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# Development of Seismic Counter Measures Against Cliff Edges for Enhancement of Comprehensive Safety of Nuclear Power Plants Part 9 : Avoidance of Cliff Edge by Introducing Seismic Isolation

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## ABSTRACT

Applications of seismic isolation technologies to nuclear power plants are very effective from the viewpoint of avoidance of cliff edges. However, when input seismic waves are extremely bigger than the design level, nonlinear characteristics of rubber bearing will appear and collision of an isolated structure with surrounding walls will occur. Thus this paper deals with avoidance of cliff edges by introducing the seismic isolation and cliff edges specific to seismically isolated structures.

Seismic response analyses were conducted to clarify the damage control effect and cliff edges by applying seismic isolation technology. An analytical model which considers nonlinearities of rubber bearings and collision of the isolated building with the surrounding walls was applied. As a result, it was confirmed that nonlinearities of rubber bearings and collision with surrounding walls can be factors of cliff edges specific to the seismically isolated structure. However the influence of collision can be suppressed by designing suitably.

Then the analytical results were evaluated from the viewpoints of physical and knowledge-oriented cliff edges. As a result, the effects of nonlinearities of rubber bearings and collision of isolated structures were large from the both viewpoints of the physical and the knowledge-oriented cliff edges. In addition, nonlinearities of rubber bearings can be the cliff edges in the wide range of the input level. On the other hand, collision of isolated structures with surrounding walls can be the cliff edge in the narrow range of the input level.

## INTRODUCTION

Seismic isolation is one of the technologies that can mitigate seismic force for structures by inserting isolation devices between ground and the structures. The natural period of a seismically isolated structure is extended by isolation devices, so that resonance with ground motion can be avoided. Natural rubber bearings are widely used as isolation devices and these have simple linear characteristics for the design earthquake level. In other words, restoring force is linearly proportional to deformation.

In Japan, the number of seismically isolated structures has been increased after the Kobe Earthquake in 1995, and more than 4,300 seismically isolated buildings except detached houses have been built (Japan society of seismic isolation, 2019). In the world, there are some examples of seismic isolation applied to industrial facilities such as storage tanks (Paolacci et al., 2013). Response acceleration of structure is reduced by applying seismic isolation technologies dramatically, thus applications of seismic isolation technologies to nuclear power plants are expected.

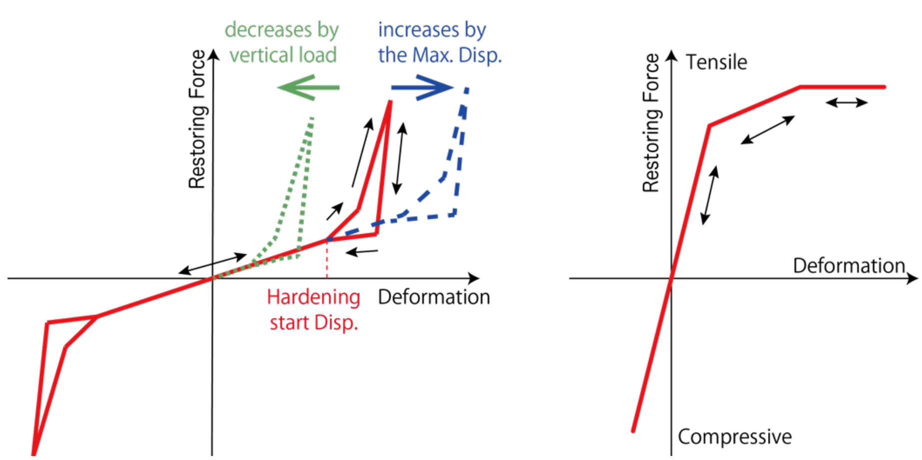
Applications of seismic isolation technologies to nuclear power plants are very effective from the viewpoint of avoidance of cliff edges, because response of seismically isolated structures is very small and simple against design earthquake level. In addition, influence on human during earthquakes is also suppressed. However, when input seismic waves are extremely bigger than the design level, seismically isolated structures have complex nonlinear behavior. For example, rubber bearings have hardening characteristics in horizontal direction and softening characteristics in vertical direction. In addition, the hardening characteristics depends on vertical load of rubber bearings. Moreover seismically isolated structures collide with their surrounding walls when response displacement is large. Therefore these phenomena may cause cliff edges specific to seismically isolated structures.

In this paper, avoidance of cliff edges by introducing the seismic isolation and cliff edges specific to seismically isolated structures were investigated by seismic response analyses. An analytical model that considers nonlinearities of rubber bearings and collision between buildings and surrounding walls was used. Analyses with various conditions were conducted and the results were evaluated from the viewpoint of the cliff edge.

## FACTORS THAT HAVE POSSIBILITIES OF CLIFF EDGES SPECIFIC TO SEISMICALLY ISOLATED STRUCTURES

### *Nonlinearities of Rubber Bearings*

In general natural rubber bearings have linear characteristics in both horizontal and vertical direction for design seismic ground motion. However rubber bearings have hardening characteristics in the horizontal direction and softening characteristics in the vertical direction for large input (Fujita et al., 1988). The hardening in horizontal direction is caused by the strain hardening of rubber material. The deformation to start hardening increases with the maximum deformation that a rubber bearing has experienced so far, and decreases with vertical load for a rubber bearing. Softening in vertical direction is caused by difference of characteristics of rubber bearings between compression and tension. The softening occurs in tensile side only. In seismic response analyses in this paper, restoring force characteristics of rubber bearings were expressed by multi-linear models as shown in Fig. 1 (Katoh et al., 1993, Minagawa et al., 2013).



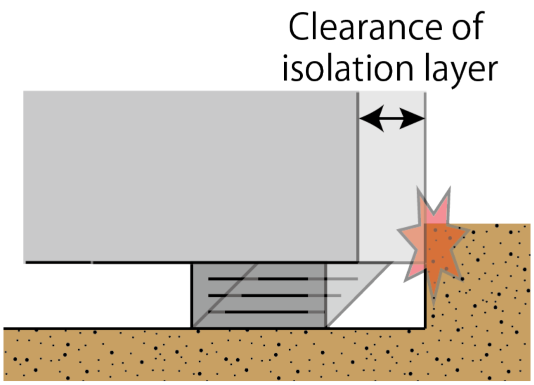

(a) Horizontal (b) Vertical

Figure 1. Restoring force characteristics of rubber bearing.

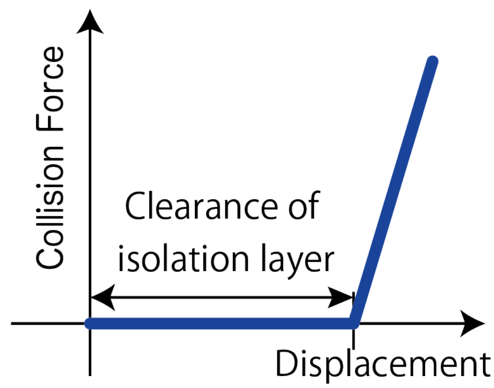
### *Collision with Surrounding walls*

Absolute response acceleration of superstructures is suppressed by applying seismic isolation, but response displacement due to the deformation of rubber bearing occurs instead. An isolation layer is generally set below the ground level, so that clearance between the isolated structure and the ground or surrounding walls are designed in order to avoid collision during earthquakes. However there are risks of collision between the isolated structure and surrounding walls when input earthquakes were extremely larger than the design.

In seismic response analyses in this paper, collision force characteristics were expressed by multi-linear models as shown in Fig. 2 (Miwada et al., 2011). Collision force doesn't occur if response displacement is smaller than the clearance, then linear restoring force by the surrounding walls occurs if response displacement exceeds the clearance. Viscous damping by the surrounding walls is also considered when collision occurs.




(a) Collision between superstructure and wall




(b) Collision force characteristics

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

## SEISMIC RESPONSE ANALYSIS FOR INVESTIGATION INTO DAMAGE CONTROL EFFECT AND CLIFF EDGE BY SEISMIC ISOLATION

### *Analytical Purpose*

Seismic response analyses were conducted to clarify the damage control effect and cliff edges by applying seismic isolation technology. The seismic response analyses were conducted by using artificial seismic waves with various level, and the relationship between input level and behavior of the seismically isolated structure was investigated.

### *Analytical Model*

An analytical model of a building shown in Fig. 3 was used for the seismic response analyses (Minagawa et al., 2017). In seismically isolated structures, deformation of rubber bearings is dominant, and deformation of the superstructure is small. Therefore the simple model with 2 mass points was applied.

The target building of isolation is a reactor building of a nuclear power plant. The model consists of an isolation layer and a superstructure layer. The lower mass indicates the isolation layer, and the upper mass indicates the superstructure. Horizontal, vertical and rotational motion of the isolation layer, horizontal and vertical motion of the target building were considered. Thus this model has 2 mass points and 5 degrees of freedom. Nonlinearities of rubber bearings, lead plugs in rubber bearings and collision model were integrated to the building model. In addition elasto-plastic deformation of the superstructure is also considered by trilinear characteristics. The isolation period was 3.4second, horizontal natural frequency of the superstructure was 4.7Hz.

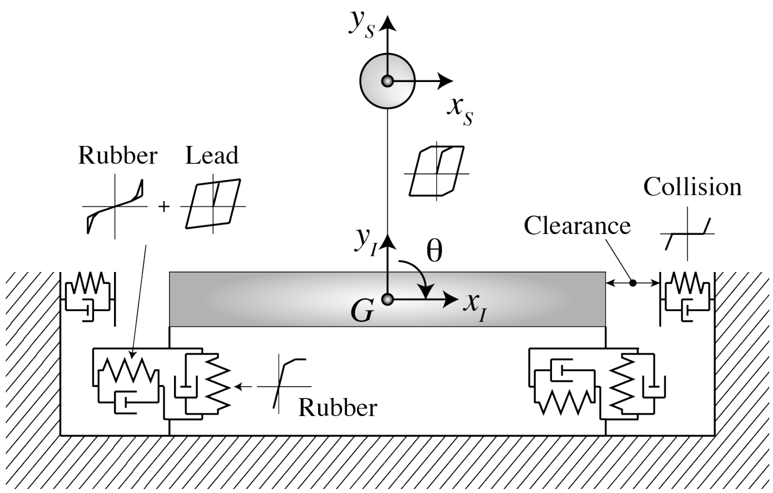



Figure 3. Analytical model of building.

***Analytical Procedure***

In order to clarify the damage control effect and cliff edges by applying seismic isolation technology, 5 types of analyses were conducted. The first is analyses to investigate the relationship between the clearance of the isolation layer and the response. The second is the same analyses as the first one but nonlinearities of rubber bearings were not considered. The third is analyses to investigate the relationship between the collision stiffness of the surrounding walls and the response. The fourth is analyses to investigate the relationship between the collision damping of the surrounding walls and the response. The fifth is analyses to investigate the relationship between the isolation period and the response.

Figure 4 shows input waves. These waves are artificial waves. The input waves were multiplied by 0.25 to 5.00 and used for the analyses. in order to investigate influence of earthquake level on cliff edges.

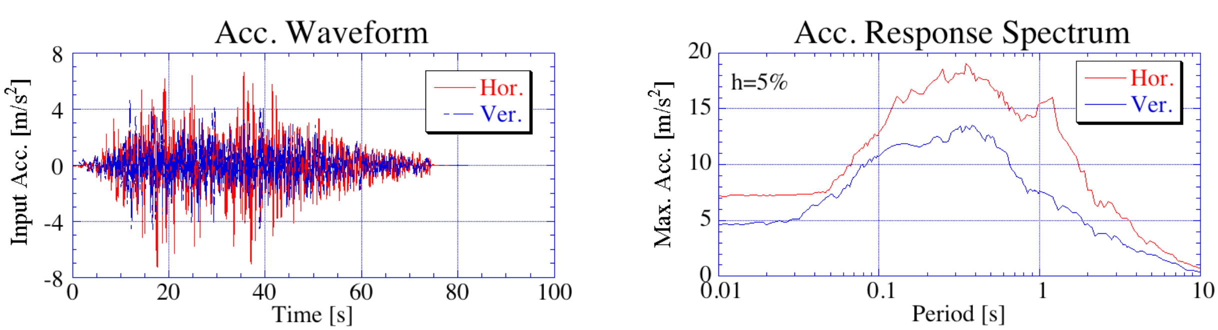



Figure 4. Input wave.

***Analytical Result***

Figures 5 to 9 show relationships between the maximum input acceleration and the maximum response acceleration of the superstructure or the maximum response displacement of the isolation layer.

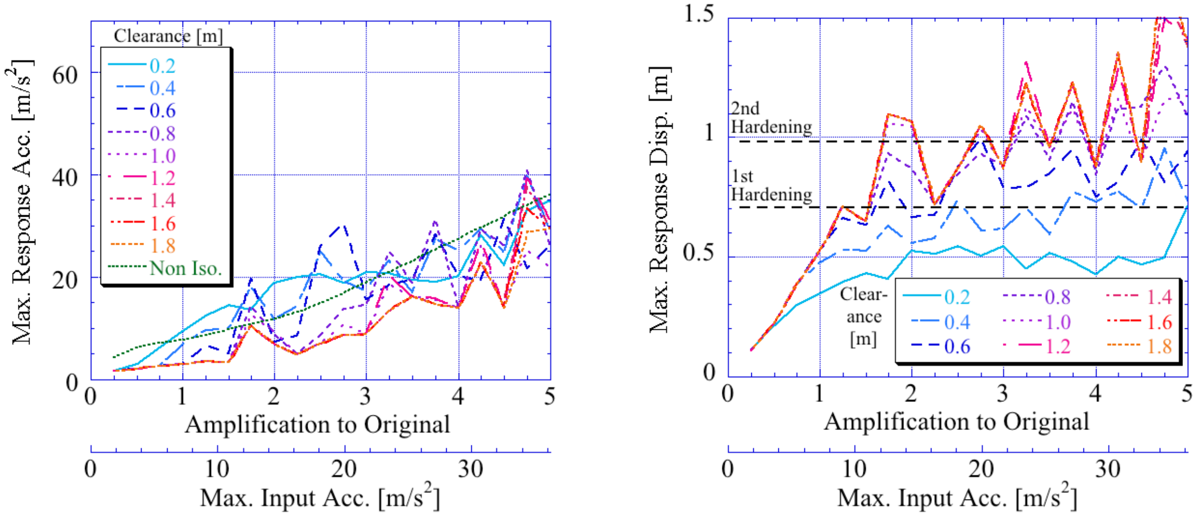
Figure 5 shows influence of clearance. As shown in Fig. 5, response acceleration increased rapidly from the small input level in the case of small clearance. In addition response acceleration decreased and response displacement increased with the increase of the clearance. These are because collision between the building and the surrounding walls occurred easily if the clearance was small. Response acceleration of the isolated structure became small compared with the non-isolated structure in the case of the clearance of more than 1.0m. Therefore the suitable setting of the clearance produces the isolation performance even if the input level is larger than the design.

Figure 6 shows influence of clearance in the case that nonlinearities of rubber bearings were not considered. As shown in Fig. 6, response acceleration of the isolated structure is larger than the non-isolated structure if input level is large. Therefore the factors that maintain isolation performance even in the large input level in Fig. 5 were combination of nonlinearities of rubber bearings and collision. In Fig.6, the response increased simply with the increase of input level, therefore unevenness of the response in Fig. 5 was caused by nonlinearities of rubber bearings.

Figure 7 shows influence of the collision stiffness of the surrounding walls. As shown in Fig. 7, response acceleration increased and response displacement decreased with the increase of the collision stiffness. Figure 8 shows influence of the collision damping of the surrounding walls. As shown in Fig. 8, response acceleration and response displacement decreased with the increase of the collision stiffness. Thus the collision influenced the response, but the influence of collision can be suppressed by designing the collision stiffness and damping carefully.

Figure 9 shows influence of the isolation period. As shown in Fig. 9, response acceleration decreased and response displacement increased with the increase of the isolation period. However the difference of response by isolation period became smaller if nonlinearities appeared.

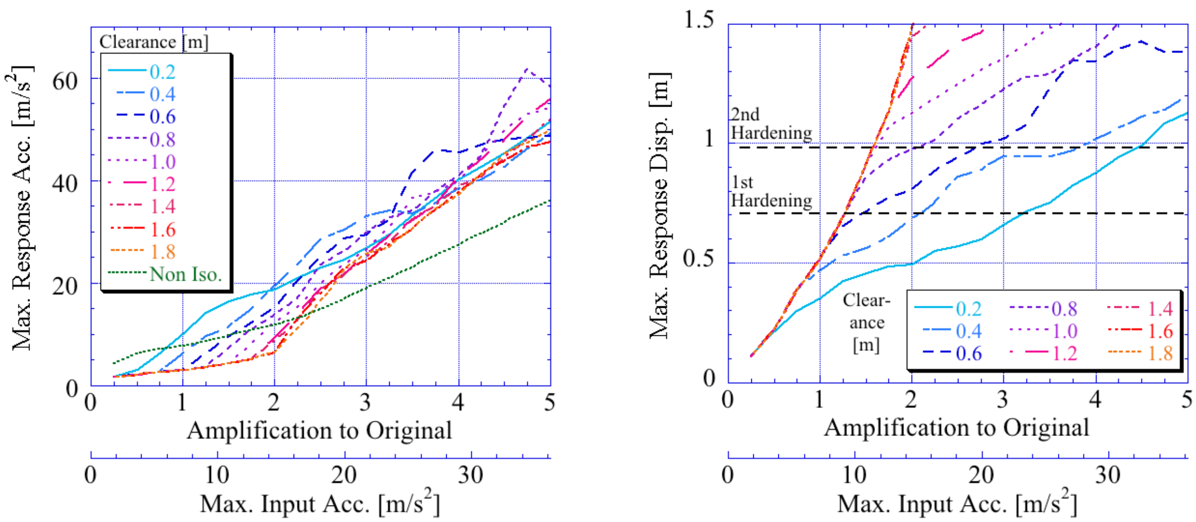
Consequently it was confirmed that hardening and softening of rubber bearings and collision with surrounding walls have large influence on response in the case of large input level. Therefore these nonlinearities can be factors of cliff edges specific to the seismically isolated structure.




(a) Max. Acc. of superstructure

(b) Max. Disp. of Isolation layer

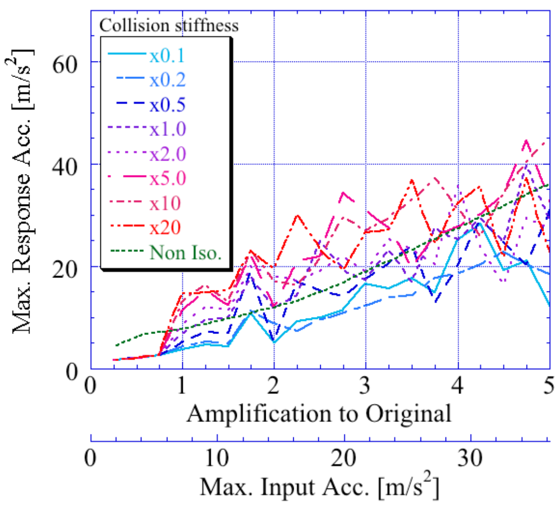
Figure 5. Relationship between input and response (Influence of clearance).

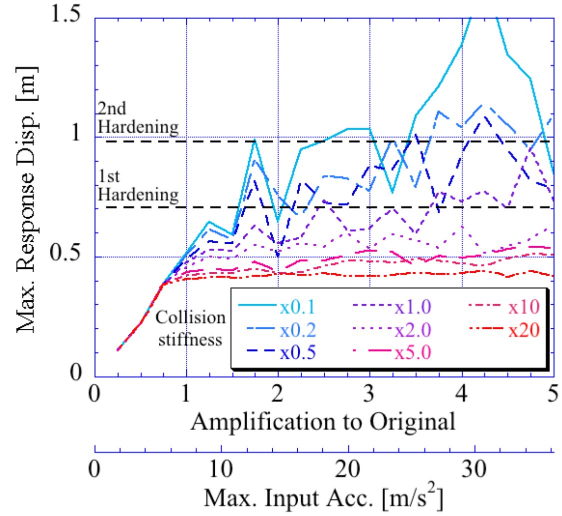



(a) Max. Acc. of superstructure

(b) Max. Disp. of Isolation layer

Figure 6. Relationship between input and response
(Influence of clearance, nonlinearities of RB were not considered).

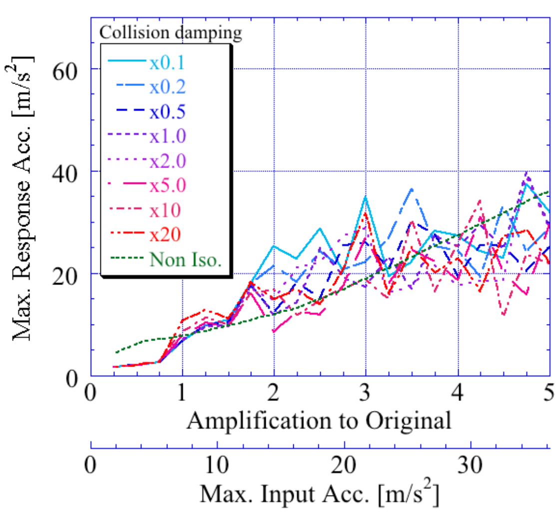


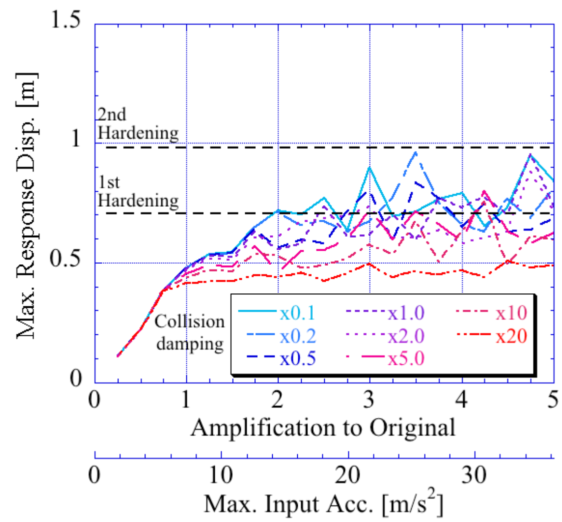




(a) Max. Acc. of superstructure

(b) Max. Disp. of Isolation layer

Figure 7. Relationship between input and response (Influence of stiffness of surrounding wall).

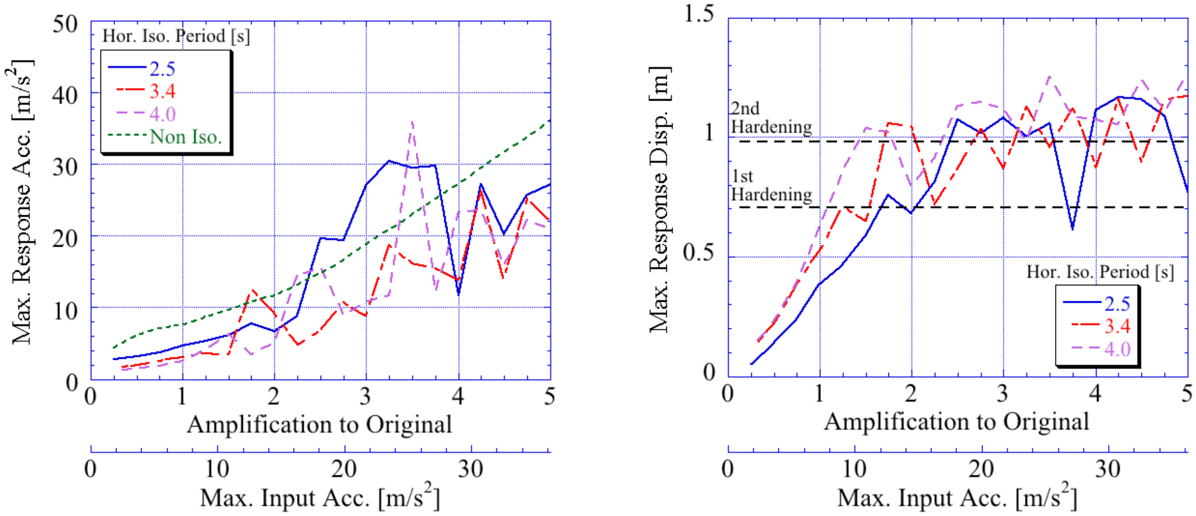



(a) Max. Acc. of superstructure

(b) Max. Disp. of Isolation layer

Figure 8. Relationship between input and response (Influence of damping of surrounding wall).




(a) Max. Acc. of superstructure (b) Max. Disp. of Isolation layer

Figure 9. Relationship between input and response (Influence of isolation period).

## CLIFF EDGE OF SEISMICALLY ISOLATED STRUCTURE

In this chapter, cliff edges specific to seismically isolated structure are evaluated based on the analytical results. This study evaluates the cliff edges from the two viewpoints, that is the physical cliff edges and the knowledge-oriented cliff edges. The analytical results presented in SMiRT 24 (Minagawa et al., 2017) were also considered for the evaluation of the cliff edges.

Table 1 shows a relationship of cliff edges of seismically isolated structures. As shown in table 1, plastic deformation of superstructures and rocking motion can be cliff edges. However this influence is small (Minagawa et al., 2017). In addition, there are many researches on the plastic deformation and rocking motion of buildings. Thus the effects of the plastic deformation of superstructures and rocking motion on the cliff edges are small from the both viewpoints of the physical and the knowledge-oriented cliff edges. On the other hand, hardening, softening and their coupling effect of rubber bearings and the collision between seismically isolated structures and surrounding walls have large influence on the cliff edges. It was confirmed from the analytical results in the previous chapter that these have large influence on response of the seismically isolated structures. In addition, the nonlinearities of seismically isolated structures that were clarified by the experiments are based on limited conditions, so there is unknown area.

Figure 10 shows the relationship between cliff edges of seismically isolated structure and input level. As shown in Fig. 10, cliff edges by hardening and softening of rubber bearings appear according to the increase of the input level. In particular, hardening depends on the maximum deformation that a rubber bearing has experienced, so it can be the cliff edge in the wide range of the input level. Then cliff edges by the plastic deformation of superstructures and rocking motion appear, but the influence is small. After that, the cliff edge by the collision appears when the response displacement exceeds the clearance between the building and surrounding walls. Although the influence is large, the range of input level is small. In addition, these cliff edges can be covered by using the analytical model which considers various nonlinearities.

Table 1: Relationship of cliff edges of seismically isolated structure

| | | Physical cliff edge | |
|---|---|---|---|
| | | Small | Large |
| Knowledge-oriented cliff edge | Small | - Plastic deformation of superstructure<br>- Rocking motion | |
| | Large | | - Hardening of rubber bearings<br>- Softening of rubber bearings<br>- Coupling of nonlinearities of rubber bearings<br>- Collision between isolated structures and surrounding walls |

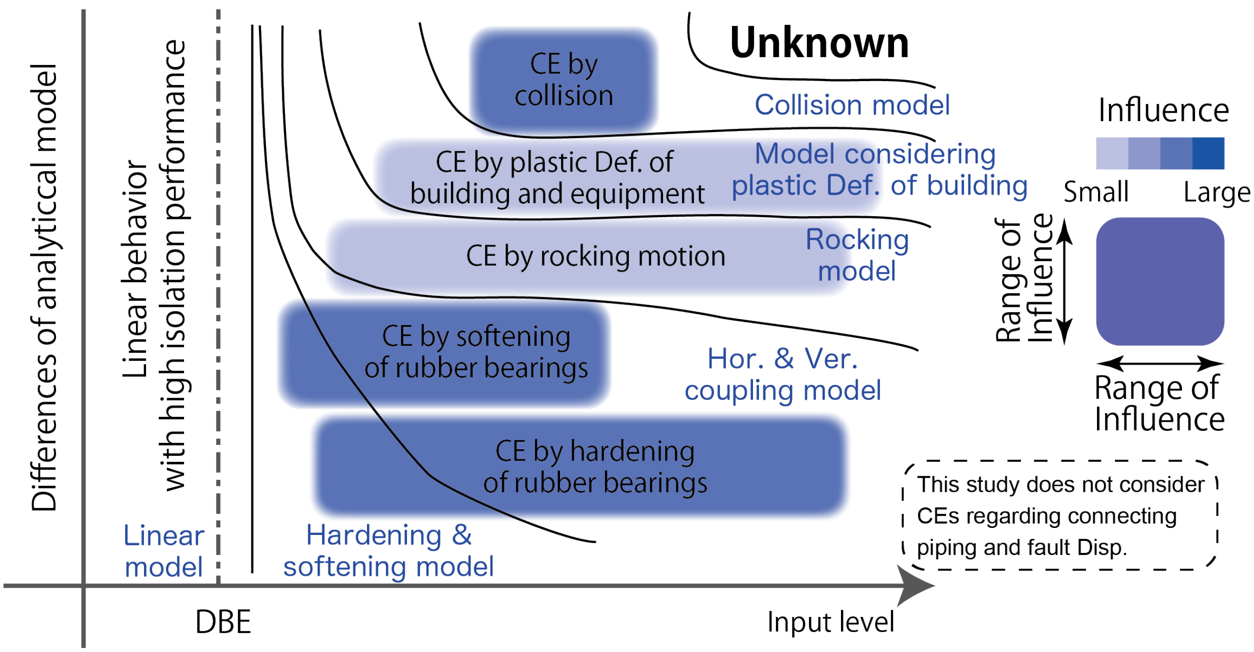



Figure 10. Relationship between cliff edges of seismically isolated structure and input level.

## CONCLUSION

In this paper, avoidance of cliff edges by introducing the seismic isolation and cliff edges specific to seismically isolated structures were investigated by seismic response analyses. Seismic response analyses using the analytical model which considers nonlinearities of rubber bearings and collision of the isolated structure with the surrounding walls were conducted, then the analytical results were evaluated from the viewpoints of physical and knowledge-oriented cliff edges. The results obtained in this paper is summarized as follows.

Nonlinearities of rubber bearings and collision with surrounding walls can be factors of cliff edges specific to seismically isolated structures.

Although collision of isolated structures declines isolation performance, the influence of collision can be suppressed by designing the clearance, the collision stiffness and the damping carefully.

Nonlinearities of rubber bearings provide complex behavior of response.

Although response acceleration decreased with the increase of the isolation period, the difference of response by isolation period became smaller if nonlinear response appeared.

The effects of nonlinearities of rubber bearings and collision of isolated structures are large from the both viewpoints of the physical and the knowledge-oriented cliff edges.

Nonlinearities of rubber bearings can be the cliff edges in the wide range of the input level. On the other hand, collision of isolated structures with surrounding walls can be the cliff edge in the narrow range of the input level.

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