EFFECTIVE COUNTERMEASURES AGAINST BOTH STRONG EARTHQUAKE MOTION AND TSUNAMI FOR WATER CYCLE FACILITY

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Abstract

Water cycle facility is a lifeline indispensable for the maintenance of daily life and industrial activity. Of the water cycle facilities, the purification centers responsible for sewage treatment are often located in the coastal areas to collect sewage by gravity flow. So, there is a risk of being damaged by both strong earthquake motion and tsunami at the time of huge earthquake. In the 2011 off the Pacific coast of Tohoku Earthquake, many sewerage facilities constructed in the coastal areas suffered major earthquake damages. In the future, the Nankai Trough earthquake is supposed to occur. Therefore, it is necessary to implement effective countermeasures against not only strong earthquake motion but also tsunami wave pressure.

From such a necessity, we have proposed “seismic-tsunami isolation constitution” based on the concept of “seismic isolation and tsunami isolation” instead of “earthquake resistance and tsunami resistance”. This seismic-tsunami isolation constitution has mitigation effects against both the strong earthquake motion and the wave pressure of tsunami. In the seismic-tsunami isolation constitution, an isolation material, namely a buffer material with low rigidity, is interposed between structure and foundation. By interposing such material, the structure can easily rotate and translate when the earthquake motion and the tsunami act on the structure. As a result, the stresses generated in the structure can be reduced. Consequently the damage and destruction of structures can be prevented and mitigated.

Effectiveness of the seismic-tsunami isolation constitution was checked based on FEM analysis by setting two analysis models, or the non-measures model and the seismic-tsunami isolation measures model. The analysis object was RC semi-underground structure with a total height of 28.4 m (13 m above ground, 15.4 m underground), 20 m wide and 14 m deep. The seismic isolation effect against strong earthquake motion was evaluated by 3-D dynamic analysis. The tsunami isolation effect against tsunami wave pressure was evaluated by 3-D static analysis. The tsunami wave pressure was acted as a static uniform load to the area of height 0 m to 6.5 m and width of 20 m. The value of tsunami wave pressure was set to be 400 kPa by taking the results of tsunami analysis based on the SPH method into consideration. The analysis program ISCEF was used for the 3-D FEM analyses.

Regarding the tsunami isolation effect, when the tsunami wave pressure acted on the structure, the maximum displacement of structure by the non-measures model was 4.52 cm. On one hand, it was 19.41 cm by the seismic-tsunami isolation measures model. The maximum tensile stress at the front of structure was 3.67 N/mm^2 by the non-measures model, and 2.81 N/mm^2 by the seismic-tsunami isolation measures model. As the results, it was confirmed that the displacement behavior of structure can be easily occurred by arranging the isolation material (buffer material) with low rigidity around the structure. And, it was also confirmed that the stress caused in the structure could be reduced, as we expected.

Keywords: water cycle facility, seismic and tsunami isolation, 3D analysis, stress reduction, disaster prevention

1. Introduction

For structures and facilities located in coastal areas, it is necessary to confirm and secure safety against both earthquake and tsunami. We proposed a concept of "seismic isolation and tsunami isolation constitution" as an effective measures technology by utilyzing buffer material with low rigidity. The applicability was examined by 3-D FEM analysis method. Seismic isolation effect was evaluated by 3-D dynamic analysis, and tsunami isolation effect was evaluated by 3-D static analysis. As a result, it was confirmed that the stresses generated by earthquake and tsunami could be reduce by the proposed constitution.

2. Necessity and purpose of study

Water cycle facilities are lifeline which are indispensable for daily life and industrial activities. Of the water cycle facilities, the purification centers that handle sewage treatment are often located in coastal areas and river basins because sewage is collected by natural flow. Consequently, there is a danger of being attacked by earhthquake and tsunami.

The 2011 off the Pacific coast of Tohoku Earthquake caused severe earthquake and tsunami damages to many sewage facilities constructed along the coastal areas. The Minami-gamou Purification Center of the Sendai City was severely damaged by the tsunami over 10 m in height [1]. By taking these damages into account, the national government [2], the local governments, the academic societies [3] and so forth have published the survey reports on seismic and tsunami countermeasures for water cycle facilities. In the future, it is expected that the Nankai Trough earthquake will occur. Under such circumstances, it is necessary to develop effectitive rational seismic countermeasures and tsunami countermeasures for structures located in the coastal areas. Then, we proposed a concept of "the seismic-tsunami isolation constitution", which has a seismic isolation effect against strong earthquake motion and a tsunami isolation effect against tsunami wave pressure. Fundamental concept of the proposed method is not "earthquake resistance nor tsunami resistance" but "seismic isolation and tsunami isolation". Its effectiveness was evaluated by numerical analysis.

3. Fundamental idea for measures against earthquake motion and tsunami

3.1 Whole conception of seismic and tsunami isolation

Whole concept of seismic and tsunami isolation is summarized as shown in Table 1. As for measures against strong earthquake motion, reduction of earthquake motion by undergrounding, reduction of seismic response by utilizing isolator, and so forth can be thought. As for measures against wave pressure of tsunami, avoidance from tsunami, seclusion from tsunami, reduction of tsunami wave pressure by devising the surface shape of structures, reduction of tsunami wave pressure by utilizing buffer material, and so forth can be thought. Fundamental concept of seismic and tsunami isolation is not resistance but avoidance.

3.2 Proposal of the seismic-tsunami isolation constitution

The fundamental concept of the seismic-tsunami isolation constitution is shown in Fig.1. In this constitution, the buffer material with low rigidity is interposed between a building and a surrounding ground. The buffer material plays a role of seismic isolation material against strong earthquake motion, and tsunami isolation material against wave pressure of tsunami. By disposing buffer material around the building, the building can easily rotate and translate when earthquake motion and wave pressure of tsunami act on the building. In this way, the stress generated in the buildings can be reduced, consequently the damage and destruction of buildings can be prevented and mitigated [4].

The main feature of this constitution is to achieve seismic isolation effect and tsunami isolation effect by the same method at once, thet is the method by utilizindg the buffer material with low rigidity.

Table 1 – Whole conception of seismic-tsunami isolation

1. Earthquake Measures ➡**Seismic isolation**
(1) Earthquake motion reduction by undergrounding (2) Earthquake motion reduction by isolator
2. Tsunami Measures ➡**Tsunami isolation**
(1) Avoiding ◇Location where tsunami does not reach ◇Disaster prevention of land use➡Drastic measures ◇Relocation at the time of redevelopment due to aging
(2) Isolation ◇Isolation by undergrounding ◇Covering by dome structure ◇Blocking by wall structure
(3) Reduction of wave pressure by structure ◇Reduction by surface shape of structure (flat, curved, etc.) ◇Reduction by arrangement considering arrival direction ◇Reduction by rotation and translation of structure
(4) Utilization of buffer material ◇Absorption of wave pressure by buffer material ◇Reduction of stress within structure
3. Compatible Measures ➡**Seismic-tsunami isolation**
◆Compatibility of tsunami isolation with seismic isolation ◆Basic concept ➡ Not resistance, but reduction and isolation

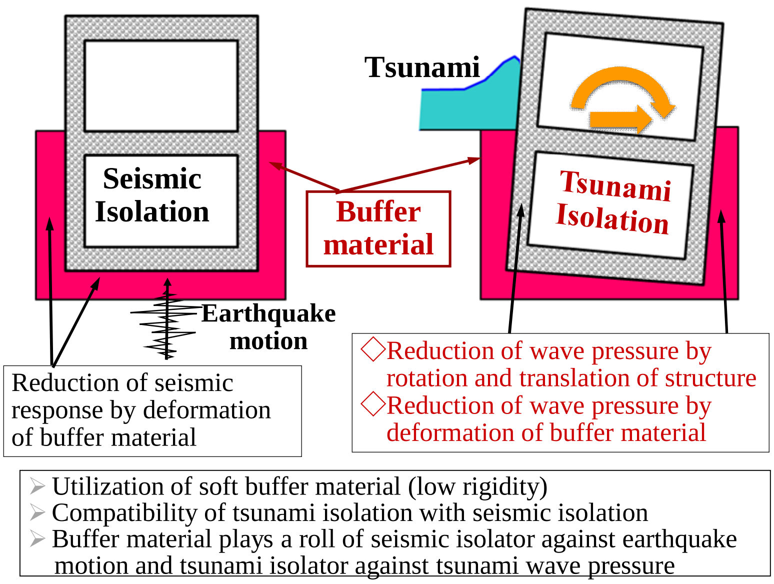


Fig. 1 – Fundamental concept of "seismic-tsunami isolation constitution"

4. Evaluation of tsunami isolation effect by 3-D analysis

4.1 Outline

The seismic isolation effect against strong earthquake motions was evaluated by 3-D dynamic analysis. And the tsunami isolation effect against tsunami was evaluated by 3-D static analysis [5]. Seismic isolation technology has been already realized, and there are many applied cases. So, we discussed by focusing on the tsunami isolation effect, here.

Two types of analysis models, a non-measures model and a isolation-measures model, were set. The tsunami isolation effect was evaluated by comparative analyses using these two models. For the analyses, the analysis program ISCEF [6] was used.

4.2 Analysis object

The analysis model is shown in Fig.2. This was set with reference to the damage cases of purification center by the 2011 off the Pacific coast of Tohoku Earthquake. The analysis object is a 4-story reinforced concrete structure with 2 floors above ground and 2 floors below ground. The size of structure is 13 m in height above ground, 15.4 m in depth below ground, 20 m in width and 14 m in depth. The thickness of walls and floors of structure are 0.5 m. The ground is assumed to be soft ground which is two-layered horizontal ground. The range of ground with a width of 76 m, a depth of 70 m, and a height of 30 m was modeled. The ground and the structure were modeled with 8-node solid element. The lateral boundary and the bottom boundary were set to be viscous boundary and rigid base, respectively. The analysis frequency range is 0.1 Hz to 30 Hz.

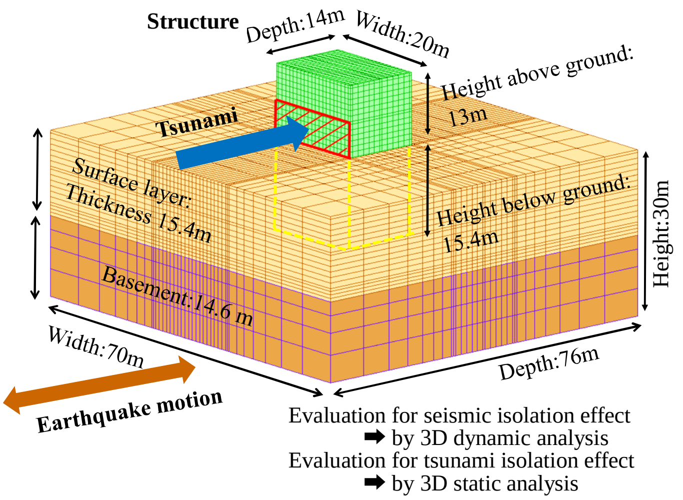


Fig. 2 – 3-D analysis model for evaluating effect of seismic-tsunami isolation constitution

4.3 Analysis cases

4.3.1 Non-measures model

The non-measures model is an analysis case in which no buffer material is placed. As shown in Fig.3, the joint elements were arranged on the contact plane between structure and ground in order to simulate the discontinuous behavior such as separation and sliding at the contact plane.

4.3.2 Isolation-measures model

The isolation-measures model is shown in Fig.4. As shown in Fig.4, the buffer material is arranged around the structure including the bottom. The thickness of buffer material around sidewall is 0.5 m, and at the base of structure is 1.5 m.

4.4 Physical property values for analysis

The physical property values of the structure and the buffer material are shown in Table 2. The physical property values of ground are shown in Table 3. The value of shear modulus of structure was assumed to be high, assuming that the structure behaves as a rigid body. As for the ground, it was assumed that the shear wave velocity is 90 m/s and 330 m/s. The physical property values of joint element were assumed as shown in Table 4.

Table 2 – Property values of structure and buffer material

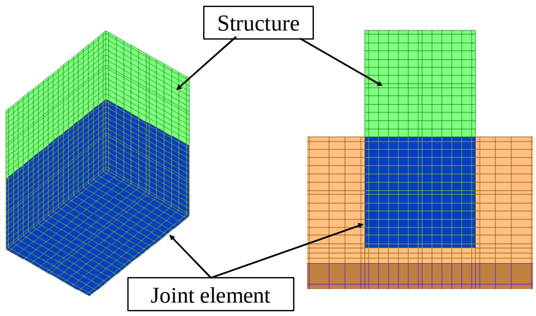
Item	Shear modulus (N/mm^2)	Density (t/m^3)	Poison's ratio	Note
Structure	14600	2.4	0.2	RC
Buffer material	0.24	1.0	0.49	

Table 3 – Property values of ground

Item	Layer thickness (m)	Shear modulus (N/mm^2)	Density (t/m^3)	Poison's ratio
Surface layer	15.4	16	2.0	0.4
Basement	14.6	240	2.3	0.35

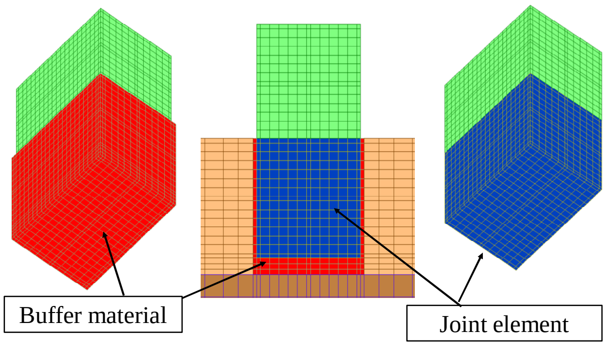
Table 4 – Property values of joint element

Item	Stiffness (N/mm^2)		Tensile strength (N/mm^2)	Shear strength (N/mm^2)
	Normal modulus	Shear modulus		
Contact plane	35040	14600	0.1	0.1



◆Non-liner behavior (opening, sliding) between structure and ground is considered by arranging joint elements.

Fig. 3 – Non-measures model



◆Buffer material is placed around structure (both side and bottom)
◆Joint elements are placed on the contact plane between structure and buffer material

Fig. 4 – Isolation-measures model

4.5 Tsunami wave pressure

For evaluating the tsunami isolation effect, the magnitude of the tsunami wave pressure was set to be 400 kPa based on the results of previous study by the SPH method [4]. As shown in Fig.5, the distribution in the vertical direction was assumed to be rectangle. The wave pressure of tsunami was acted as static uniform load on the front wall of structure, where the width is 20 m and the height is 0 m to 6.5 m.

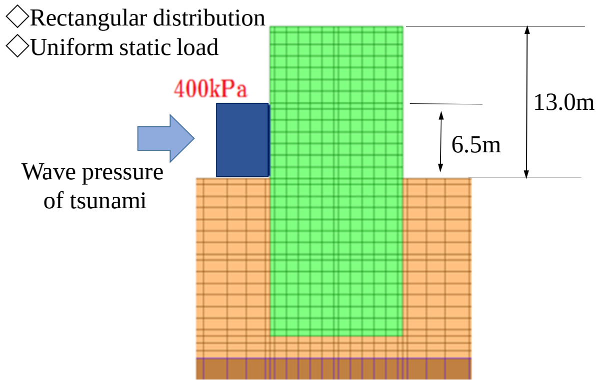


Fig. 5 – Value and distribution shape of tsunami wave pressure

4.6 Analysis results on tsunami isolation effect

4.6.1 Displacement of structure by tsunami wave pressure

The comparison of analysis results between the non-measures model and the isolation-measures model in regard to the distribution of displacement of structure is shown in Fig.6. The values at representative output positions are shown in Table 5, and the representative output positions are shown in Fig.7.

The maximum displacement of structure by the non-measures model and by the isolation-measures model was 4.52 cm and 19.41 cm, respectively. The intention of seismic-tsunami isolation constitution is to make it easy for the structure to rotate and translate. The intended results were obtained by 3-D analysis.

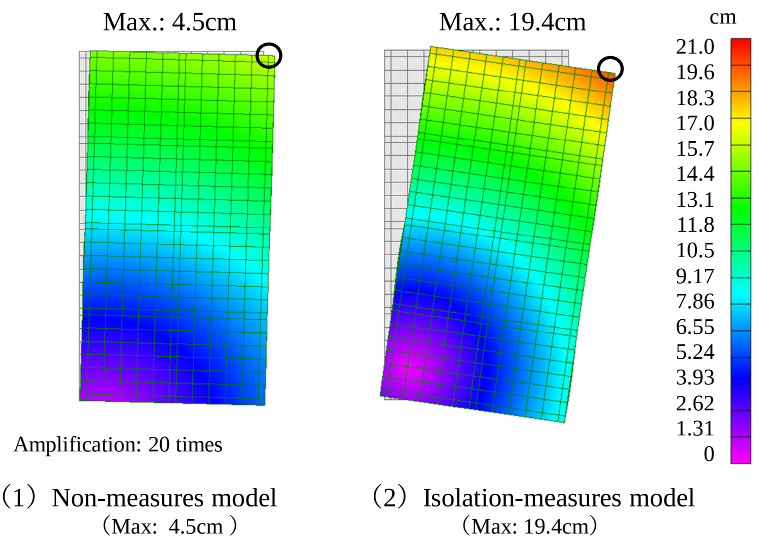


Fig. 6 – Disrtibution of maximum displacement of structure

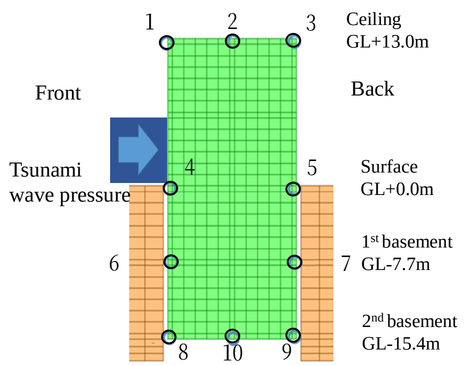


Fig. 7 – Representative output positions for displacement of structure

Table 5 – Comparison of maximum displacement of structure

No.	Position	Non-measures model (cm)	Isolation-measures model (cm)
1	Ceiling・front	4.20	17.46
2	Ceiling・center	4.26	17.80
3	Ceiling・back	4.52	19.41
4	Surface・front	2.29	8.00
5	Surface・back	2.84	11.64
6	1st basement・front	1.29	3.36
7	1st basement・back	2.09	9.06
8	Bottom・front	0.41	1.92
9	Bottom・center	1.66	8.60
10	Bottom・back	0.81	3.93

4.6.2 Stresses in the structure due to tsunami wave pressure

The comparison of the analysis results by the non-measures model and by the isolation-measures model for the stress in the structure due to the tsunami wave pressure is shown in Fig.8. The values at representative output positions are shown in Table 6. The representative output positions are shown in Fig.9. At position 17 (front of the structure, G.L.0m), the maximum tensile stress was 3.67 N/mm^2 by the non-measures model and 2.81 N/mm^2 by the isolation-measures model. At position 15 (front of the structure, G.L. + 6.50m), the maximum tensile stress was 3.51 N/mm^2 for the non-measures model and 3.58 N/mm^2 for the isolation-measures model.

At the front of structure, when the tsunami acts, the tensile stresses tend to become smaller by the isolation-measures model than by the non-measures model due to the rotation of the structure. At the bottom and side of structure, the shear stresses tend to become larger by the isolation-measures model than by the non-measures model. However, the values of stress is relatively small at the bottom and the side wall of structure. So, it will be important to pay attention to the front wall of structure when verifying the damage and destruction of structure.

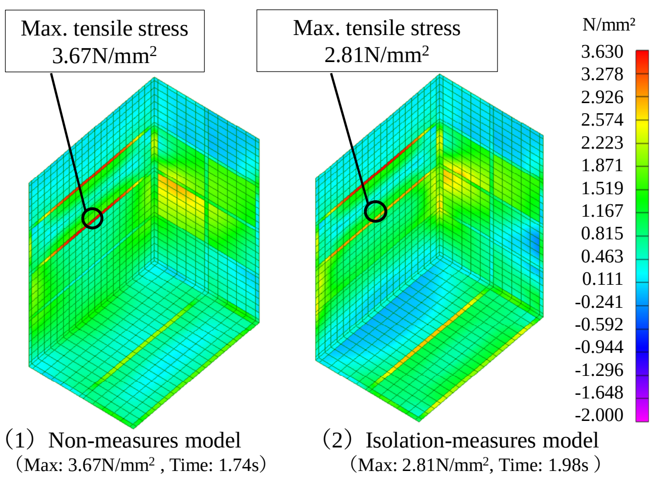


Fig. 8 – Distribution of maximum tensile stress in structure

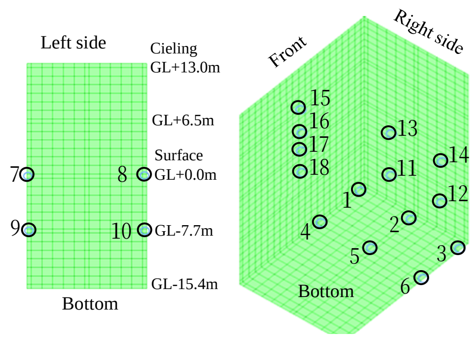


Fig. 9 – Representative output position for maximum principal stress

Table 6 – Comparison of maximum tensile stress in structure

No.	Position	Non-measures model (N/mm^2)	Isolation-measures model (N/mm^2)
1	Bottom・right side・front	0.26	0.17
2	Bottom・right side・center	0.69	1.53
3	Bottom・right side・back	1.22	1.51
4	Bottom・middle・front	1.27	0.39
5	Bottom・middle・center	2.09	2.75
6	Bottom・middle・back	1.80	2.02
7	Surface・left side・front	0.50	1.62
8	Surface・left side・back	0.08	0.14
9	1st basement・left side・front	1.68	2.71
10	1st basement・left side・back	0.09	0.06
11	Right side・GL-11.5m・ front	0.64	0.97
12	Right side・GL-11.5m・back	0.47	0.77
13	Right side・GL-3.0m・ front	2.26	1.63
14	Right side・GL-3.0m・back	1.27	0.03
15	Front・center・GL+6.5m	3.51	3.58
16	Front・center・GL+3.0m	0.47	0.17
17	Front・center・GL+0.0m	3.67	2.81
18	Front・center・GL-3.8m	0.58	0.90

4.6.3 Consideration

In regard to the displacement behavior against tsunami, it was confirmed that the rotation and translation of structure easily generated by disposing the buffer material. Regarding the stresses caused by tsunami, the stresses slightly increased on the side wall and the bottom of structure with the rotation. However, the stresses in the front wall of structure reduced. The stress values were relatively small at the bottom and the side wall, but large at the front wall. Therefore, attention should be payed to the front wall of structure when verifying the damage and destruction of structure.

5. Conclusions

◆In order to develop a rational countermeasures against both earthquake and tsunami for the land structures in coastal area, we have studied and proposed “a seismic-tsunami isolation constitution”,

◆Fundamental concept of the proposed method is not “earthquake resistance nor tsunami resistance” but “seismic isolation and tsunami isolation”. Avoidance, seclusion, reduction, isolation are the fundamental conception of this study.

◆Main feature of this constitution is to realize seismic isolation effect and tsunami isolation effect simultaneously by same thought and same way.

◆In this constitution, the buffer material with low rigidity is interposed around the structure. And, the structure can easily rotate and translate when the earthquake and the tsunami act.

◆Effectiveness of the seismic-tsunami isolation constitution was checked by 3-D FEM analyses by setting two analysis models, one is the non-measures model and another is the seismic-tsunami isolation-measures model.

◆As the results of 3-D FEM analyses, it was confirmed that the displacement behavior of structure could be easily occurred by arranging the buffer material around the structure. And, it was also confirmed that the stress caused in the structure could be reduced, as we expected.

◆The buffer material plays a role of seismic isolation material against strong earthquake motion, and tsunami isolation material against tsunami wave pressure.

◆The seismic-tsunami isolation constitution is useful for reducing the stresses in the structure caused by earthquake and tsunami, preventing the dameges by erathquake and tsunami, improving the safety of structure.

◆For future issues, the effect of shape of distribution of tsunami wave pressure, the effect of incidence angle of tsunami to the structure, the effect of shape of outside of structure, the effect of rigidity of buffer material can be mentioned.

6. Acknowledgements

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7. References

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