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Division VII

DEVELOPMENT OF SEISMIC COUNTERMEASURES AGAINST CLIFF EDGES FOR ENHANCEMENT OF COMPREHENSIVE SAFETY OF NUCLEAR POWER PLANTS (PART 3: CLIFF EDGE EFFECT OF SEISMICALLY ISOLATED CRITICAL STRUCTURES)

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ABSTRACT

Seismic isolation is a technology that can reduce seismic force for structures by inserting isolation device between structures and ground. Rubber bearings are well known and widespread isolation device. When nuclear power plants adopt seismic isolation technology, the seismic response decreases as well as ordinary buildings, and it has simple linear behavior for design seismic waves. Therefore uncertainty of the response is little. In addition, impacts on a human by an earthquake are decreased, so the seismic isolation technology is an effective countermeasure against cliff edges. However, when input seismic waves are big, rubber bearings have complex nonlinear behavior. Additionally there is a risk that seismically isolated structures come into collision with their surrounding walls.

In this paper, influence of seismically isolated structures on cliff edges and effectiveness of seismic isolation technology as a countermeasure against cliff edges are investigated.

First, nonlinear analysis models of rubber bearings were constructed. The models took hardening in the horizontal direction, the softening in vertical direction and their interaction into account. Then, a model that considers collision between structures and their surrounding walls were constructed. The collision was expressed by elasto-plastic characteristics of the surrounding walls. Finally, seismic response analyses using above-mentioned models were carried out, and cliff edge effect of seismically isolated structures was investigated.

INTRODUCTION

Seismic isolation is a technology that can reduce seismic force for structures and improve seismic reliability. Seismically isolated structures are isolated from ground by inserting isolation device between structures and ground. In other words, natural period of the seismically isolated structures is extended by the isolation device so that resonance with seismic ground motion can be avoided. Several types of seismic isolation device have been proposed, and rubber bearings are more widespread among them. In Japan, the number of seismically isolated structures has been increased after the Kobe Earthquake in 1995, and effect of the seismic isolation technology was demonstrated in the Grate East Japan Earthquake in 2011. More than 3,900 seismically isolated buildings except detached houses have been built in Japan as of 2014 (Japan society of seismic isolation, 2017).

When the seismic isolation technology is applied to reactor buildings and the important buildings in nuclear power plants, the response would extremely reduce compared with the conventional earthquake-resistant structures. In addition, rubber bearings, the superstructure and components in the superstructure vibrate linearly for design seismic ground motion, so the responses have simple and clear characteristics. Therefore uncertainty regarding seismic response is small compared with the conventional earthquake-resistant structures. It is also expected that unexpected events hardly occur and influence on human inside the superstructure reduces. Consequently the seismic isolation is an effective technology against cliff edges not only for the building itself but also for components and human in the buildings.

On the other hand, various problems would appear if input seismic ground motion and deformation of rubber bearings are extremely large. For example, nonlinear and complicated behavior of rubber bearings occurs, or superstructures collide with surrounding walls. These problems cause the cliff edges.

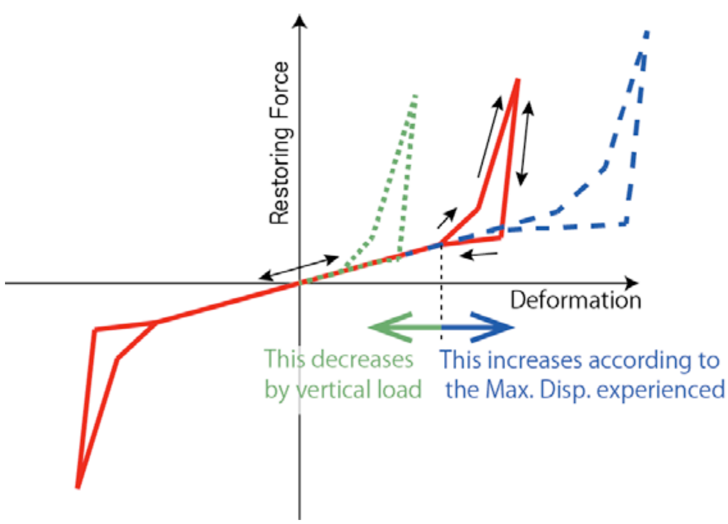
Therefore, this paper describes influence of seismically isolated structures on cliff edges and effectiveness of seismic isolation technology as a countermeasure against cliff edges. First, restoring force models of rubber bearings, a collision force model and a building model for seismic response analysis is constructed. Each model takes nonlinearity into account. Then, seismic response analyses are carried out in order to investigate cliff edge effect of seismically isolated structures.

CONSTRUCTION OF ANALYSIS MODEL

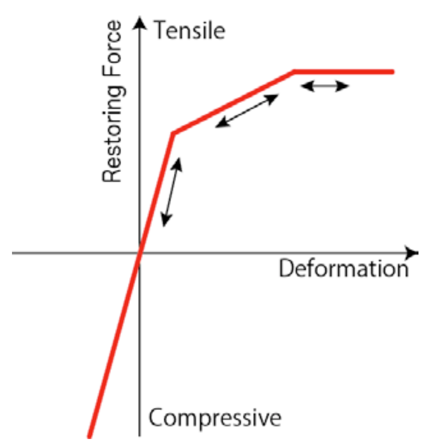
Restoring Force Model of Rubber Bearing

Rubber bearings have linear characteristics in both horizontal and vertical direction for design seismic ground motion. These characteristics are well known as so-called Hooke's Law. However, when deformation of rubber bearings is large, hardening in the horizontal direction and softening in the vertical direction occur (Fujita et al., 1988). The hardening is caused by the strain hardening of rubber material, and softening is caused by difference of characteristics of rubber bearings between compression and tension. Multi-linear models were proposed by Katoh et al. (1993) in order to express these nonlinearities in numerical analyses. In addition, nonlinearity in the horizontal direction depends on vertical load, and this analysis model was proposed by Minagawa et al. (2013)

Figure 1 shows analysis models of rubber bearings considering nonlinearities.



(a) Horizontal



(b) Vertical

Figure 1. Restoring force characteristics of rubber bearing.

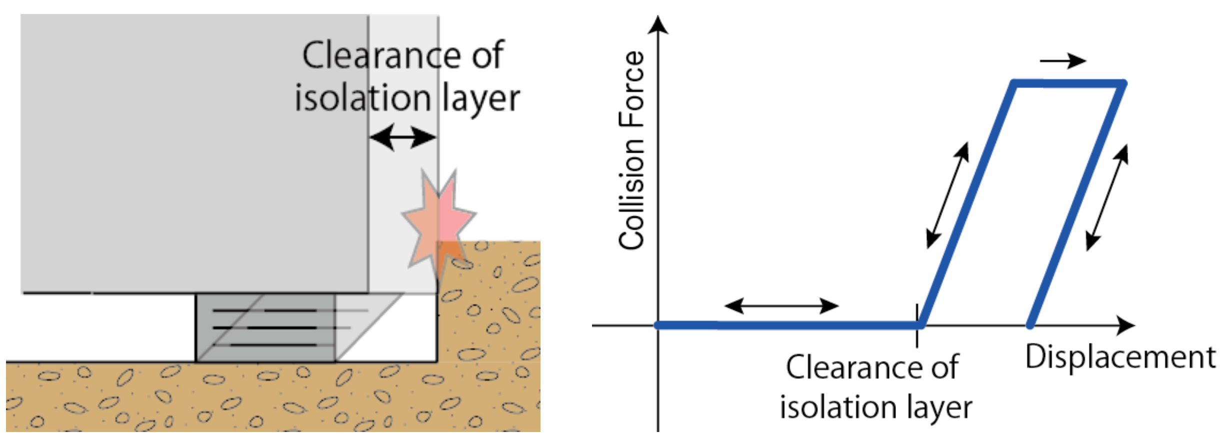
The hardening characteristics in the horizontal direction are presented by 5 straight lines as shown in Fig. 1 (a). The hardening starting deformation increases according to the maximum deformation that the rubber bearing experienced, and this effect is called the coupling effect. The hardening starting deformation decreases depending on the vertical load for the rubber bearing, and this effect is called the maximum displacement dependency. In the design criteria of Japan, the rubber bearings must maintain its linearity against a deformation of more than 1.5 times of the design.

The softening characteristics in the vertical direction are presented by 3 straight lines as shown in Fig. 1 (b). The linear characteristic is retained in the compressive side, and the softening occurs only in the tensile side. This softening is caused by difference of the stiffness of rubber bearings between compression and tension, so the softening starts at where the deformation of rubber bearing is zero, namely the natural length. This softening doesn't have a coupling effect with the horizontal direction.

Collision Model with Surrounding Wall

A seismically isolated structure reduces the absolute acceleration of the superstructure by deformation of rubber bearings. Thus relative displacement between the superstructure and ground occurs. Isolation device are generally set in a basement floor, so that a sufficient clearance is provided in order not to collide with the surrounding walls. However, in the case of extremely large earthquakes like one which are considered in PRA, collision between the superstructure and the surrounding walls may occur. Therefore a collision model is constructed.

A collision force model shown in Fig. 2 was constructed in this study. The collision force operates on the superstructure, when response displacement of the isolation layer exceeds the clearance of the isolation layer, as shown in Fig. 2 (b). In this model, restoring force of a surrounding wall is presented by bilinear characteristics assuming that elasto-plastic deformation in the surrounding wall occurs by the collision. The clearance shifts in consideration of collapses of the surrounding walls after the collision.



(a) Collision between superstructure and wall (b) Collision force characteristics

Figure 2. Collision force characteristics between superstructure and surrounding wall.

Building Model

Figure 3 shows a building model for seismic response analysis. A reactor building of a nuclear power plant is assumed as a seismic isolation target. The building model consists of an isolation layer and a superstructure layer. Horizontal and vertical motion of the isolation layer, horizontal, vertical and rotational motion of the superstructure layer were considered. In other words, the building model is 2 masses and 5 degree of freedom system model. Elasto-plastic deformation of the superstructure is also expressed by trilinear characteristics.

Finally the rubber bearing models, the collision force model, the building model, a damper model of the isolation layer, a lead plug model of the isolation model were integrated.

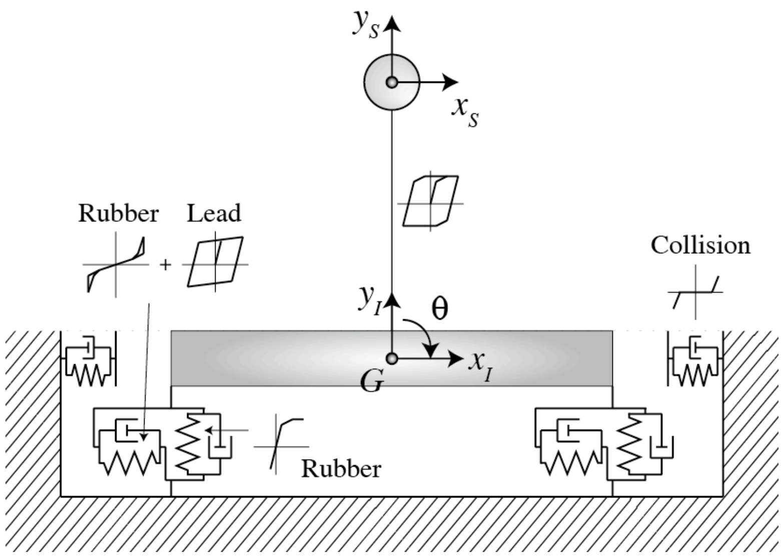


Figure 3. Building model for seismic response analysis.

SESIMIC RESPONSE ANALYSIS FOR INVESTIGATION INTO CLIFF EDGES

Procedure

Seismic response analysis was carried out in order to investigate influence of seismically isolated structures on cliff edges and effectiveness of seismic isolation technology as a countermeasure against

Table 1: Analytical condition.

Condition #	Nonlinearity of RB	Coupling effect of RB	Rocking motion	Nonlinearity of building	Collision with wall
0	×	×	×	×	×
1	○	○	○	○	○
2	×	×	○	○	○
3	○	×	○	○	○
4	○	○	×	○	○
5	○	○	○	×	○
6	○	○	○	○	×

cliff edges. In a seismically isolated structure, nonlinearities of rubber bearings and collision with surrounding walls cause cliff edges. Therefore seismic response analyses with various conditions as shown in table 1 were conducted. For example, condition #0 doesn't consider any nonlinearities and rocking motion, condition #1 considers all nonlinearity and rocking motion, condition #2 considers rocking motion and nonlinearities except the rubber bearings, condition #3 considers rocking motion and nonlinearities except the coupling effect, condition #4 considers all nonlinearities but doesn't consider rocking motion, condition #5 considers rocking motion and nonlinearities except the nonlinearity of the superstructure and condition #6 considers rocking motion and nonlinearities except collision.

In addition, amplitude of the input waves that is mentioned below was varied in order to investigate influence of earthquake level on cliff edges.

Analysis model

The above-mentioned analysis model was applied in this analysis. The horizontal isolation period is 3.4 s, vertical natural frequency of isolation layer is 16 Hz, the clearance of the isolation layer is 0.4 m, stiffness of the surrounding wall is 12 times of 1st stiffness of the rubber bearing, and plastic deformation of the surrounding wall was not considered. These parameters are selected provisionally and drastically in order to investigate influence of seismic isolation, so these are not actual design.

Input Wave

Input waves shown in Fig. 4 were applied in the analyses. These waves are artificial waves. The maximum acceleration in the vertical direction is about 2/3 of that of the horizontal direction. It is confirmed from the velocity response spectrum of Fig. 4 that the horizontal input wave has the maximum velocity of about 3 m/s at isolation period that is 3.4 second. Therefore these input waves are very severe for the isolated structure. Input waves were multiplied by 0.25 to 5.00 and used for in the analyses.

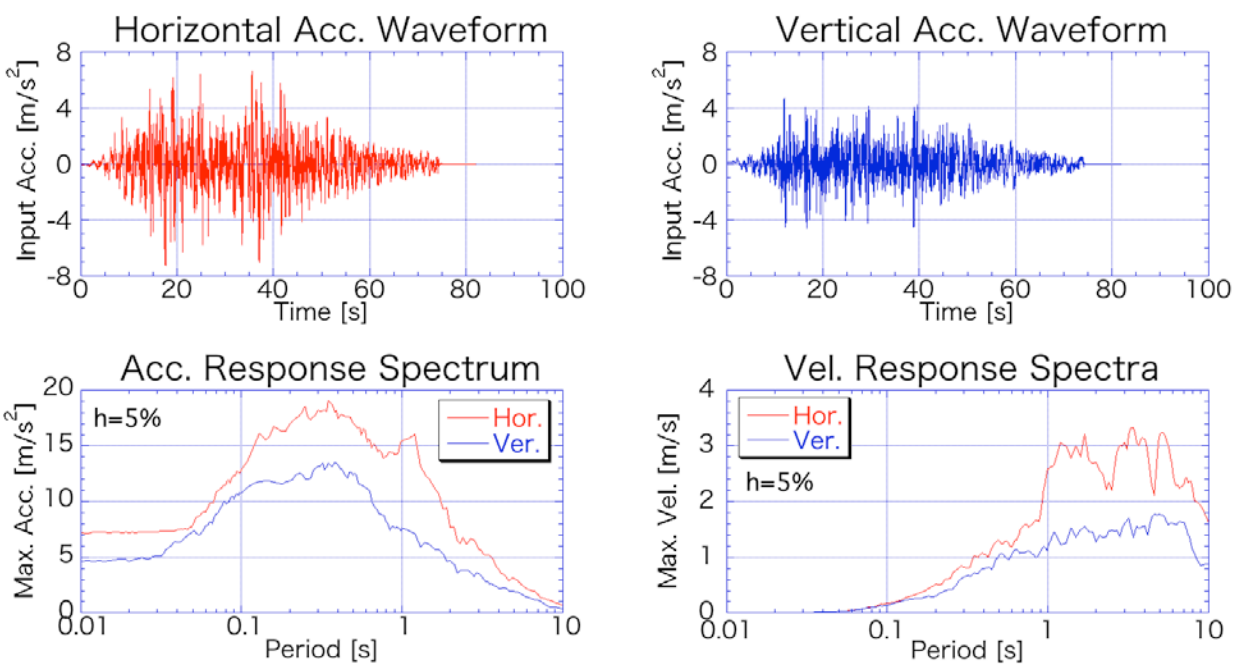


Figure 4. Input wave.

Analysis Results

Figure 5 shows time histories when 5 times of original input waves were input, as an example of analysis results. All nonlinearities and rocking motion were considered in this result. From Fig 5, it was confirmed that all nonlinearities were simulated. The horizontal response acceleration had large acceleration like spikes, and this was caused by collisions between the superstructure and the surrounding walls. The vertical response displacement had large displacement in only positive side, and this was caused by softening of rubber bearings. The restoring force characteristics of collision force had loops, and these are caused by viscous damping of the surrounding wall.

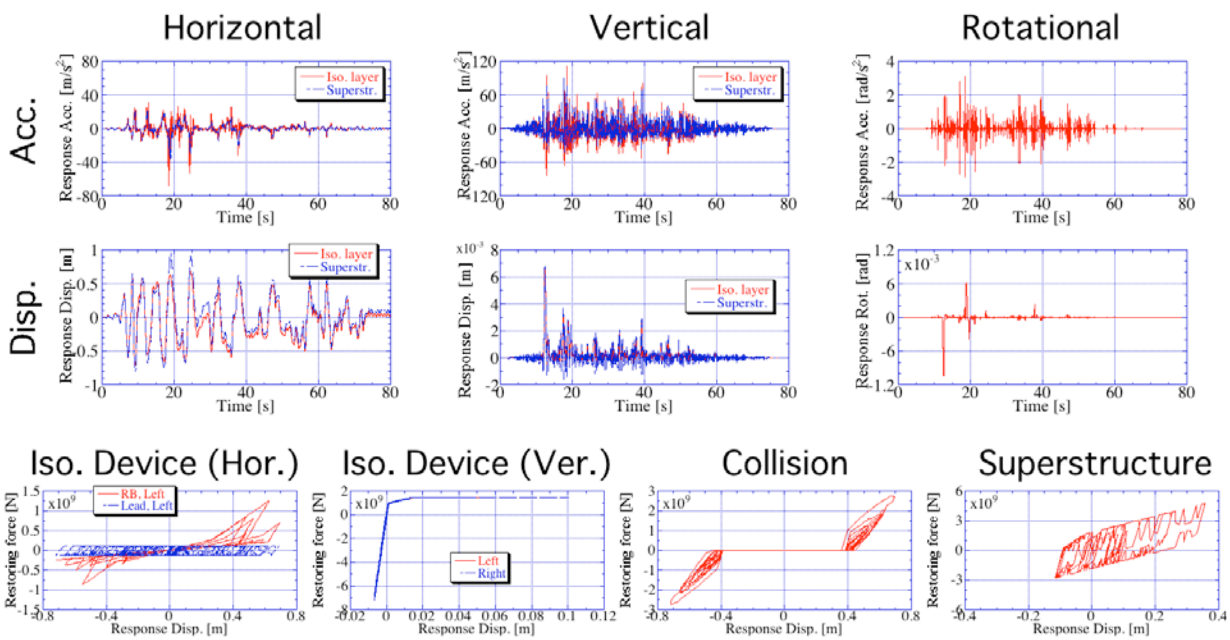
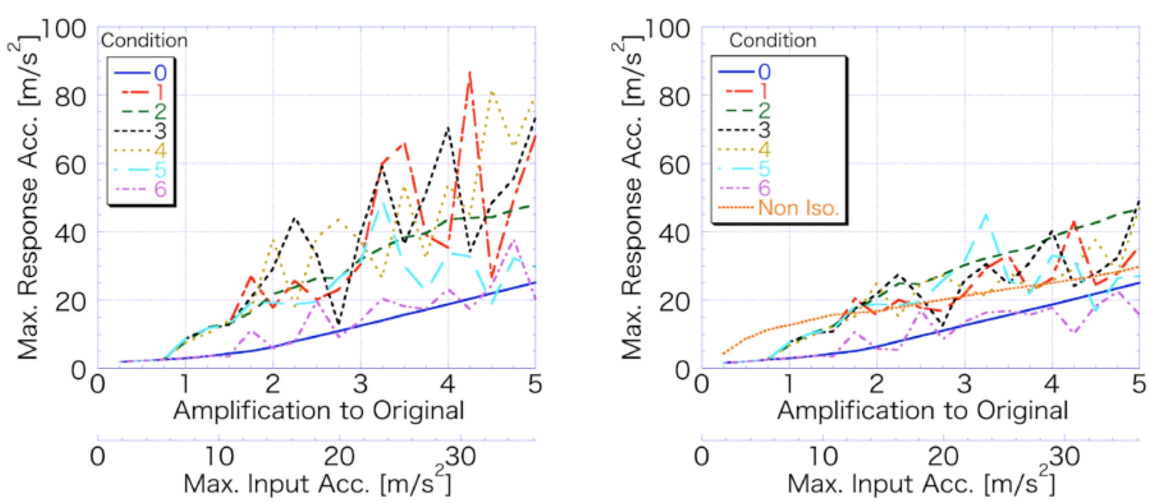


Figure 5. Time history (condition #1, original wave × 5.0).

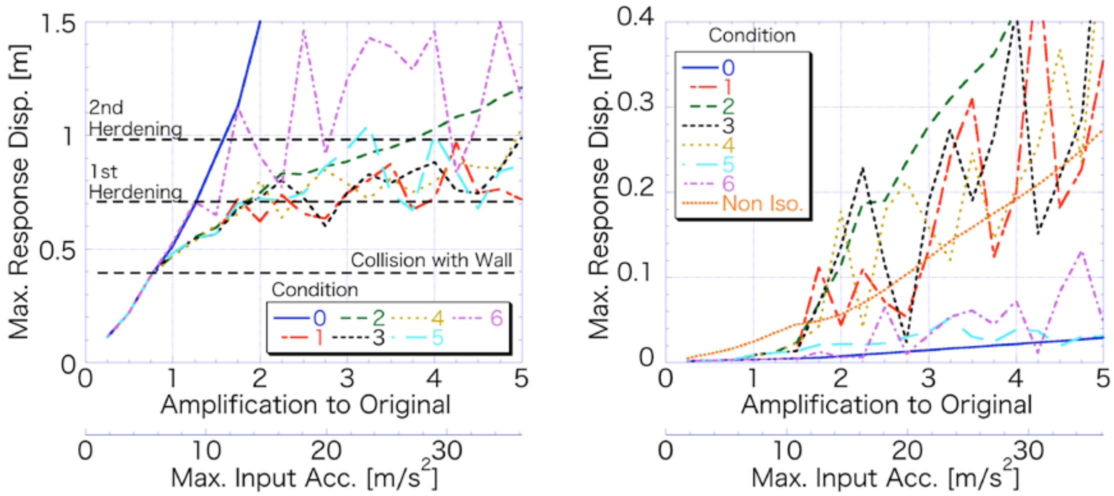


(a) Isolation layer (b) Superstructure

Figure 6. Relationship between input and response (horizontal response acceleration).

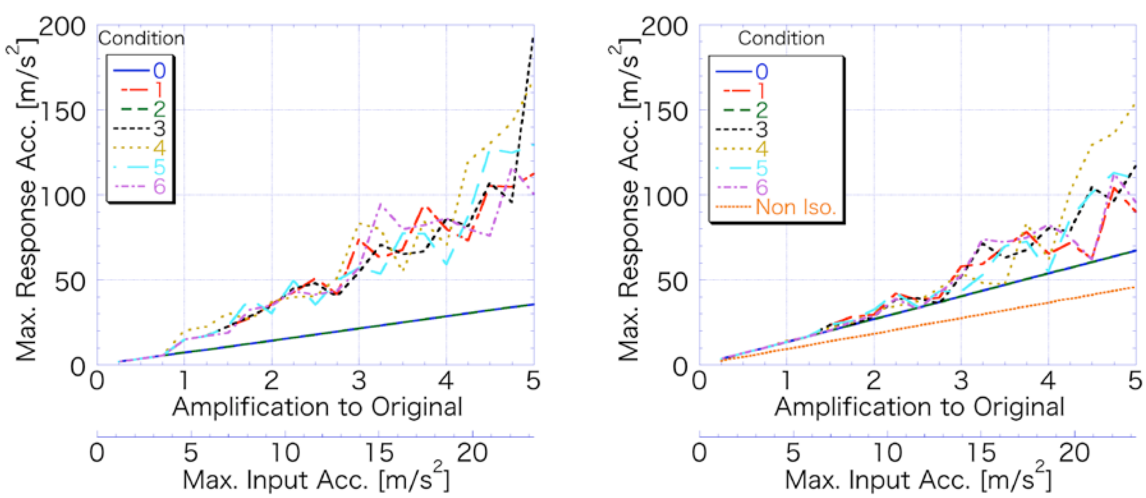
Figures 6, 7, 8 and 9 show comparison of the maximum values of horizontal response acceleration, horizontal response displacement, vertical response acceleration and vertical response displacement, respectively.

From comparison of horizontal response acceleration shown in Fig. 6, response of conditions #0 (all nonlinearities were not considered) and #2 (nonlinearities of rubber bearings were not considered) increased smoothly, so nonlinearities of rubber bearings have influence on variability of response. Response of conditions #0 and #6 (collision was not considered) were smaller compared with the others, so collisions between the superstructure and the surrounding walls has influence on increase of response. Response of conditions #1 (all options were considered) and #4 (rocking motion was not considered) were similar to each other, so influence of rocking motion on response is small. In addition, response of the superstructure was smaller than that of the isolation layer. Therefore transmission of response from



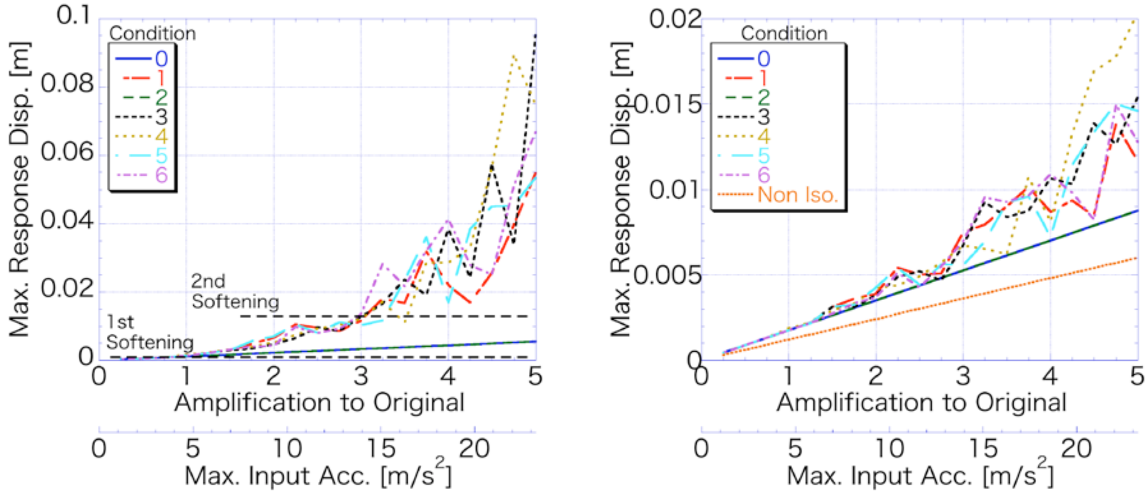
(a) Isolation layer (b) Superstructure

Figure 7. Relationship between input and response (horizontal response displacement).



(a) Isolation layer (b) Superstructure

Figure 8. Relationship between input and response (vertical response acceleration).



(a) Isolation layer (b) Superstructure

Figure 9. Relationship between input and response (vertical response displacement).

the isolation layer to the superstructure is small, though very large acceleration occurred at the isolation layer by nonlinear behavior. However response of the isolated superstructure exceeded that of the non-isolated structure because of collision.

From comparison of horizontal response displacement shown in Fig. 7, response of conditions #0 and #2 increased smoothly as well as horizontal response acceleration, so nonlinearities of rubber bearings have influence on variability of response. Response of conditions #0 and #6 were larger than the others, so collision between the superstructure and the surrounding walls has influence on suppression of response. Response of the superstructure of conditions #0 and #5 (nonlinearity of the superstructure was not considered) were smaller than the others, so nonlinearity of the superstructure has influence on increase of response of superstructure. Response of superstructure of condition #6 was relatively small, so collision between the superstructure and the surrounding walls has influence on increase of response of superstructure.

From comparison of vertical response acceleration shown in Fig. 8, response of conditions #0 and #2 increased linearly, so nonlinearities of rubber bearings have influence on increase of response. On the other hand, response except conditions #0 and #2 was similar to each other, so influence of nonlinearities except rubber bearings on response is small. In addition, response of the superstructure and the isolation layer is comparable. However response of the isolated superstructure exceeded that of the non-isolated structure, because input to the superstructure was amplified by the isolation layer.

From comparison of vertical response displacement shown in Fig. 9, same tendencies as vertical response acceleration were confirmed. In other words, nonlinearities of rubber bearings have influence on increase of response, and influence of nonlinearities except rubber bearings on response is small. In addition, increase of response of the isolation layer was remarkable.

CLIFF EDGES OF SEISMICALLY ISOLATED STRUCTURE

In this section, influence of seismically isolated structures on cliff edges and effectiveness of seismic isolation technology as a countermeasure against cliff edges are discussed. This study considers two types of cliff edge, namely a physical cliff edge and a knowledge-oriented cliff edge. The physical cliff edge is a cliff edge by changes of physical state based on increase of seismic ground motion, and knowledge-oriented cliff edge is a cliff edge by occurrence of events which are out of our knowledge.

Physical Cliff Edge

Response of a seismically isolated building decreased against the design basis earthquake as shown in Fig. 6 (b). Therefore it is expected that response of components and human in the building decreased as well, so seismic isolation is effective technology to avoid physical cliff edges.

On the other hand, physical cliff edges occurred according to increase of input wave. In the horizontal direction, physical cliff edges should occur by hardening of rubber bearings. The hardening makes the isolation period shorter, and causes sudden changes of response. In addition, collision between superstructures and surrounding walls causes large collision force and large pulsive acceleration. In the vertical direction, physical cliff edges should occur by softening of rubber bearings. The softening enlarges displacement in the positive side, and causes large load by landing in the compressive side.

Knowledge-oriented Cliff Edge

As mentioned above, response of a seismically isolated building decreased against the design basis earthquake as shown in Fig. 6 (b). Therefore it is expected that response of the building itself, components and human in the building respond linearly, simply and clearly, thus uncertainty regarding seismic response is small compared with the conventional earthquake-resistant structures.

On the other hand, knowledge-oriented cliff edges occurred according to increase of input wave. Design criteria doesn’t take nonlinear behavior of rubber bearings and collision between superstructures and surrounding walls into account by considering enough margin, so occurrence of these phenomena is unexpected events. In addition, nonlinear models used in the analyses were very simple, and parameters used were provisional. Actual behavior is out of our knowledge, so further experiments and investigations are required for accurate modeling of rubber bearings and collision.

CONCLUSION

This paper proposed analysis models of a seismic isolated structure considering nonlinearities of rubber bearings and so on, and influence of seismically isolated structures on cliff edges and effectiveness of seismic isolation technology as a countermeasure against cliff edges were investigated based on seismic response analysis results.

As a result, it was confirmed that response of a seismically isolated structure for design basis wave was small compared with non-isolated structure, and the response remained simple and clear. Therefore seismic isolation is an effective technology to avoid cliff edges. However several cliff edges by nonlinearities of rubber bearings and collision occurred against large earthquake than design. Further experiments and investigations for construction of accurate models of rubber bearings and collision are required in order to avoid knowledge-oriented cliff edges more.

In the future, additional seismic response analysis will be conducted, because parameters of the analysis model in this paper were restrictive and drastic.

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