Dynamic Soil-Structure Interaction of a Building Supported by Piled Raft and Ground Improvement During the 2011 Tohoku Earthquake

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SUMMARY
Recently, in an increasing number of cases, the grid-form ground improvement against liquefaction was used for buildings. However, the dynamic soil-structure interaction of a building with ground improvement has not become clear. We collect many earthquake observation records including the 2011 off the pacific coast of Tohoku earthquake at a base-isolated building with the ground improvement. In this paper, we studied the dynamic soil-structure interaction of the building. First, the records were analyzed concerning the soil-structure interaction. Then, the earthquake response analysis was conducted to simulate the record using a detailed three dimensional finite element model. By the analysis, the input loss effect was confirmed. Moreover, the contribution of the grid-form ground improvement to the input loss was estimated.

Keywords: The 2011 off the pacific coast of Tohoku earthquake, soil - structure interaction, grid-form ground improvement

1. INTRODUCTION

In recent years, it has become apparent that in some cases ground improvement has been used instead of piles even for the support of large-scale buildings, such as thermal power generation plants. Moreover, in an increasing number of cases, a grid-form ground improvement with a piled foundation is implemented as a countermeasure for liquefaction. The ground improvement is implemented by the deep mixing method using cement-type solidification materials and improved ground with a higher stiffness compared to original ground is created. This improved ground is thought to lead to a dynamic soil-structure interaction effect and affecting the input motion to the building.

The authors have been conducting seismic observation at a twelve-story base-isolated building supported by piled rafts and a grid-form ground improvement in the Koto ward of Tokyo since the building was constructed (Tanikawa et al., 2011; Yamashita et al., 2011) and a large number of seismic responses were successfully recorded during many earthquakes including The 2011 off the pacific coast of Tohoku earthquake and the ensuing aftershocks. Observations of the ground and the building at this location have been conducted and because the effect of dynamic soil -structure interaction between the ground and the building when the grid-form ground improvement is provided has been clearly confirmed, this becomes the focal point of this paper. Furthermore, a three dimensional finite element model that models the ground, the piles, and the grid-form ground improvement in as much detail as possible has been created to conduct simulation analysis of the building response and analysis of the interaction effect.

2. OBSERVED BUIDING AND SEISMIC OBSERVATION SYSTEM

2.1. Overview of Building

The building is a twelve-story residential building located in the Koto ward in Tokyo. It is a reinforced concrete structure with a base isolation system and has an area of 33.25m x 30.05m and a height of 38.7 m above the ground surface. The base isolation system consists of 12 lead rubber bearings and 4 natural rubber bearings combined with rotational friction dampers and oil dampers. Figure 1 shows a schematic view of the building and the foundation with typical soil profiles.

The soil profile down to a depth of 7 m is made of fill and loose silty sand. Between depths of 7m to 44m, there lies a very-soft alluvial clay strata with N-values of 0 to 3, and the sand-and-gravel layer with N-values of 60 or higher appears at a depth of 44m or deeper.

The foundation is a piled raft foundation combined with a grid-form ground improvement. Figure 2 shows the layout of the piles and the grid-form ground improvement. The grid-form ground improvement method was employed for the loose silty sand layer between depths of 3m to 7m, which has a potential of liquefaction at a ground acceleration of 200cm/s^2. As a countermeasure for the liquefaction, a piled raft foundation was created by inserting sixteen 45m long bored precast concrete piles with diameters of 0.8 to 1.2m to reduce settlements. The ends of the piles reach the sand-and-gravel layer. The piled raft foundation design was described in detail in a paper (Yamashita et al., 2011)

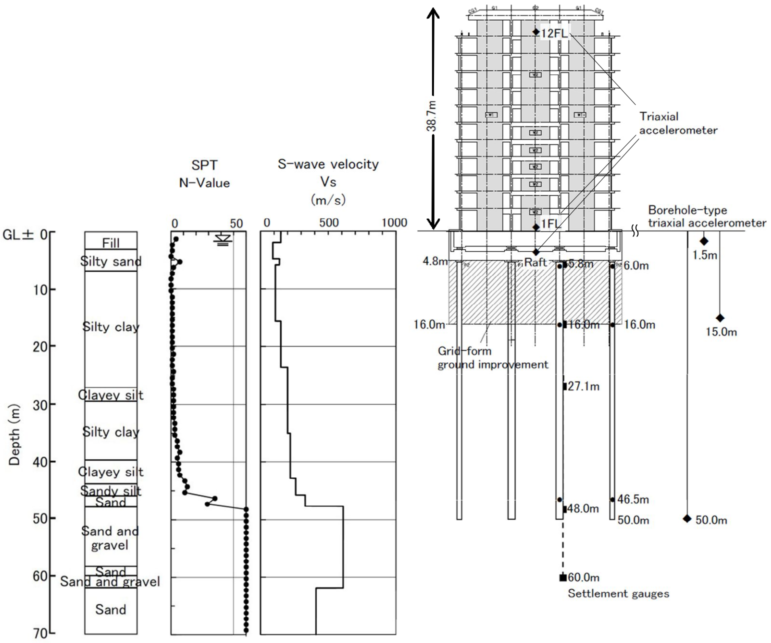


Figure 1. Schematic view of the building and foundation with soil profile

2.2. Overview of Seismic Observation

The seismic observation of the ground and the building was conducted at the same time as a long-term measurement of the load acting on the piled rafts and the grid-form ground improvement. Figure 1 shows the locations of the accelerometers. The measurements for the building were conducted at 3 levels: above the pit in which the base-isolation system was installed (below the base-isolation system), the first floor, and the twelfth floor. The measurements for the ground were conducted at 3 depths: the surface of the ground (depth of 1.5m) approximately 10m away from the building, a depth of 15m at the bottom of the grid-form ground improvement, and a depth of 50m at the end of the piles in the sand-and-gravel layer.

The accelerometer orientations were adjusted in line with the building, which is a slightly shift from the actual orientations. However, the orientations more or less correspond to north, south, east and west and therefore they are referred to as NS direction and EW direction hereinafter. The accelerometer orientations in the ground were also verified to confirm that these corresponded with the accelerometer orientation in the building with regard to the long-period components and the orientations of the underground observation points were corrected.

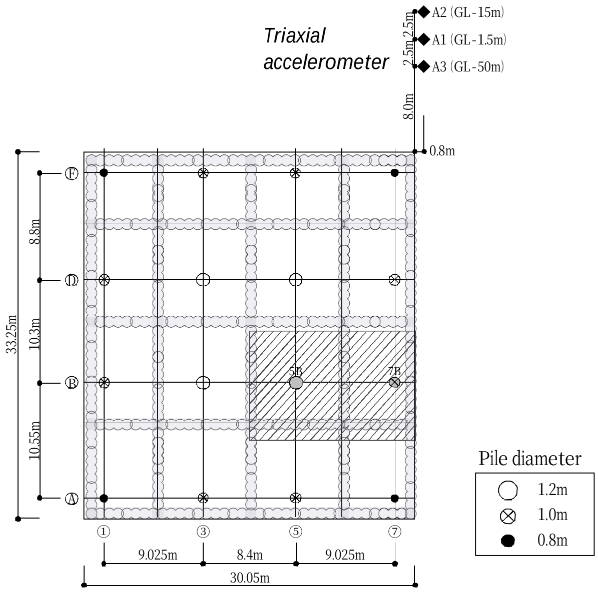


Figure 2. Layout of piles and grid-form ground improvement with locations of monitoring devices

3. STUDY OF OBSERVED SEISMIC RESPONSE

3.1. Seismic Records

During the 2011 off the Pacific coast of Tohoku earthquake, the seismic response was successfully recorded for 600 consecutive seconds. Figure 3 shows the time histories of the EW acceleration of the ground and the structure.

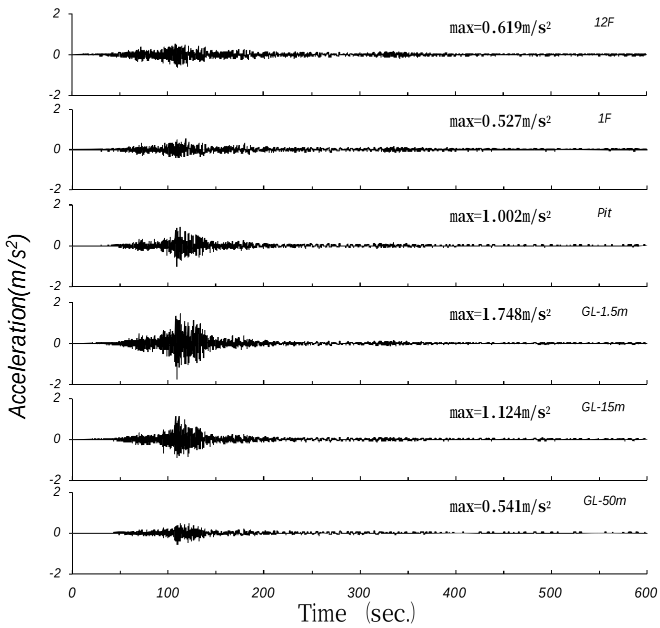


Figure 3. Time histories of EW acceleration during the 2011 off the Pacific coast of Tohoku earthquake

A lot of good seismic data was also gathered for the many aftershocks. Therefore, in the following study, the ground and building responses were studied using the 5 records with relatively high acceleration were chosen from the many observation records. Table 1 shows the earthquakes used in this study. The earthquake epicentre and magnitude data is based on earthquake data from the Japan Meteorological Agency as it is thought this data is relevant from the perspective of observation time and scale.

Because horizontal responses are important in an earthquake-resistant design, we focus NS direction and EW direction in this study and are going to examine vertical responses in the next step. Figure 4 shows the distribution of the peak acceleration. Excluding data from the main earthquake and the biggest aftershock, the peak acceleration on the ground surface was approximately 20cm/s^2, which indicates a small earthquake. Irrespective of the scale of the earthquake, there is a tendency for the ground surface (depth of 1.5m) acceleration to be amplified 2 to 3-fold to the bearing stratum (depth of 50m) acceleration.

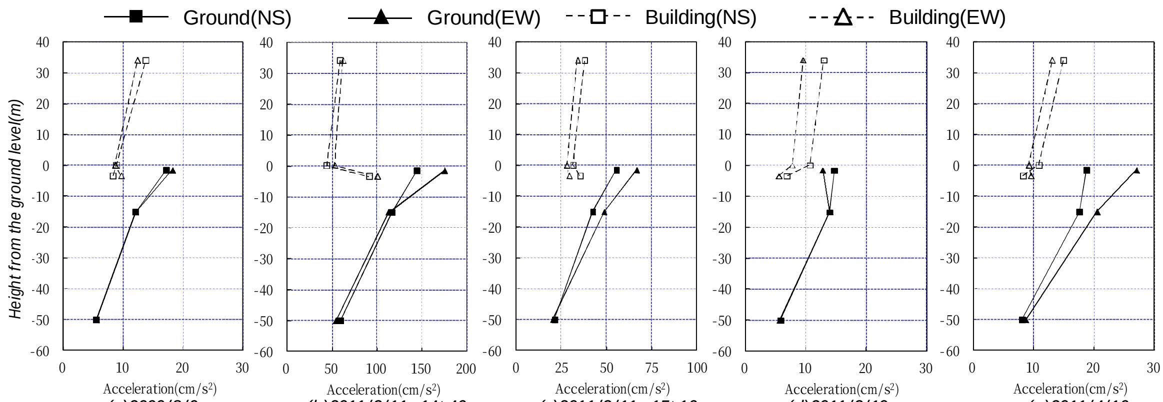
The building is a base-isolated building that uses lead rubber bearings, and a reduction in the acceleration due to the base-isolation system is rarely apparent during small earthquakes in which the lead plug does not yield. However, this base-isolation system functioned effectively during the main earthquake as the acceleration peak response value was reduced by approximately 1/2 compared with the base-isolation pit. Furthermore, the peak acceleration for the first floor and the twelfth floor above the base-isolation system exhibited almost the same value and the amplification of the superstructure was small.

Due to the fact the base-isolation pit is inserted to a depth of 4.8m and the grid-form ground improvement is provided to a depth of 15m, the acceleration above the base-isolation pit is considerably reduced compared with the ground surface, and is close to the response value of the ground at a depth of 15m or is a value even smaller than that.

As a result, it is confirmed that during the main earthquake the acceleration was reduced by approximately 40% compared with that of the ground surface due to the interaction effect and was reduced further to 1/2 due to the base isolation. Accordingly the peak acceleration of the building was 30% of that of the ground surface.

Table 1. List of earthquakes used in this study

Origin time	epicenter	Magnitude(Mj)	note
2009/ 8/ 9 19:55	South off Tokaido	6.8	
2011/ 3/11 14:46	Off the Pacific cost of tohoku	9.0	Main earthquake
2011/ 3/11 15:15	Off Ibaraki pref.	7.4	Biggest aftershock
2011/ 3/19 18:56	Northern Ibaraki pref.	6.1	
2011/ 4/16 11:19	Southern Ibaraki pref.	5.9	



(a)2009/8/9 (b)2011/3/11 14:46 (c)2011/3/11 15:16 (d)2011/3/19 (e)2011/4/16

Figure 4. Distribution of the peak acceleration for the ground and the building

3.2. Response Reduction on the Base-isolation Pit

We studied the relationship between the ground response and the base-isolation pit response. The high stiffness of the base-isolation pit compared to the ground and the grid-form ground improvement are thought to cause input loss, which is one of the typical dynamic soil - structure interaction effects.

In order to verify this point, the amplitude ratio of the acceleration response spectrum above the base-isolation pit to the ground surface is calculated and the results are shown in Figure 5. The ratio decreases considerably on the short period side. At 0.1 sec, the ratio becomes 0.4 to 0.6, showing a tendency for typical input loss. Moreover, this tendency is almost always the same irrespective of the scale of the earthquake.

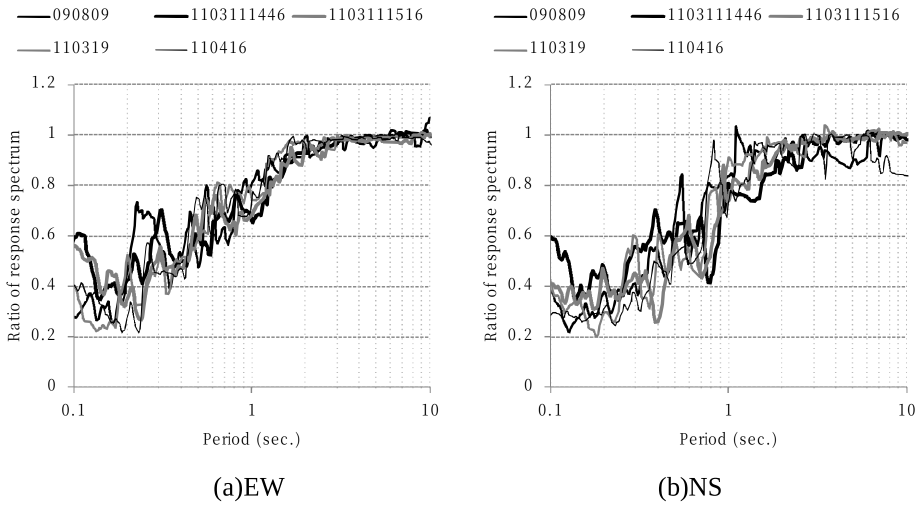


Figure 5. Ratio of the acceleration response spectrum above the base-isolation pit to the ground surface

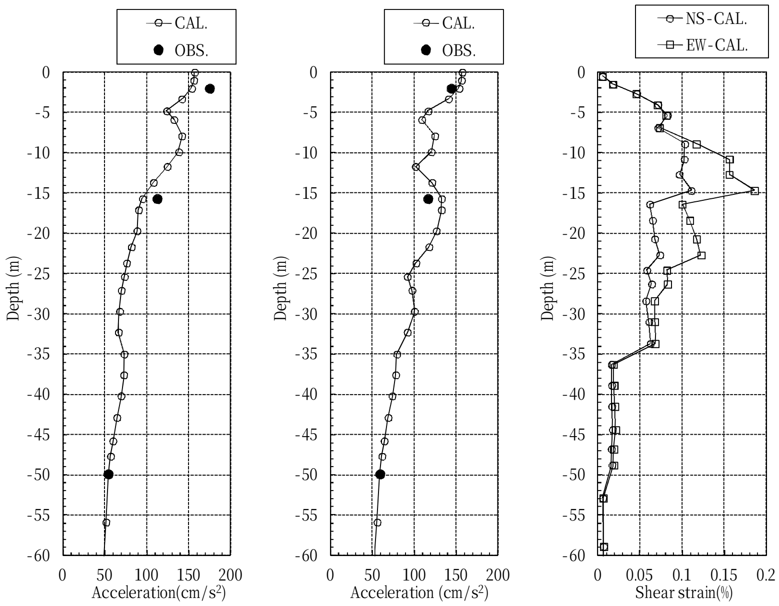
4. SIMULATION ANALYSIS OF THE OBSERVATION RECORDS

The observation records clearly confirm the interaction effect and therefore, with the aim of conducting detailed analysis, we modelled the ground, the piles and the grid-form improved ground in as much detail as possible using three dimensional finite element method (FEM) and conducted simulation analysis for the main earthquake. We focused horizontal components (NS direction and EW direction) in this simulation.

4.1. Ground Response Analysis

First, we conducted simulation analysis of the ground response during the main earthquake. Simulation analysis of the observation records was conducted using one-dimensional equivalent linear analysis with consideration of the strain characteristics of the ground. The G/Go-γ, h-γ relationship for each layer based on the soil investigation is applied.

The observation records for the deepest of the 3 depths, 50m, were used as the input when conducting the analysis. The peak values of the calculated results are shown in Figure 6 and the observed acceleration results were successfully simulated. Based on the calculated results, we found that the peak for the ground strain distribution is 0.2% and overall the distribution is almost 0.1%. In consideration of the ground strain level, the reduction in ground stiffness is relatively small.



(a)Acceleration EW (b) Acceleration NS (c) Shear strain

Figure 6. Distribution of peak values for the ground response

4.2. Response Analysis for the Ground, Foundation and Building

4.2.1. Creating the FEM model

Figure 7 shows the three dimensional FEM model created in this study. The total number of nods was 92187 and the total number of elements was 91258.

a) Modelling of ground

The reduction in ground stiffness is relatively small and therefore we used a linear analysis that employs equivalent stiffness and equivalent damping based on the one-dimensional equivalent linear analysis conducted for the ground response. Moreover, because the results for the one-dimensional equivalent linear analysis for NS direction were different from those for the EW direction, the results for EW direction, in which the ground shear strain was larger, was used for this analysis. The three dimensional model of the ground was modelled to 60m from the outside of the building in order to minimize the influence of the model boundary. North and south side boundaries are tied each other and east and west side boundaries are tied each other (cyclic boundary). A viscous boundary was used for the bottom surface.

b) Modelling of the piles and the grid-form ground improvement

The piles were modelled using beam elements and the grid-form ground improvement using shell elements. The stiffness of the grid-form ground improvement was set to Vs= 800m/s based on the design strength with reference to previous investigations.

c) Modelling of the base-isolation system

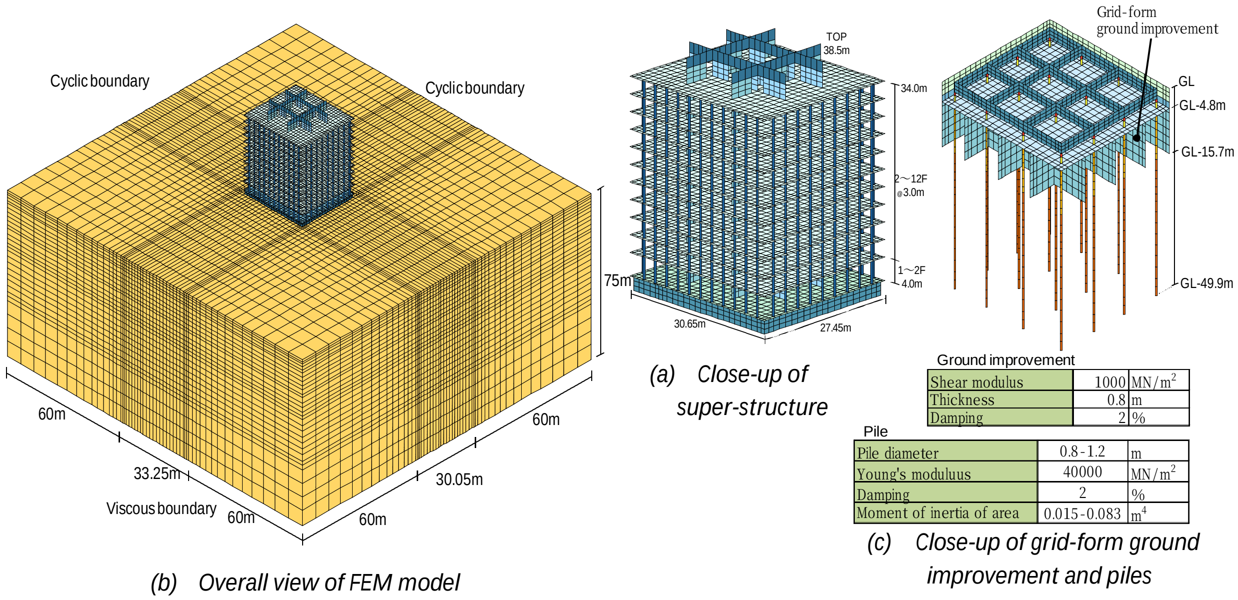
For the base-isolation system, the characteristics based on the specifications for each device that were determined at design were used without any changes, and these were modelled using bilinear-type spring elements.

d) Modelling of the building

In order to agree with the actual layout of the design drawing, the columns were modelled using beam elements and earthquake-resistant walls and the floors were modelled using shell elements. Moreover, because the building is unlikely to become non-linear at the seismic excitation level for the base isolation, linearity was applied for the material. We verified that the natural period when the first floor is fixed in the model almost corresponds to the actual measurements.

e) Input seismic motion

The upward transmitting wave at a depth of 75m, which was set as the bottom depth of the three dimensional FEM model, was calculated by the one-dimensional equivalent linear analysis and input for the bottom of the three dimensional model.



(a) Close-up of super-structure

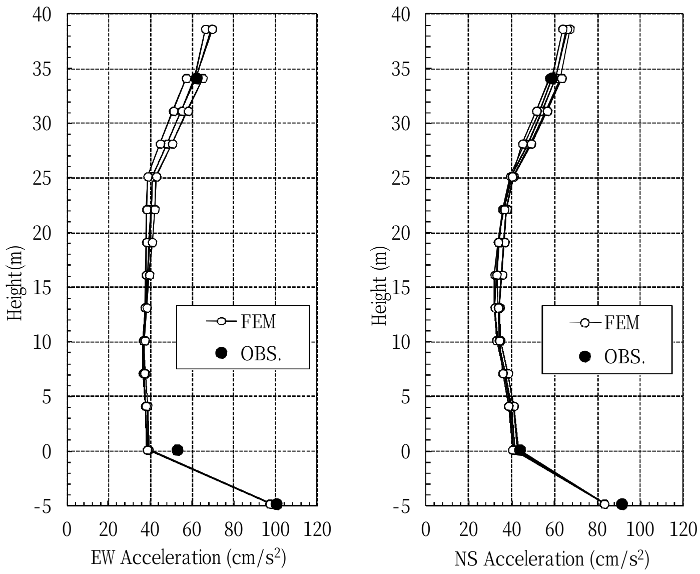
(b) Overall view of FEM model

(c) Close-up of grid-form ground improvement and piles

Figure 7. Three dimensional FEM model

4.2.2. Results of the simulation analysis

Figure 8 shows the analysis and observation correspondence for the building peak acceleration distribution. Figure 9 shows the analysis and observation correspondence for the acceleration response spectrum for the ground surface, above the base-isolation pit and the twelfth floor of the building. It was verified that they all correspond well. Figure 10 shows a comparison of the analysis and observations for the acceleration response spectrum ratio above the base-isolation pit to that for the ground surface. The observation results for the earthquakes and aftershocks other than the main earthquake were plotted together in Figure 5. The response reduction effect above the base-isolation pit as was observed was also successfully simulated in the analysis results.



(a) EW (b) NS

Figure 8. Comparison of the analysis and observations for the peak acceleration of the building

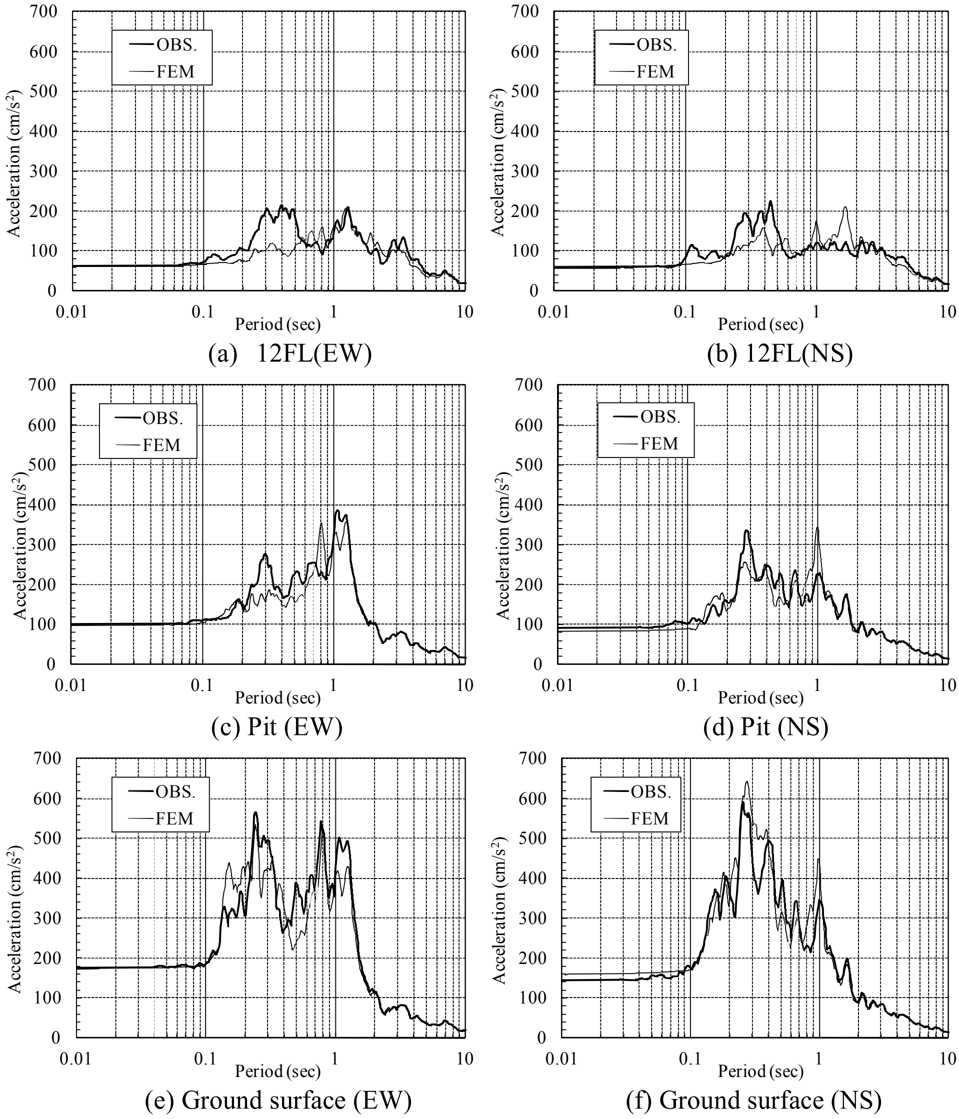


Figure 9. Comparison of the analysis and observations for the acceleration response spectrum

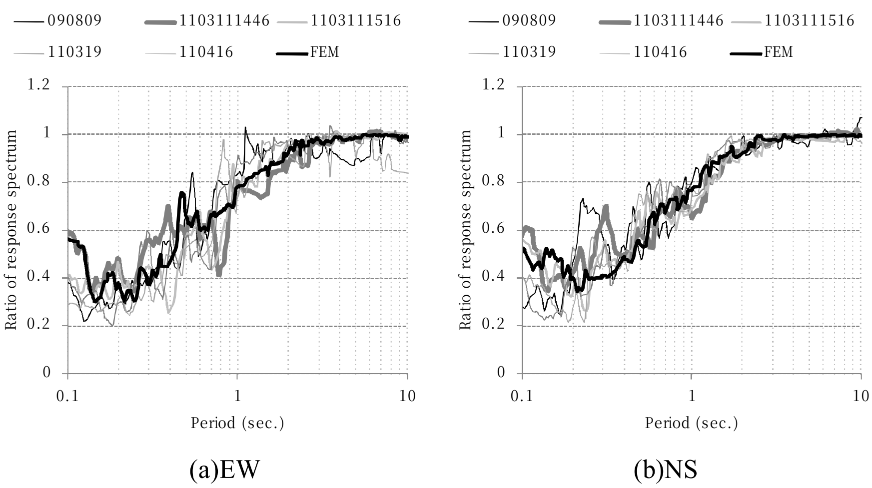


Figure 10. Comparison of the analysis and observations for the acceleration response spectrum ratio above the base-isolation pit to that for the ground surface

4.2.3. Study of factors affecting the interaction effect

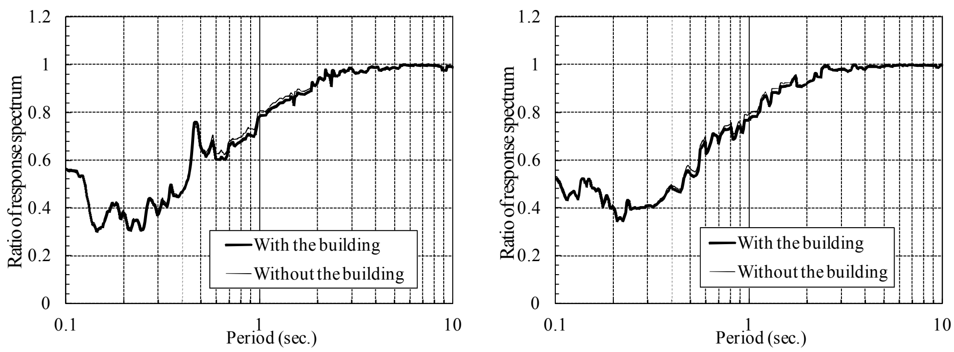
We confirmed that the results of the observation can be explained using analysis and therefore used the three dimensional FEM model created in this paper to study some factors that affect the input loss effect.

a) Impact of inertial interaction

The response above the base-isolation pit is a combination of the ground response and building response. In other words, the response is produced as a result of combining the inertial interaction and the kinematic interaction. Therefore, we created an analysis model without the building to study how much the response above the base-isolation pit changes when the impact of the building is excluded. Figure 11 shows a comparison of the response spectrum amplitude ratio above the base-isolation pit with that of the ground surface. The results do not include the inertial interaction of the building, but there is little difference between results with the impact of the building and without the impact of the building, and we found that input loss is due to the kinematic interaction for the base-isolation pit and the grid-form ground improvement.

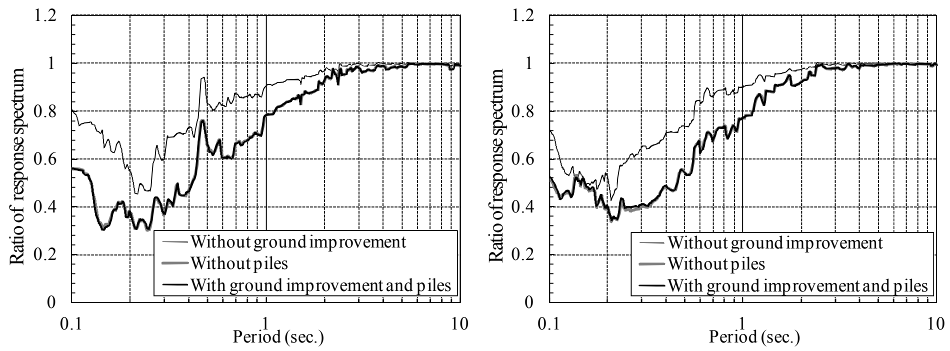
b) Impact of the grid-form ground improvement and the piles

It is thought that the impact of the input loss effect from the foundation is affected by the base-isolation pit, the grid-form ground improvement and the piles. Here, we conducted two studies. One is a study of an analysis without the grid-form ground improvement to confirm the impact of the grid-form ground improvement on the input loss effect and the other is an analysis without the piles. Figure 12 shows a comparison of the response reduction ratio above the base-isolation pit with and without the grid-form ground improvement or the piles. When there is no pile, the change of the response spectrum ratio is not seen and the piles have no impact for the response reduction. On the other hand, when there is no grid-form ground improvement, the response reduction above the base-isolation pit is reduced by half and it is confirmed that the grid-form ground improvement has the same impact as that of the base-isolation pit.



(a)EW (b)NS

Figure 11. Comparison of the acceleration response spectrum ratio above the base-isolation pit to that of the ground surface concerning the existence or nonexistence of the building



(a)EW (b)NS

Figure 12. Comparison of the acceleration response spectrum ratio above the base-isolation pit to that of the ground surface concerning the existence or nonexistence of the ground improvement and the piles

5. CONCLUSUIONS

We successfully obtained observation records at a twelve-story base-isolated building with a piled raft and a grid-form ground improvement during many earthquakes including the 2011 off the Pacific coast of Tohoku earthquake and the ensuing aftershocks, and confirmed the dynamic soil-structure interaction of the ground and the building when the grid-form ground improvement is employed. We narrow down this study to horizontal responses which are important in an earthquake-resistant design.

According to the observation records, we found that the peak acceleration of horizontal components above the base-isolation pit is reduced to 40 to 60% compared with the ground surface. This behaviour is apparent from small earthquakes to the 2011 off the Pacific coast of Tohoku earthquake.

When the acceleration response spectrum ratios of the ground surface and above the base-isolation pit were compared, the degree of reduction increased as in the short period from close to 2 seconds, and an input loss effect due to the foundation was clearly apparent. Although the stiffness of the ground was reduced during the main earthquake, the results showed that the input loss trend remained unchanged.

We modelled the ground, the foundation, and the building in as much detail as possible using a three dimensional FEM model to simulate the observation records during the main earthquake. As a result, we confirmed that the observation records were successfully simulated. We thus obtained results which, using analysis, could explain the input loss above the base-isolation pit.

There is base-isolation pit and a grid-form ground improvement located under the ground beneath the subject building, and both of these affect the response reduction above the pit. As a result of studying the impact analytically, we verified that the base-isolation pit and the improved ground each contribute 50% to the response reduction.

Because we have got a large number of earthquake records, we are going to push forward more detailed analysis including those records in future. Furthermore, we are going to study the soil-structure interaction about the vertical direction.

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