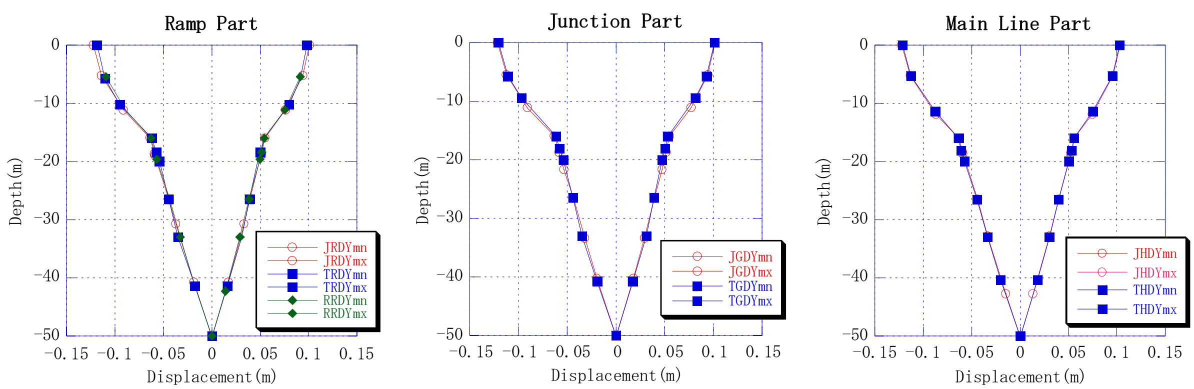


Fig.8 Comparison of displacement responses in ramp, junction and main line due to Y-direction input

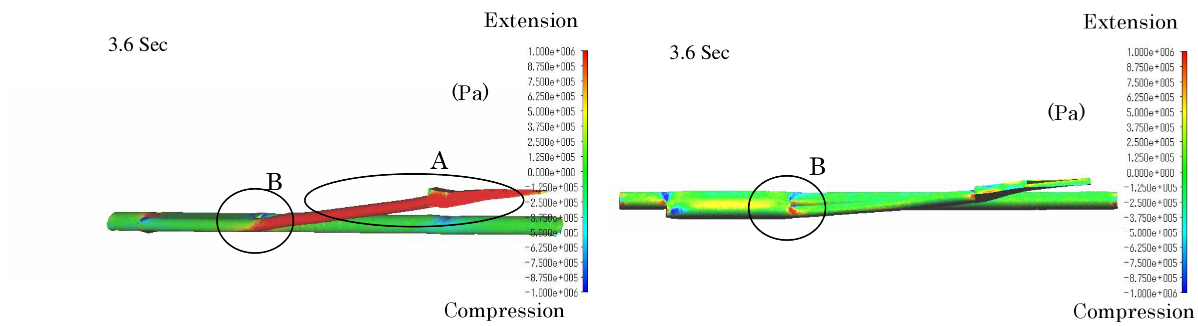
Stress distribution

It has been confirmed that the response behavior of the tunnel depends on the direction of input motion.

As an illustration, the changes of the stress distribution accompanying the deformation of the tunnel are shown in Figure 9. The deformation and the axial stress distribution of the tunnel at the time of 3.6 sec. are shown herein for X-direction and Y-direction inputs.

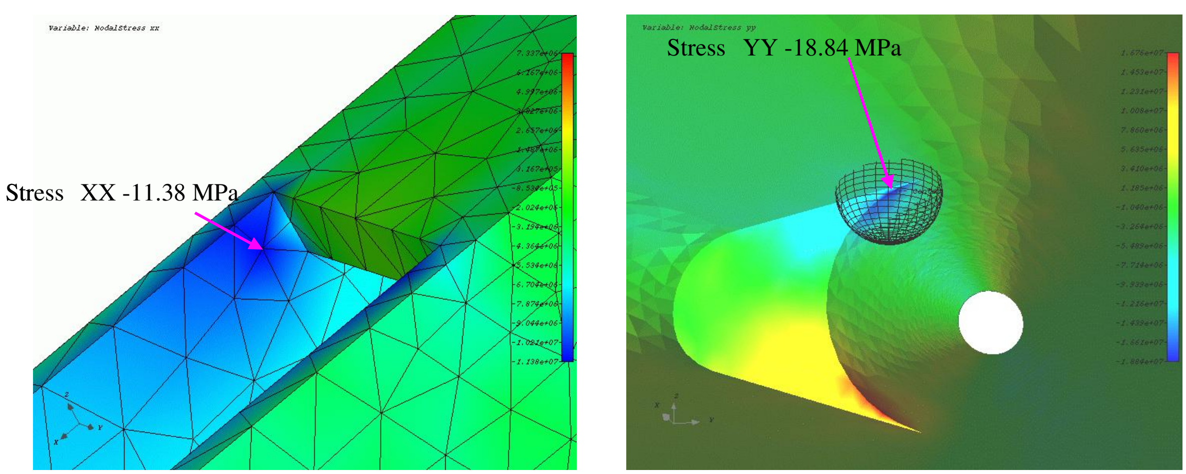
In the case of X-direction input, many areas of red color can be found in the part of the ramp tunnel, which indicates that tensile stress is around 1MPa. Especially, there is a stress concentration in the A and B areas of the ramp tunnel. On the other hand, in the case of Y-direction input, large stress can be observed in the junction part of the ramp tunnel, which acts as the access from junction part to the ground.

The reason of the occurrence of the stress distribution pattern obtained from the two analyses can be considered as the follows. The special section stress occurs in the ramp tunnel due to the difference in the depth of tunnel under X and Y direction inputs, which means the difference in the displacement response



(a) X-Direction (b) Y-Direction

Fig.9 Axial stress distribution in tunnel under the input in the orthogonal direction of the tunnel



(a) Stress XX-11.38Mpa (b) Stress YY-18.84MPa

Fig.10 Location of the maximum stress in the orthogonal direction of the tunnel

of the ground at different depths.

Figure 10 shows the locations of the maximum stress in the tunnel axial direction and the orthogonal direction of the tunnel axis under X direction and Y direction inputs, respectively. In the case of X-

direction input, it is considered that large stress occurs because of the response variation of the ground in ramp tunnel area due to the variation of the depth of the ramp tunnel.
As for the case of Y-direction input, large stress occurs in the wall of the junction of the tunnel in the orthogonal direction of the tunnel axis.

CONCLUSION

It is obtained from the analysis that, in the case of axial direction input, large stress arises in the axial direction of the ramp tunnel due to the large deformation in this direction. Moreover, the shear stress obtained from the evaluation shows that they could not be ignored. In the current design of the shield tunnel, the aseismic behaviors in the sectional direction and the axial direction are evaluated separately, and the behavior of complex structure can not be evaluated. The numerical analysis in this study reveals the basic concept of new aseismic design method.

In this analysis, the characteristics of the dynamic behavior of the tunnel junction part, which the existing design method and the small-scale FEM analysis can not evaluate, are investigated, and can be concluded as the followings.

(1) Special sectional force occurs in the ramp line part due to the difference in the depths of the tunnel, i.e. the difference in the displacement response of the ground.
(2) Very large and complicate sectional force can be observed in the steel shell and the mid-wall around the junction part of the main line and ramp line.
(3) The shear force acting on the surface of the tunnel caused by the ground has large effects on the sectional force of the tunnel not only in the orthogonal direction but also in the parallel direction of the tunnel axis.

In the future study, further numerical analysis will be performed. The evaluation method of junction part will be established and the aseismic measures to reduce various effects will be put forward.

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