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SEISMIC RESPONSE OF LARGE UNDERGROUND PURIFICATION RESERVOIR INDUCED BY EARTHQUAKE MOTION IN THE SHORT-AXIS DIRECTION

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ABSTRACT: The facilitation of a water supply is important to human life. So, the maintenance of a reliable water supply function during earthquake is strongly required. From such necessity, we studied the seismic response of a large underground purification reservoir by 3D dynamic analysis. As a result, it became clear that the stresses by earthquake motion will concentrate in the connections at the top of middle pillars inside the reservoir. In order to evaluate the seismic performance accurately, it is necessary to faithfully analyze the middle pillars according to the actual shape and arrangement.

Key Words: Water supply facility, seismic performance verification, 3D dynamic analysis, dynamic stress, underground purification reservoir

1. INTRODUCTION

After the 1995 Hyogoken-nanbu earthquake, considerable earthquake damage of water supply facilities was reported. Similarly, damage was also reported due to the Mid Niigata Prefecture earthquake in 2004 1), the 2005 West Off Fukuoka Prefecture earthquake, the Noto Hanto earthquake in 2007 2), the Niigata-ken Chuetsu-oki earthquake in 2007 3), the Iwate-Miyagi Nairiku earthquake in 2008 4). During the Great East Japan earthquake in 2011, tremendous damage of aqueducts, transmission pipes and distribution pipes occurred in the coastal area of the Iwate Prefecture, the Miyagi Prefecture and the Fukushima Prefecture. Furthermore, a lot of damage of water purification plants and pumping stations occurred in the area of the Ibaraki Prefecture and the Chiba Prefecture 5), 6). Many water supply facilities were constructed in the 1960s–1980s, and these aged existing facilities have reached a time when they must be updated. At present, the earthquake proof rate of water purification facilities remains in about 22% 7). Future occurrences of like the Nankai Trough earthquake, the Tokyo Inland earthquake, and so forth, are expected. Under such circumstances, verification and securing of seismic performance of water supply facilities is strongly required 8).

The Guidelines for Formulation of Earthquake Resistant Plans of Water Supply 9), prescribe to improve the seismic performance of individual structures, in order to make the facilities tough and safe against earthquakes. Further, it prescribes to take seismic measures in order to maintain the water supply function, from source to the users. As for the seismic performance verification of a structure with significant social impact, it is necessary to estimate accurately the phenomena during earthquake and to realize a reliable verification. Considering this requirement, we carried out the dynamic response analysis for the water supply facility, and considered analysis methods for accurate and reliable verification of seismic performance.

In this study, we chose an underground purification reservoir, and the distribution reservoirs made of reinforced concrete, as an analysis object. The underground purification reservoir is a facility to stock and supply safe drinking water, which is sterilized and filtered. When cracks occur at the purification reservoir by strong earthquake motion, it becomes difficult to keep the quality of water in a safe and good condition because of an inflow of dirty water from the outside. Consequently, it becomes difficult to maintain the water supply function. Therefore, we carried out a three-dimensional dynamic analysis in regard to earthquake response of the underground purification reservoir by paying our attention to the occurrence of cracks. Based on the results of three-dimensional analysis, we considered the effectiveness of the three-dimensional analysis for seismic performance verification. We also made a three-dimensional analysis model of the coupled underground purification reservoir and ground system. Earthquake motion was input in the short-axis direction of the underground purification reservoir. With regard to the failure of reinforced concrete, it is known that the deterioration of concrete is caused by tensile stress or shear stress before the yield of reinforcing bar 10). Using earlier experiences, we made the evaluation of stress caused by strong earthquake motions, as the principal objective. The reinforced concrete structure was modeled by using solid elements, because the reinforced concrete is a unified structure of reinforcing bar and concrete 11).

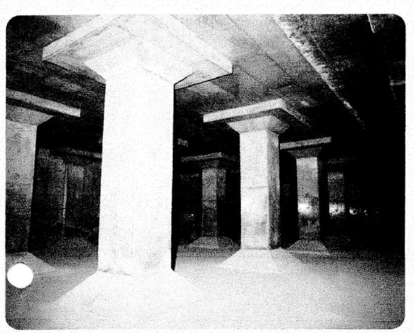
2. THREE-DIMENSIONAL DYNAMIC ANALYSIS METHOD

2.1 Outline

In this study, the underground purification reservoir of 73m in length, 51m in width and maximum18m in height is set up as the analysis object in reference to the update plan of existing plant. Photo 1 12) shows an example of the internal situation of underground purification reservoir. It is supposed that the many pillars inside the reservoir, will have an important influence on the earthquake response and seismic performance of underground purification reservoir, so the pillars were modelled one by one in order to reproduce the actual situation faithfully. The analysis model was made as a coupled structure-ground system. Earthquake motion was input in the short-axis direction of the structure. We evaluated dynamic stress, acceleration response and displacement response during earthquake, while putting the principal objective in the dynamic stress.

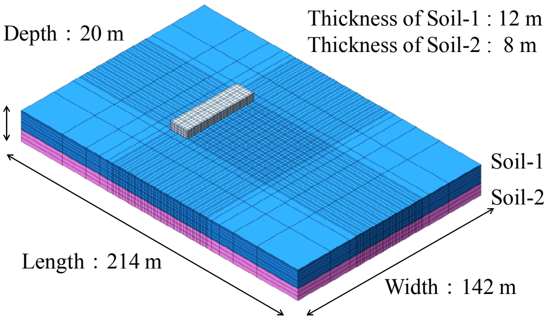
2.2 Three-dimensional dynamic analysis model

The underground purification reservoir, which consists of earthquake resistant walls, baffle walls and pillars, has one floor above ground and two floors underground, which have the stairwells. The overburden of the underground purification reservoir is 0.5m. Because the baffle walls do not have an earthquake resistant function, the baffle walls were omitted in modeling. The pillars and the earthquake resistant walls were modeled faithfully to the actual design drawings. Figure 1 shows the FEM model of the coupled structure-ground system. Figure 2 shows the underground purification reservoir, where the ground is not displayed. Figure 3 and 4 show the situation of FEM model inside the reservoir. As for the ground, two layered horizontal ground of 214m in length, 142m in width and 20m in depth was modeled. The ground and structure were modeled by using solid elements. In order to reduce calculation time and model-size, the earthquake resistant walls and the pillars were defined with 1 element over the thickness-direction. As for the boundary conditions, the lateral boundary was set as the viscous boundary, and the bottom boundary as the rigid boundary. The water inside the reservoir was not included in the model, and the empty condition was set. The numbers of elements and nodes in the analysis model are 31,342 and 30,209, respectively. The analysis program DIANA was used.

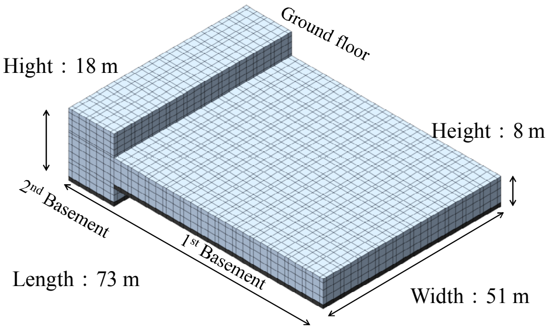


Inside of underground purification reservoir
（Reference：City of Sapporo, Waterworks Bureau）

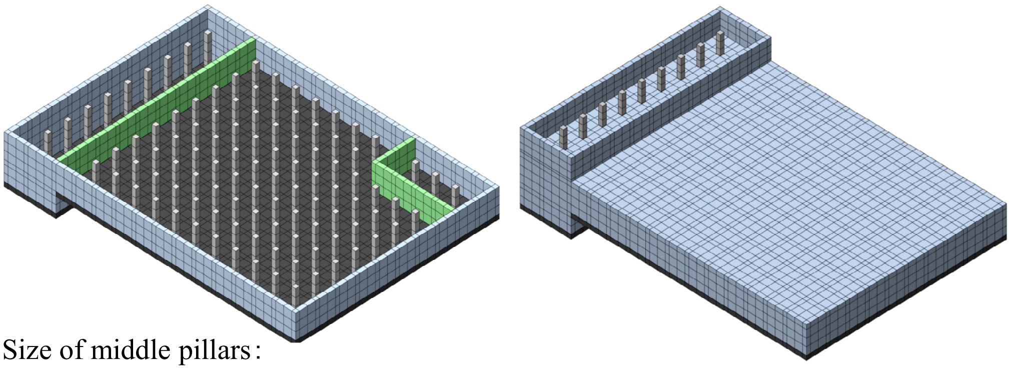
Photo 1 Example of inside of underground purification reservoir



(Coupled model of structure and ground)
Fig. 1 Whole view of analysis model



(Display only structure)
Fig. 2 Analysis model of purification reservoir



Size of middle pillars:
width 1 m, depth 1 m, height 6 m
Thickness of walls : 1 m

（1） Inside of 1st and 2nd basement

Thickness of ceiling slab: 1 m
Thickness of bottom plate : 1 m

（2） Inside of ground floor

Fig. 3 Analysis model inside the underground purification reservoir

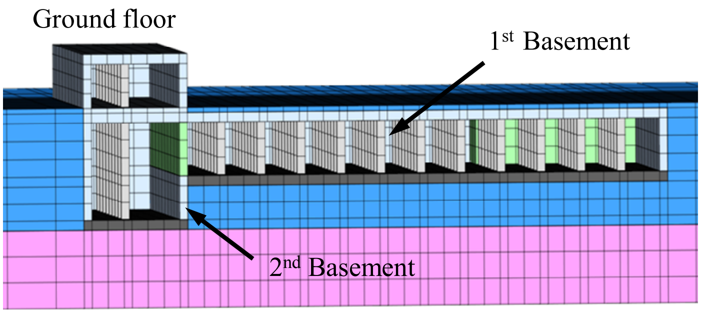


Fig. 4 Modeling profile inside the underground purification reservoir (Longitudinal section)

2.3 Input Earthquake Motion

Level-2 earthquake ground motion assumed by the City of Sapporo 13) was used as an input earthquake motion, which is shown in Figure 5. Maximum acceleration is 633.64 Gal and duration time is 10 sec. Acceleration response spectra is shown in Figure 6. Based on the previous examination 14) , 15), as shown in Figure 7, the earthquake ground motion was applied in the short-axis direction.

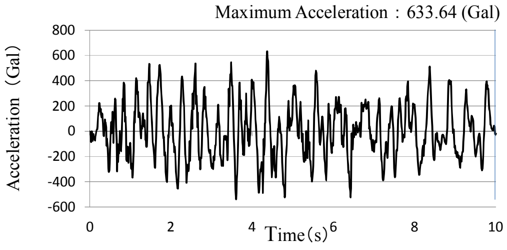


Fig. 5 Input earthquake motion

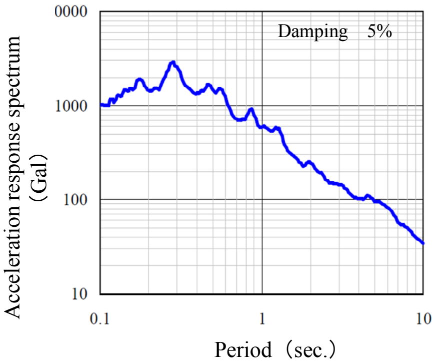


Fig. 6 Acceleration response spectrum

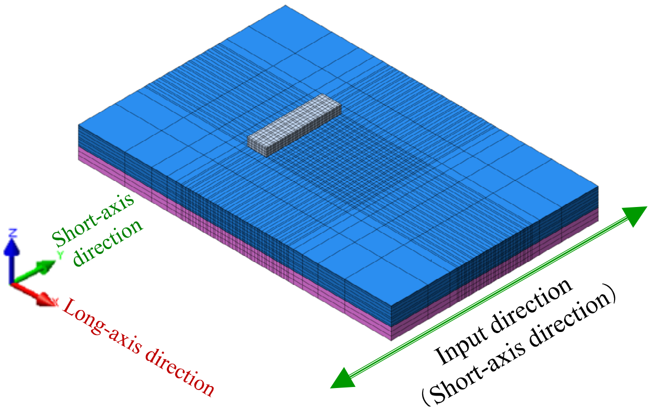


Fig. 7 Input direction of earthquake motion

2.4 Dynamic property values for analysis

The underground purification reservoir is a reinforced concrete structure, and the dynamic property values, as shown in Table 1, were used for analysis. Two kinds of physical property values of the ground were set in order to compare the influence of the stiffness of the ground. Figure 8 shows the result of cyclic tri-axial test performed for the target ground. The dynamic property values of stiff soil were set as shown in the upper row of Table 2 by assuming a case where the dynamic strain level is relatively small. The dynamic property values of soft soil were set as shown in the lower row of Table 2 because the dynamic strain level estimated by the dynamic analysis was around 2×10^{-4}–8×10^{-4}. The primary natural frequencies of the stiff soil and the soft soil are 0.25 sec. and 1.58 sec., respectively.

Table 1 Dynamic property value of structure

Item	Dynamic shear modulus (N/mm^2)	Density (g/cm^3)	Dynamic Poisson's ratio	Damping Factor
RC underground reservoir	9400	2.35	0.2	0.04

Table 2 Dynamic property value of soil

Item		Layer Thickness (m)	Dynamic shear modulus (N/mm^2)	S-wave velocity (m/s)	Density (g/cm^3)	Dynamic Poisson's ratio	Damping Factor
Stiff soil	Soil-1	12	90	210	2.06	0.4	0.08
	Soil-2	8	506	480	2.20	0.4	0.08
Soft soil	Soil-1	12	18	93	2.06	0.4	0.08
	Soil-2	8	100	213	2.20	0.4	0.08

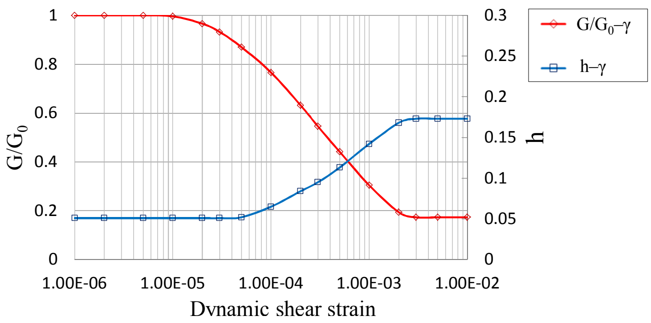
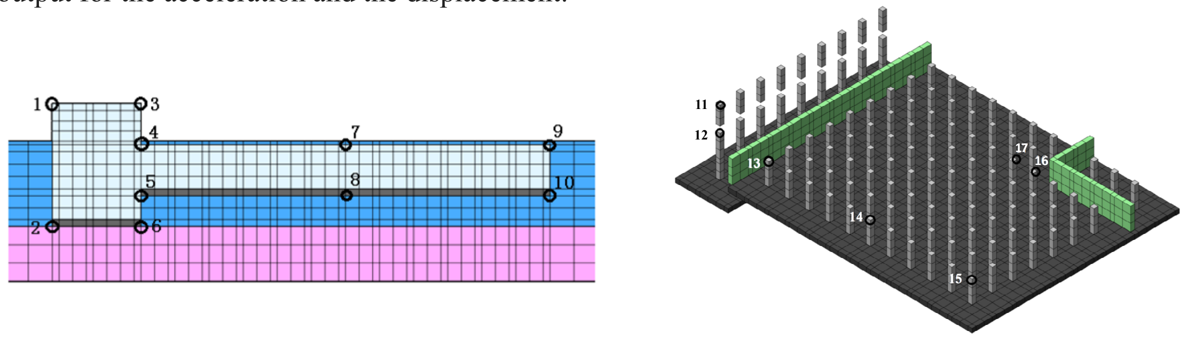


Fig. 8 Dynamic nonlinear characteristics of soil

2.5 Representative output position

The representative output position of earthquake response is shown in Figure 9. The analyzed values of the representative elements were output for the stress, and those of the representative nodes were output for the acceleration and the displacement.



(1) Outer wall of the reservoir

(2) Pillars inside the reservoir

Fig. 9 Representative output position

3. THREE-DIMENSIONAL DYNAMIC ANALYSIS RESULTS

3.1 Acceleration response

Figure 10 shows the distribution of maximum acceleration around the purification reservoir when the earthquake motion was input in the short-axis direction. And the comparison of maximum acceleration between Case 1 (Stiff soil model) and Case 2 (Soft soil model) is shown in Table 3. In this analysis, the maximum acceleration response became larger in the stiff soil model than in the soft soil model at any representative output position. Generally, it is thought that the acceleration response depends on the mutual influence of spectral characteristics of ground motion and the vibration characteristics of ground, and the short period components will be amplified in the stiff ground and the long period components will be amplified in the soft ground. When the long period component of earthquake motion is dominant, the acceleration response of soft ground will become larger than that of stiff ground. In this analysis, the acceleration response of the stiff soil model became larger than that of the soft soil model, because the short period component of earthquake motion was dominant.

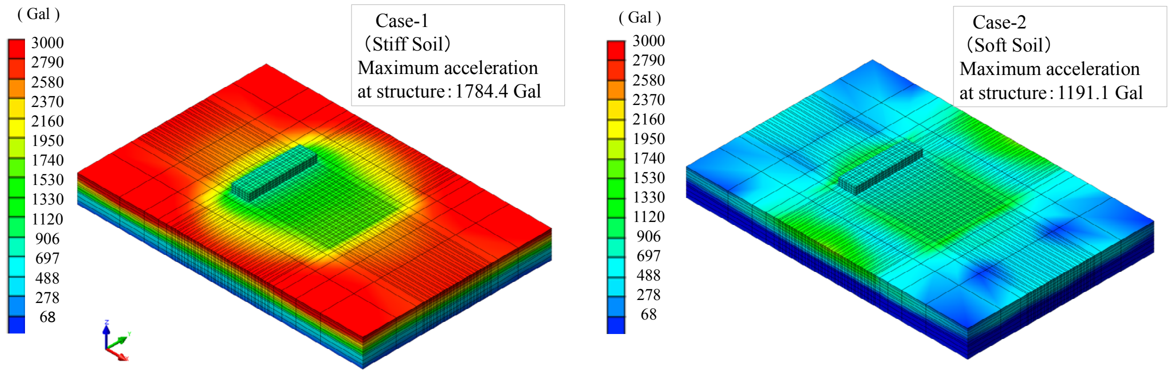


Fig. 10 Distribution of maximum acceleration around underground purification reservoir

Table 3 Earthquake response at representative output position

Position				Maximum acceleration (Gal)		Maximum displacement (mm)		Maximum tensile stress (N/mm^2)	
				Case-1 Stiff soil	Case-2 Soft soil	Case-1 Stiff soil	Case-2 Soft soil	Case-1 Stiff Soil	Case-2 Soft soil
1	Outer wall	1st B	Ceiling, Left end	1100.3	972.8	13.4	25.2	0.04	0.03
2		2nd B	Base, Left end	769.8	733.9	7.59	20.3	13.6	10.3
3		1st B	Ceiling,Right end	1154.6	975.7	14.7	28.9	0.09	0.06
4			Ceiling, Left end	1122.5	916.7	14.2	28.1	5.23	4.74
5			Base, Left end	936.5	803.6	11.1	26.0	4.24	3.48
6		2nd B	Base, Right end	789.0	688.7	7.83	23.4	12.3	11.2
7		1st B	Ceiling, Center	1633.6	1070.3	23.8	40.8	2.06	1.29
8			Base, Center	1171.1	843.2	15.7	36.8	3.32	2.17
9			Ceiling,Right end	1784.4	1119.1	28.7	52.5	6.54	5.01
10			Base, Right end	1552.1	968.3	24.9	50.8	6.74	4.29
11	Pillar	1st F	Upper end	1113.8	963.1	13.8	26.7	0.16	0.01
12		2nd B	Upper end	1072.4	902.5	13.2	25.8	0.36	0.53
13		1st B	Left end	1189.6	927.0	15.7	30.0	3.16	1.06
14			Center	1601.6	1053.5	23.3	40.7	10.0	4.45
15			Right end	1725.9	1096.0	27.3	50.1	1.13	0.15

(Note) Underline: tensile stress 5N/mm^2 or more, Representative output position: see Fig. 9
1st B: first basement, 2nd B: second basement, 1st F: first floor

As shown in Fig. 10, in the stiff soil model, the acceleration response was relatively simple, whereas in the soft soil model, the acceleration response of the surrounding area of the reservoir was rather complicated. As for this, it is considered that when the earthquake motion propagates from the underground to the ground surface, the amplification becomes large in the surrounding ground with low rigidity, the amplification becomes small in the reservoir with high rigidity, and the earthquake motions are dispersed and reflected at the junction between the structure with high rigidity and the ground with low rigidity.

3.2 Displacement response

The maximum displacement distribution is shown in Figure 11. The comparison of the maximum displacement of the representative output point is shown in Table 3 above. The displacement means the relative displacement from the base of the analysis model. From Table 3 and Fig. 11, it can be seen that the displacement response in the soft soil model is larger than that in the stiff ground model. In the soft soil model, the dynamic shear modulus of the ground is 1/5 of that of the stiff soil model. As the result, the displacement response of the ground increased, and it is considered that the influence of the ground response was extended to the purification reservoir. The majority of the purification reservoir is located underground, so it is considered that the purification reservoir is susceptible to the displacement behavior of the surrounding ground during large earthquakes. When the ground around the purification reservoir is soft, it is thought that the displacement response is even increased due to the influence of the strain dependence of the dynamic shear modulus. The purification reservoir is a part of water supply system, so it is not an individual and independent structure but a composite structure connected with structure and pipe. When the purification reservoir and pipe are connected, the relative displacement between them becomes a more important factor that affects damage and destruction during earthquake. In particular, when the surrounding ground is soft, it becomes necessary to accurately and quantitatively evaluate the relative displacement during earthquake. In the analysis result here, the relative displacement between the outer wall of the reservoir and the ground at a distance of 1.5 m from the outer wall was about 8.2 mm for the stiff soil model and about 21.8 mm for the soft soil model. In addition, the interlayer deformation angle of the purification reservoir was about 1.4×10^{-3} at the maximum through the stiff soil model and the soft soil model.

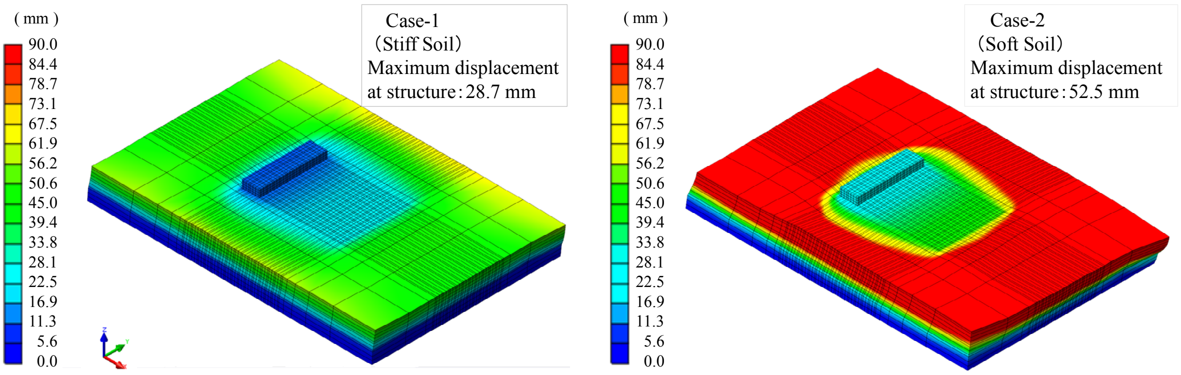


Fig. 11 Distribution of maximum displacement around underground purification reservoir

3.3 Stress caused by earthquake motion

Concrete is strong against compression, but weak against tension, so we arranged the analysis results by focusing on the tensile stress at the time of earthquake as an index for estimating the possibility of occurrence of cracks. Figure 12 shows the maximum tensile stress distribution on the outer wall members of the purification reservoir, and Figure 13 shows the maximum tensile stress distribution on the earthquake resistant walls and the middle pillars inside the purification reservoir. The value of maximum tensile stress at representative output position (see Fig. 9) is shown in Table 3 described above. The value of the maximum tensile stress means the stress caused by the strong earthquake motion, so the initial stress is not superimposed. The left side of Fig. 12 and Fig. 13 is the analysis result of the stiff soil model, and the right side is the analysis result of the soft soil model. From Fig. 12, it can be seen that the tensile stress caused by earthquake motion increased at the portion where the shape of structure changed, and the portion where the rigidity changed due to the presence of the earthquake resistant walls. Also, from Fig. 13, it can be seen that the tensile stress caused by earthquake motion became large at the top of the pillars. As for the displacement against the input earthquake motion used this time, the amount of displacement became larger in the soft soil model than in the stiff soil model. Since the dynamic shear modulus was set lower in the soft soil model than the stiff soil model, the displacement in the soft soil model became larger. On the other hand, the tensile stress caused by earthquake became larger in the stiff soil model than in the soft soil model. The purification reservoir is a structure with high rigidity, so it is considered that the coupled action between the purification reservoir and the ground became larger in the stiff soil model, or in the ground with high rigidity.

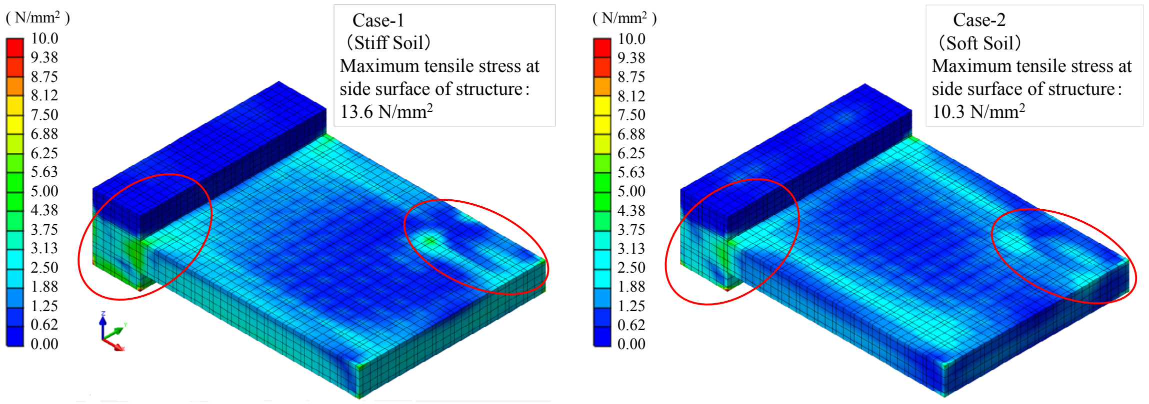


Fig. 12 Distribution of maximum tensile stress on the outer wall members of underground purification reservoir

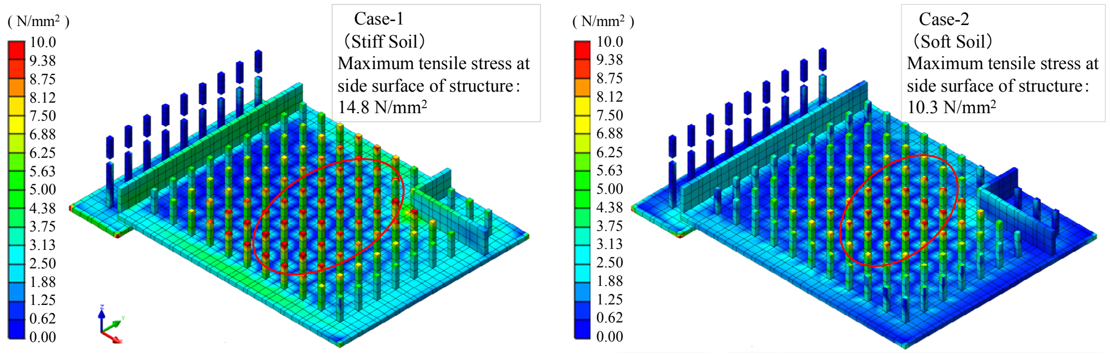


Fig. 13 Distribution of maximum tensile stress on the members locate inside of underground purification reservoir

The dynamic tensile strength of concrete is assumed to be about 3–5 N/mm^2. In Table 3 above, the evaluated value exceeded the strength at position 2, 6, 9, 10 and 14. Position 2 and 6 are located at the boundaries between the purification reservoir and the ground. Therefore, it is considered that the distortion of the purification reservoir increased due to the influence of the deformation of the ground, and as a result, the tensile stress increased at the junction of the ground and the purification reservoir. Position 14 is the top of the pillar inside the purification reservoir. Based on the results of this analysis, we could confirm that there is a possibility of large earthquake stress occurring in pillars inside the purification reservoir. The top of the pillar is the connection between the pillar and the ceiling, and the quantitative evaluation of tensile stress at these connecting parts is important. In this study, we focused on the evaluation of the earthquake response the whole system, which combined the purification reservoir and the ground. With regard to the important parts for estimating earthquake damage, such as the top of pillar, the part of shape change, the part of rigidity change and so forth, it is necessary to perform the analysis with detailed mesh division and the analysis taking the influence of dynamic nonlinear characteristics into account.

4. SUMMARY

In this study, we considered that the occurrence of cracks is important in the case of evaluating the seismic performance of the underground purification reservoir. Then, we set up the FEM model of the whole system composed of underground purification reservoir and ground, and carried out three-dimensional dynamic analysis by focusing on the evaluation of tensile stress caused by strong earthquake motion. As a result regarding the earthquake ground motion used here, the displacement decreased when the surrounding ground became stiff, and the acceleration and the stress increased. But, when the surrounding ground became soft, the displacement increased, and the acceleration and the stress decreased.

It is considered that the acceleration response changes largely due to the mutual effect between the spectral characteristics of earthquake motion, the dynamic property of the structure, and the ground. The influence of the stiffness of the ground changes between the case of applying the short period earthquake motion and the case of applying the long period earthquake motion.

In general, the stress and the displacement caused by strong earthquake motion are important indicators for evaluating the damage or destruction of structure. With regard to the structures with high rigidity, such as those to be evaluated in this study, it is more important to evaluate the stress. The tensile stress and the shear stress are more important for evaluating the seismic performance of the concrete structure. On the other hand, when the structure and the pipe are connected, the relative displacement between structure and pipe is the important evaluation indicator. So, it is necessary to improve accuracy of such an evaluation indicator in order to improve the reliability of seismic performance verification. Furthermore, it is considered that the stress during earthquake will become large at the change part of the shape and the dynamic rigidity, the top of the middle pillars, etc. Therefore, it is also important to devise a design consideration and a countermeasure consideration for these parts for the purpose of improving the seismic performance.

Based on the results of this analysis, it is considered that damages of pillars inside the underground purification reservoir may provide severe influence on the continuity of water supply function. In the event that cracks are induced in the ceiling slab due to the damage of middle pillars by earthquake, it is considered there is a risk that external water will penetrate or flow into the underground purification reservoir and contaminate the purified water. For the lifeline facilities with high social importance like water supply facilities, it is necessary to accurately estimate the phenomena occurring during strong earthquakes in advance. In order to conduct the seismic performance evaluation with high accuracy and reliability, it is necessary to faithfully analyze the middle pillars and the earthquake resistant walls in the structure according to the actual shape and arrangement. We consider the accurate three-dimensional dynamic analysis as a numerical experiment using a computer. Three-dimensional dynamic analysis with high accuracy is a useful and effective means for predicting and estimating the phenomena which will appear at the time of large earthquake.

5. AFTERWORD

The water supply facilities are composed of various structures and equipment such as water supply reservoirs, pumping stations, water supply pipes, water pipe bridges, etc. Therefore, quantitative evaluation of seismic influence will be necessary not only for the individual structure but also for the connected structure by taking mutual effect among reservoir, pipeline and adjacent structures into consideration. As a future task, we will study the mutual influence of large-scale underground purification reservoir and pipeline at the time of earthquake.

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REFERENCES

1) Mid Niigata Prefecture Earthquake Water Works Field Survey Team (Water Supply Division, Health Service Bureau, Ministry of Health, Labor and Welfare): Report on Water Works Damages due to the Mid Niigata Prefecture Earthquake in 2004, pp. 11-13, 2005.（in Japanese）
2) 2007 Noto Hanto Earthquake Water Supply Utilities Facilities Damages Survey Team (Water Supply Division, Health Service Bureau, Ministry of Health, Labor and Welfare): Report on Water Supply Utilities Damages due to the Noto Hanto Earthquake in 2007, pp. 23-72. 2007.（in Japanese）
3) 2007 Niigataken Chuetsu-oki Earthquake Water Supply Facilities Damages Survey Team (Water Supply Division, Health Service Bureau, Ministry of Health, Labor and Welfare): Report on Water Supply Utilities Damages due to the Niigataken Chuetsu-oki Earthquake in 2007, pp. 31-82, 2008.（in Japanese）
4) Ministry of Health, Labor and Welfare (Water Supply Division, Health Service Bureau,) and Japan Water Works Association: Report on Water Supply Utilities due to the Iwate-Miyagi Nairiku Earthquake in 2008, pp. 25-55, 2009.（in Japanese）
5) Ministry of Health, Labor and Welfare (Water Supply Division, Health Service Bureau,) and Japan Water Works Association: Report of Field Survey Team on Water Supply Utilities Damages due to the Great East Japan Earthquake in 2011, pp. 53-141, 2011.（in Japanese）
6) Kuwata, Y. and Katagiri, S.: Emergency Report of JSCE Survey Team (Earthquake Engineering Committee) on Damages due to the Great East Japan Earthquake in 2011, Chapter 10, pp. 1-61, 2011.（in Japanese）
7) Ministry of Health, Labor and Welfare: Status of Earthquake Resistance in Water Service (2013), pp. 1-17, 2014.（in Japanese）
8) Japan Water Works Association: Issues and Measures for Earthquake Resistance in Water Service, pp. 1-7, 2008.（in Japanese）
9) Ministry of Health, Labor and Welfare: Guidelines for Formulation of Earthquake Resistant Plans of Water Supply, pp. 8-10, 2008.（in Japanese）
10) Japan Society of Civil Engineers: Introduction to Earthquake Engineering-The Professional Engineer's Perspective, pp. 110-111, 2001.（in Japanese）
11) Japan Society of Civil Engineers: Guidelines for Seismic Design of Civil Engineering Structures, Chapter 7, Calculation of Response Values of Structures, pp. 103-106, 2011.（in Japanese）
12) Waterworks Bureau, City of Sapporo: Production plant of Water-The Shiraikawa Water Purification Plant, pp. 14, 2013.（in Japanese）
13) Inoko, K., Ohtake, K., Narita, K., Hayashikawa, T. and Ariga, Y.: Influence Analysis of the Ground Surface Inclination and Newly Constructed Structures on Existing Structures, *Journal of JSCE A1 (Structural and Earthquake Engineering)*, Japan Society of Civil Engineers, Vol. 70, No. 4, pp. I_9-I_20, 2014.（in Japanese）
14) Ariga, Y., Miura, C., Inoko, K. and Takehara, K.: Seismic Response of Large Underground Purification Reservoir induced by Earthquake Motion in the Long-axis Direction, *Proceedings of*

the 34th JSCE Earthquake Engineering Symposium, Japan Society of Civil Engineers, pp. 1-8, 2014.（in Japanese）

15) Ariga,Y., Ishikawa, T., Inoko, K., Ohtake, K., Narita and Takehara, K.: Three-Dimensional Dynamic Analysis for Relative Displacement between Old and New Water Supply Facilities, *Journal of JSCE A1 (Structural and Earthquake Engineering)*, Japan Society of Civil Engineers, Vol.69, No. 4, pp. I_491-I_500. 2013.（in Japanese）

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