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# EARTHQUAKE RESPONSE OF HEAT EXCHANGER BUILDING IN UNIT NO. 3 OF ONAGAWA NUCLEAR POWER PLANT

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## ABSTRACT

Seawater heat exchanger building in Unit No. 3 of Onagawa are fully embedded in the ground, and the analysis of earthquake observation records indicates that the building has a feature where the earthquake amplification of the building is extremely low. Studies so far performed made it known that the reproduction of the observed records is difficult in a lumped mass system in which the embedding effect was expressed using lateral soil springs.

Therefore, a model that is a combination of a three-dimensional ground model and a lumped mass system building model was generated to perform the simulation analysis of the Sanriku Offshore Earthquake (hereafter referred to as the “3.9 Earthquake”) that occurred on March 9, 2011 immediately before the 2011 Great East Japan Earthquake (hereafter referred to as the “3.11 Earthquake”). As a result, it was found that the response at the upper part of the building is restrained by the vibration of the surface layer of the ground in an opposite phase to the building in the vicinity of the primary natural frequency of the building because the frequency of the primary mode of the building is close to that of the secondary mode of the surface layer of the ground. In addition, it was also recognized that the primary dominant frequency of the transfer function in the building portion is shifted to the lower frequency by approximately 10%, due to the embedding effect.

Then, the stiffness of the building at the 3.11 Earthquake was studied. When the interaction between the building and the ground is not considered, it is necessary to reduce the stiffness of the building to 0.8 times from design stiffness in order to make the primary dominant frequency conform to the observation record of the 3.11 Earthquake. It was found that, when the embedding effect is considered, the model with the design stiffness of the building mostly corresponds to the primary dominant frequency of the observation record.

Moreover, a simulation analysis of the April 7, 2011, Miyagi Offshore Earthquake (hereafter referred to as the “4.7 Earthquake”) that is the largest aftershock occurred 27 days after the 3.11 Earthquake was performed to study the influence of the 3.11 Earthquake on the degradation of the stiffness of the ground. The simulation results of the sequential analyses of the 3.11 Earthquake and the 4.7 Earthquake to which the stiffness degradation of the surface layer of the ground due to the 3.11 Earthquake was considered, and those of an independent analysis in which only the 4.7 Earthquake was considered on an initial ground model were compared to obtain the result that the independent analysis corresponds to the observation record better than the sequential one. Therefore, it was evaluated that the influence of the stiffness degradation of the ground due to the 3.11 Earthquake was relatively small at the time of the 4.7 Earthquake.

## INTRODUCTION

Since the seawater heat exchanger building in Unit No. 3 of Onagawa are fully embedded in the ground, the building shows a particular vibration characteristics in which an amplification factor (roof/foundation) in the observation is restrained. Although it seems as if the apparent response suggests high damping in the building, and the value replaced as equivalent material damping corresponds to 20%, it is difficult to explain using a general damping model.

In the previous report,1) analytical studies of the March 9, 2011, Sanriku Offshore Earthquake and the March 11, 2011, Great East Japan Earthquake (hereafter referred to as the “3.9 Earthquake” and “3.11 Earthquake,” respectively) were performed, and the cause of the behavior in which the amplitude of the building is restrained was evaluated that the vibrations of the upper section of the building and the upper zone of the surface layer of the ground in opposite phases in the vicinity of the primary natural frequency restrain the response of the building because the frequency of the primary mode of the building is close to that of the secondary mode of the surface layer of the ground. In this paper, the April 7, 2011, Miyagi Offshore Earthquake (“4.7 Earthquake”) that is the largest aftershock is added to the object to be studied, and an analysis model that incorporated the latest results of the ground investigation and the data of ground excavation situation during construction is incorporated to perform a response simulation analysis of each earthquake and an influence evaluation of the interaction between the building and the ground. The results are shown below.

## CHARACTERISTICS OF GROUND AND BUILDING AND ANALYSIS CONDITIONS

The seawater heat exchanger building in Unit No. 3 of Onagawa is a structure of which whole sections are embedded in the ground. Its plan view and sectional view are shown in Figure 1. The plan is approximately 40 m square and the depth is 27.3 m. The bottom of foundation is in contact with hard bedrock, and the side ground is backfilled by excavated rock after excavating the surface layer of the ground (approximately Vs = 900 m/s). Vs of backfill was set based on the latest result of the ground investigation as Vs = 90 – 420 m/sec as shown in Figure 2.

The detail (sectional view) of the building section of the analysis model and the overview of the model are shown in Figures 3 and 4, respectively. As shown in Figure 3, the building section was expressed by bending shear elements and lumped mass, and the side and bottom grounds were expressed with a three-dimensional finite element model consisting of solid elements. All the surface layers of the ground were expressed by backfill based on the ground characteristics described in the document prepared for construction. The model was assumed to be 1/2 symmetrical and the horizontal area of 200 m × 100 m and the depth of 90 m were simulated. Simulation region was set to secure the ground region with a length about twice the side lengths of the building around the building considering the range of the ground influenced by the building response. In addition, since the plan of the building is nearly square, the difference of response property in the X- and Y-directions and the influence of twisting response were judged small. Thus, a symmetrical model was adopted. As for the element size of the ground, the ground was decided to have approximately 29,000 elements by assuming transmission frequency as 20 Hz or more and by vertically dividing into elements considering the consistency with the lumped mass positions in the building. The ground of the sides of the building is restrained by linking horizontal (or rotational) degree-of-freedom with a building lumped mass system. The boundary condition around the ground was assumed to be a viscous boundary for both the sides and the bottom. Sequential nonlinear analysis based on the three-dimensional FEM program was used.

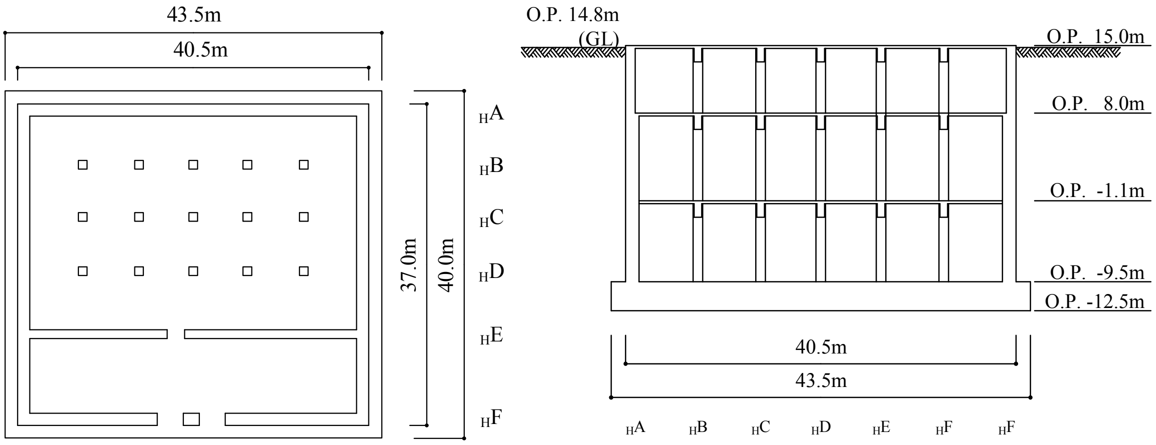


Figure 1. Plan view of the third floor of basement (left) and sectional view (right) of seawater heat exchanger building

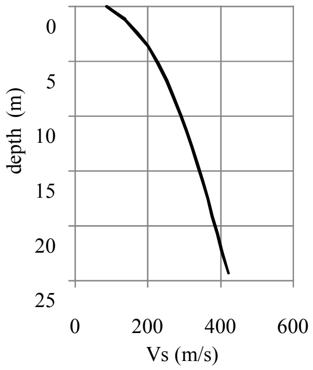


Figure 2. Vs profile of backfill

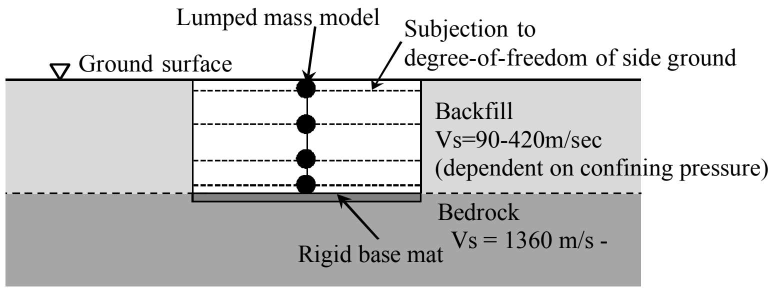


Figure 3. Overview of model (sectional view)

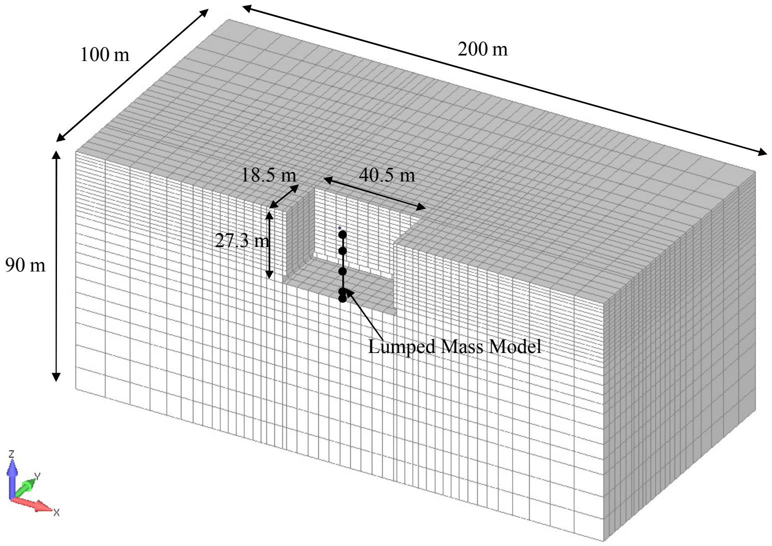


Figure 4. Model view

Although the building is a reduced model of a lumped mass system, the degree-of-freedom of the node of the side ground of the building was subjected to the node of a building lumped mass system at a level the same as the ground concerned because the influence of the external wall surface of the building on the peripheral ground is simulated as shown in Fig. **5**. This gives a stiffness equivalent to that of the building lumped mass system to the external wall surface. At this time, the following two cases of restrained conditions are compared:

- Only horizontal displacement of the ground is subjected to the building
- Both horizontal displacement and rotation of the ground are subjected to the building

Simulation analyses of both cases are performed to compare them in order to find the most appropriate restriction conditions of the building and the side ground.

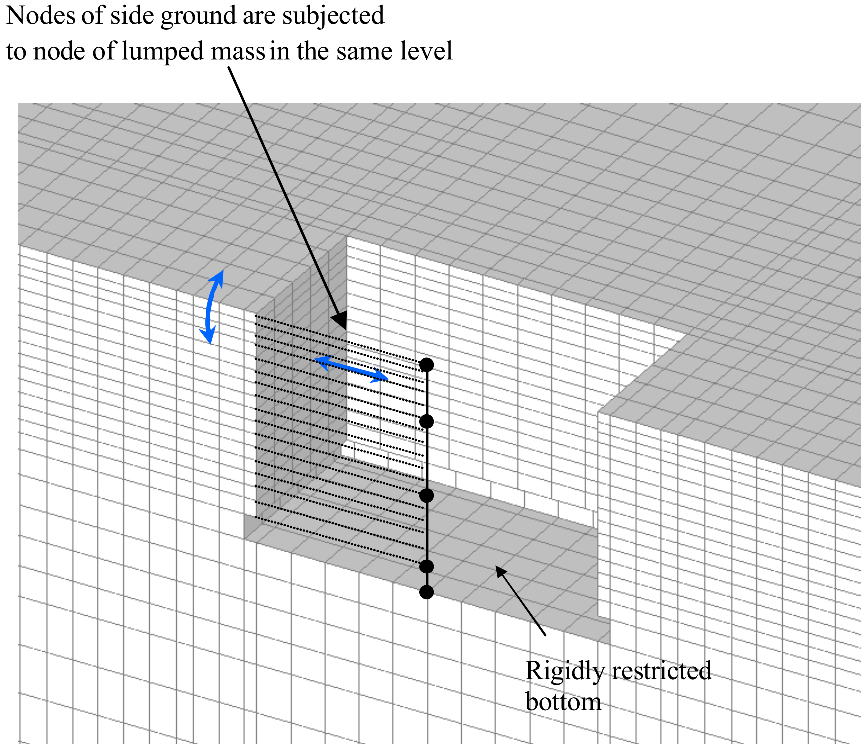
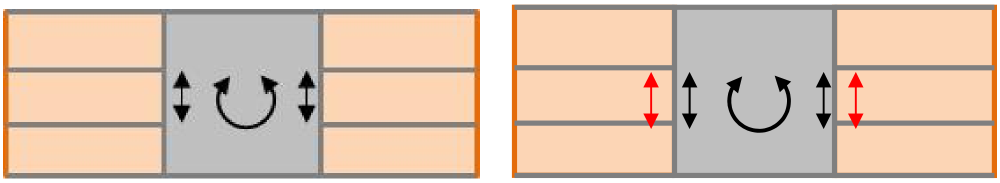


Figure 5. Restrained condition of building side ground

A simulation analysis of the observation record of the 3.9 Earthquake is performed to study the most appropriate restrained condition of the building and the side ground. Here the influence in case of the vertical degree-of-freedom of the side ground subjected to the rotational degree-of-freedom of the building and in case of the former not subjected to the latter as shown in Figure 6 was compared. As shown in Figure 7, the vertical degree-of-freedom of the side ground subjected to the rotational degree-of-freedom of the building eliminates the valley of 7 Hz of the analysis result and improves the matching degree of a transfer function. The model taking the vertical interaction of the side ground into consideration is thought to be the model closer to the actual behavior of the building. In the analyses hereafter, the model in which the vertical degree-of-freedom of the side ground is subjected to the rotational degree-of-freedom of the building is adopted.



Without subjection With subjection

Figure 6. Concept of side ground subjected to vertical degree-of-freedom

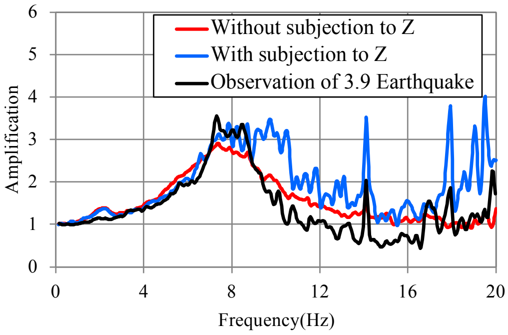


Figure **7.** Influence of side ground subjected to vertical degree-of-freedom

In the observation record, the NS direction is used for each of the 3.9 Earthquake, 3.11 Earthquake, and 4.7 Earthquake. In order to consider the contact of the building side with the ground, the horizontal and rotational degrees-of-freedom of the side ground was subjected to the building lumped mass. As shown in Table 1, the Rayleigh damping of 3% of a type proportional to the initial stiffness as material damping was given to the ground and the building. The building was assumed to be linear because it is within the elastic range and given design stiffness. Nonlinear characteristics of the ground were simulated with an HD model. The response spectrum of the observation record for the building foundation shown in Fig. 8 shows that the 4.7 Earthquake is in the amplitude level close to that of the 3.11 Earthquake. Input wave 2E to the model bottom was estimated by performing convergent calculation2) so that the response of foundation in the analysis result matches the above observation records (E+F).

Analysis cases are shown in Table 2. The influence of the existence of the ground interaction on the building response was evaluated in detail in the analysis of the 3.9 Earthquake as described later. As for the 3.11 Earthquake, the influence in case of assuming the stiffness reduction of the building was evaluated. As for 4.7 Earthquake, the influence of the non-linearization of the ground during the 3.11 Earthquake on the subsequent 4.7 Earthquake was evaluated.

Table 1: Setting for analyses (damping and input wave)

| | |
|---|---|
| Damping | Ground and building: Type proportional to initial stiffness<br>Rayleigh damping of 3% of type proportional to initial stiffness at frequency of 4 Hz and 8 Hz |
| Input waves | - NS direction in March 9, 2011, 11:45 Sanriku Offshore Earthquake<br>Main quake for 40 sec<br>- NS direction in March 11, 2011, 14:56 Great East Japan Earthquake<br>Main quake for 40 sec<br>(4.7 sequential analyses include subsequent earthquake)<br>- NS direction in April 7, 2011, 23:32 Miyagi Offshore Earthquake<br>Main quake for 40 sec |

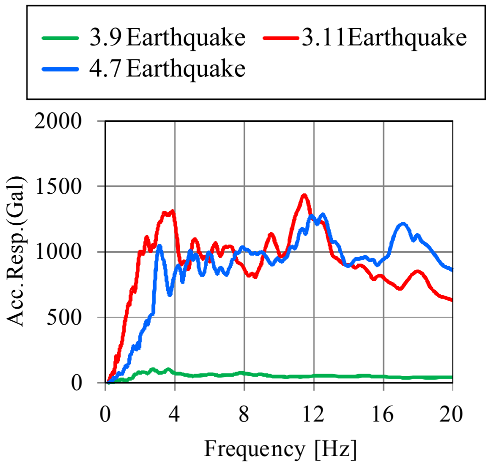


Figure 8. Acceleration response spectrum of observation record for foundation (h = 5%)

Table 2: Cases of analysis

| Input earthquake | Surface layer of ground | Stiffness of building | Interaction of building side |
|---|---|---|---|
| 3.9 Earthquake | Linear | Design stiffness | Considered |
| 3.9 Earthquake | | | Not considered |
| 3.11 Earthquake | Nonlinear | | Considered |
| 3.11 Earthquake | | Design stiffness × 0.8 | |
| 4.7 Earthquake (independent) | | Design stiffness | |
| 3.11 and 4.7 Earthquakes (sequential) | | | |

## SIMULATION ANALYSIS

First, the analysis of the 3.9 Earthquake was performed. A comparison of the transfer function (upper section/foundation) of the building in the analysis result with the observation record is shown in Figure 9. Focusing on the peak of approximate 8 Hz, the predominant frequency of the building, shows that the analysis results correspond to the observation record both in amplitude and frequency. The peak of 3 Hz in the analysis record is a little lower in frequency than the peak of 4 Hz in the observation record. Although this peak frequency is considered to correspond to the primary frequency of backfill, the difference of the tendency in the NS and EW direction is already known. Therefore, this phenomenon cannot be explained by pure parallel layered ground, and the possibility that the frequency is affected by the neighboring building is considered.

In order to study the basic vibration mode between the ground and the building, a stationary sine wave of 8 Hz was entered. A snapshot of the deformation view is shown in Figure 10. The secondary mode of the ground and the primary mode of the building are linked mostly in the opposite phase. This study reviewed the property of the ground and found the vibration property almost similar to that of the previous report.

In addition, in order to evaluate the influence of the interaction of the ground at the building side on the building response, the response was evaluated by removing the dependence condition of the ground and the building side. Comparison of this and the aforementioned simulation analysis (case with interaction) is shown in Figure 11. In the case of no interaction, the response of the building is amplified by about 20 times, and this fact shows that the existence of the interaction significantly affects the response. Furthermore, in terms of frequency, the absence of the interaction results in a peak frequency of approximately 9 Hz, allowing the natural frequency of the building to appear. On the other hand, the presence of the ground interaction allows the peak frequency to be approximately 8 Hz. The reduction of frequency by 10% corresponds to the reduction of about 20% according to rough conversion to stiffness. This means that the influence of the side ground and the stiffness itself of the building does not change. This influence should be noted in the analysis of the observation record.

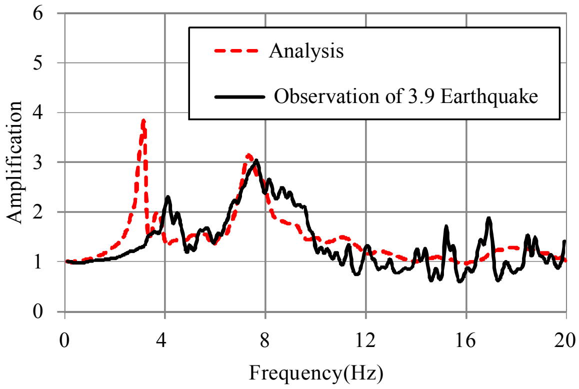


Figure 9. Transfer function of building during 3.9 Earthquake (upper section/foundation)

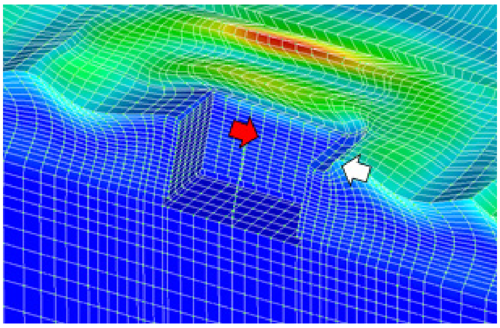


Figure 10. Deformation of ground and building when sine wave of 8 Hz is entered

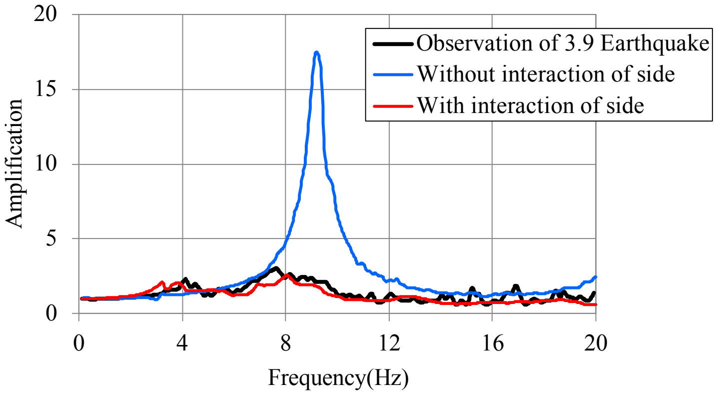


Figure 11. Influence of interaction of side ground on response
(3.9 Earthquake) Comparison of influence of dependence condition of side ground

Second, sequential nonlinear analysis of the 3.11 Earthquake was performed. In order to study the influence of the stiffness of the building, a comparison of the design stiffness for the building in case the building stiffness is assumed similarly to the aforementioned 3.9 Earthquake and in case the design stiffness is reduced to 0.8 times is shown in Figure 12. In the case of assuming the building stiffness as the design stiffness, the peak frequency and amplitude of the analysis results mostly correspond to the observation record. On the other hand, when the building stiffness is reduced to 0.8 times, the amplitude and peak frequency are excessively smaller than those in the observation record, that is to say, they do not correspond. Since no cracks due to the earthquake were observed in this building in the inspection investigation after the actual earthquake, it is thought that stiffness degradation due to crack generation did not occur.

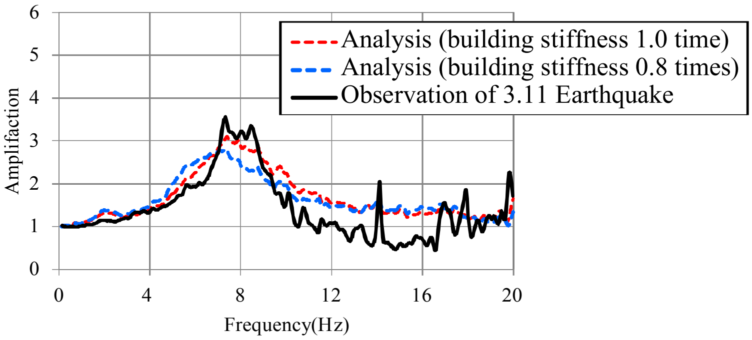


Figure 12. Transfer function of building during 3.11 Earthquake and influence of building stiffness

Last, sequential nonlinear analysis of the 4.7 Earthquake is performed. Comparison of the transfer functions in the case of the independent analysis of only the 4.7 Earthquake and in case of the analysis using continuous waveform of the 3.11 and 4.7 Earthquakes is shown in Figure 13. Here the transfer function of only the main quake portion of the 4.7 Earthquake is evaluated in the sequential analysis so as to compare the independent analysis. The sequential analysis showed a little larger amplitude, and the non-linearization of the ground is considered to have reduced the restrain effect of the ground. However, the difference between the independent and sequential analyses is relatively small. The sequential analysis does not necessarily improve the consistency with the observation record, and it cannot be judged that the stiffness reduction of the surface layer of the ground due to the 3.11 Earthquake exerted an influence.

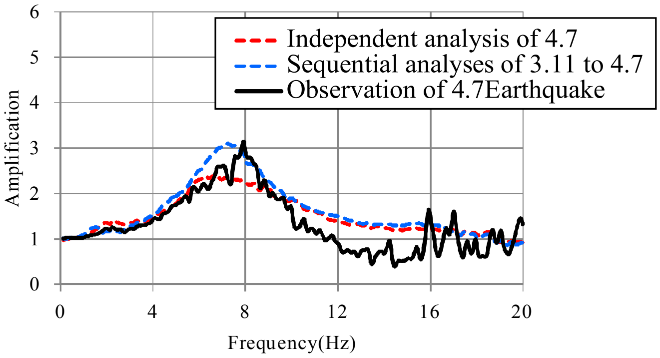


Figure 13. Transfer function of building (sequential analyses of 4.7 and 3.11 Earthquakes)
Comparison of main quake portions of 4.7 Earthquake

## STUDY OF INFLUENCE OF SEPARATION OF SIDE GROUND

There is a possibility that separation of the ground at the building side occurred during the 3.11 Earthquake. Therefore, double-nodes and joint elements were set at the node of the building side as shown in Figure 14 to perform the separation analysis. The study is performed by assuming internal viscous damping at each section and assuming the damping of the joint element as zero so as not to allow the damping of the joint element to affect the evaluation result.

Moreover, although the study so far performed used the Rayleigh damping, it is not used this time because the damping proportional to mass always works in the Rayleigh damping without being related to whether separation occurred or not. Although the condition is different from that in the case of the Rayleigh damping, it is considered not to arise as a problem because the purpose is to evaluate the qualitative influence caused by separation.

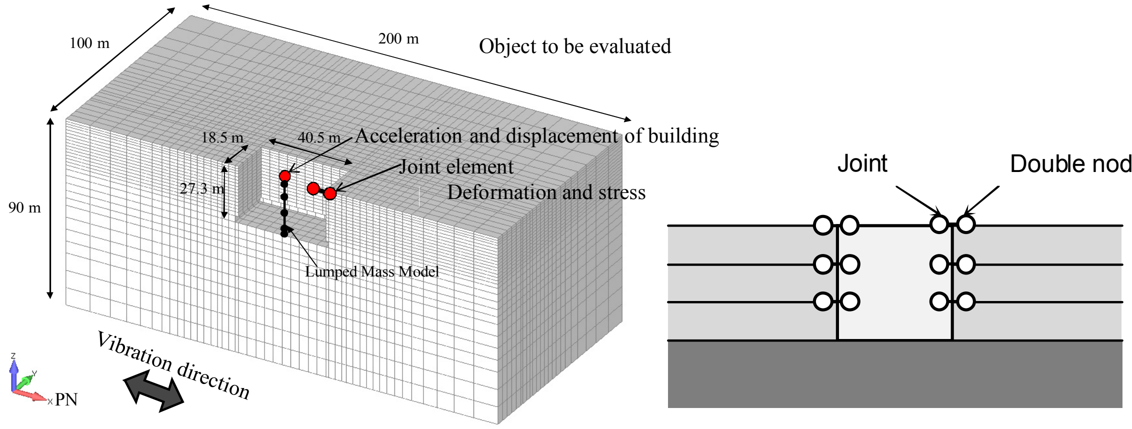


Figure 14. Model view and joint elements

The outline of the analysis conditions is shown in Table 3. Both adhesion and separation were assumed to have the same damping condition. However, the separation analysis adopted shorter time intervals in order to stabilize the numerical values for impact force.

Table 3: Cases of analysis

| | Damping type | Damping of ground (4Hz) | Damping of building (8Hz) | Damping of joint | Time interval |
|---|---|---|---|---|---|
| Contact | Proportional to initial stiffness, each part by internal viscous damping | 3% | 3% | — | 0.01 sec |
| Separation | | 3% | 3% | 0% | 0.001 sec |

The results of the evaluation of the transfer function and the comparison with the observation record are shown in Figure 15. When considering separation, a high response is found in the high frequency region of the transfer function, and the degree of matching with the observation record drops. Therefore, it is difficult to consider any influence from the building and the side ground during the 3.11 Earthquake.

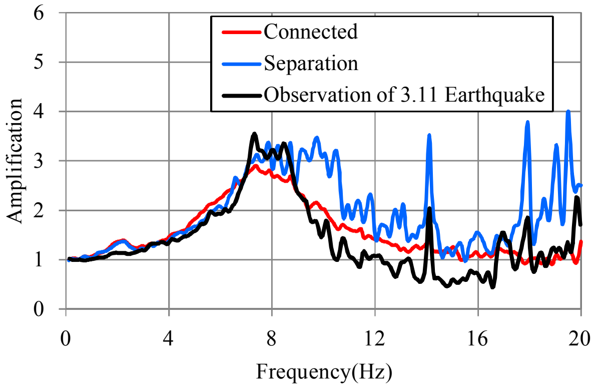


Figure 15. Comparison of transfer functions of building (contact and separation)

## CONCLUSION

Based on the ground property obtained from the latest results of the geological investigation, earthquake response analyses of the seawater heat exchanger building in Unit No. 3 of Onagawa for the 3.9, 3.11, and 4.7 Earthquakes were performed to study the reproducibility of the transfer function of the upper section of the building from a foundation. A study of 3.9 Earthquake, an earthquake with small amplitude, showed that the primary peak frequency of the transfer function of the building shifts to the lower frequency apparently by considering the influence of the side ground. In addition, the result that the model in which the vertical degree-of-freedom of the side ground is subjected to the rotational degree-of-freedom of the building as restraint conditions of the building and the side ground shows that better reproducibility of the observation record was obtained.

Since the analysis of even the 3.11 Earthquake with high amplitude also shows that the peak frequency corresponds to the observation record in a design stiffness model, it is thought that the stiffness of the building was not reduced even in the 3.11 Earthquake. The results of the sequential input analysis of the 3.11 Earthquake and 4.7 Earthquake, the largest aftershock, allow an estimate of the influence of the stiffness reduction of the ground due to the 3.11 Earthquake on the ground during the 4.7 Earthquake as relatively small.

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