The Use of a Base Isolation System for an Emergency Diesel Generator to Reduce the Core Damage Frequency Caused by a Seismic Event

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ABSTRACT

A seismic-induced core damage frequency (CDF) of a nuclear power plant can be remarkably reduced by an application of a base isolation system for an Emergency Diesel Generator (EDG). The effectiveness of the seismic isolation effect of a base isolation system for an EDG set was demonstrated through a shaking table test for a scaled EDG model by using a uniform hazard spectrum. The results of the shaking table test demonstrated that the base isolation system can significantly reduce the seismic force transmitted to an EDG set from the table. A seismic fragility analysis method for a base isolated structure was developed, and then the effect of a seismic isolation of an EDG set on its seismic fragility curve was investigated through a fragility analysis. It is shown that the probability of a failure of the EDG set is dramatically decreased by introducing the base isolation system, and, as a result, the HCLPF (High Confidence of Low Probability of Failure) value increases remarkably. Finally, when the base isolation system is introduced to the EDG set, the core damage frequencies were evaluated. A case study showed that a reduction of 47 percent of a seismic-induced CDF can be achieved by the base isolation system, and finally a plant level CDF can be reduced by 19 percent.

INTRODUCTION

An Emergency Diesel Generator (EDG) is the primary power source to supply AC power to the Class 1E power systems and equipment when the main turbine generator and offsite power source are not available in nuclear power stations. The EDG reduces the probability of a station blackout (SBO) due to a failure of AC power and finally it reduces the core damage frequency. For the purpose of improving the integrity of an EDG set, a spring-damper system has been adopted as a vibration and seismic isolation system because it is able to reduce the mechanical vibration level on the floor during an operation of the engine as well as the seismic force transmitted to an EDG body from the ground during an earthquake[1-3].

The basic concept of a base isolation is to decouple a structure from the horizontal components of an earthquake ground motion by interposing a soft layer with a low horizontal stiffness between the structure and the foundation. This soft layer gives the structure a much lower fundamental frequency than its fundamental frequency for a fixed base and also much lower than the predominant frequencies of the ground motion. When a destructive earthquake occurs, since most of the deformation behavior is concentrated on the soft layer, the remainder of the structure will remain nearly elastic. Thus, a floor acceleration and interstory drift of a structure will be significantly reduced and also damage to structural elements will be dramatically reduced. Also, the elastic behavior of an isolated structure will give a more reliable response than conventional structures. An application of a base isolation system to nuclear facilities will improve the plant safety margin against the design basis earthquake as well as a beyond design basis seismic event due to its superior seismic performance. Base isolation of individual components is especially beneficial in a situation where existing components and their supports have to be requalified for higher seismic loads. By using a base isolation, it may be possible to avoid an expensive retrofitting of a supporting facility and foundation.

There are limited studies on a seismic isolation of equipment and components in spite of the potential advantages that an application of a base isolation system for equipment and components can improve the seismic safety of a nuclear power plant. Kelly[4], Hall[5], and Ebisawa et al.[6] proposed the use of base isolation systems for improving the seismic capacity of various components. The results of their studies indicate that the use of a base isolation in light secondary equipment or a large component can be beneficial in reducing the accelerations experienced by a component. Especially, Ebisawa et al. studied a base isolation of a nuclear component by experimental and numerical methods, and developed the technical basis for a seismic isolation of nuclear components. They also carried out various experiments including field tests against real earthquakes in order to obtain test data for a component base isolation. They concluded in their study that a seismic base isolation can improve the seismic resistance of nuclear components and decrease their functional failure probability. Huang et al.[7] showed that considerable reductions of the seismic demands on secondary systems in a nuclear power plant can be realized by seismic isolation systems. Also, recent studies have shown that the increase of a seismic capacity of an Emergency Diesel Generator can remarkably reduce the core damage frequency in nuclear power plants[8, 9].

This study evaluates a core damage frequency (CDF) of a nuclear power plant when an Emergency Diesel Generator is mounted on a base isolation system. Firstly, the contribution of a failure of equipment and components to the CDF was investigated and a failure mode of each equipment and component was also investigated. Secondly, the seismic isolation effect of the base isolation system for the EDG set was evaluated through a shaking table test for a scaled EDG model by using a uniform hazard spectrum. Thirdly, a seismic fragility analysis method for a base isolated structure was developed, and then the effect of a seismic isolation of an EDG set on its seismic fragility curve was investigated through a fragility analysis. Finally, when the base isolation system is introduced to the EDG set, the core damage frequencies were evaluated through a case study.

CONTRIBUTION TO CORE DAMAGE FREQUENCY

The contribution of a seismic-induced failure of a component or equipment to the plant core damage frequency was evaluated for most nuclear power plants in Korea. Figure 1 shows the contribution ratios of safety-related components and equipment to the seismic-induced CDF for Yonggwang Nuclear Unit 5&6, Ulchin Nuclear Unit 3&4, and Ulchin Nuclear Unit 5&6. It is found from Figure 1 that an Emergency Diesel Generator, an Offsite Power System, a Condensate Storage Tank, a Battery Rack, and a Battery Charger have a high contribution to the seismic-induced CDF in nuclear power plants. Above all, the contribution ratio of the EDG is so high that an increase of the seismic capacity of an EDG is essential to reduce the total plant CDF. The CDF contribution ratios of the EDG in Yonggwang Nuclear Unit 5&6, Ulchin Nuclear Unit 3&4, and Ulchin Nuclear Unit 5&6 are 29.8, 20.5, and 29.7 percent, respectively.

Table 1 shows a failure mode and a HCLPF (High Confidence of Low Probability of Failure) value of the important equipments for each nuclear unit. The HCLPF value of the EDG is relatively lower than that of the Condensate Storage Tank. Therefore, if one equipment item or component has to be selected for improving the seismic safety of a nuclear power plant, the first choice should be the EDG. The failure mode of the EDG is known as a concrete coning failure due to a pulling out of the anchor bolts as shown in Table 1. Thus, to increase the seismic capacity of the EDG, a base isolation system can be introduced instead of an anchor bolt.

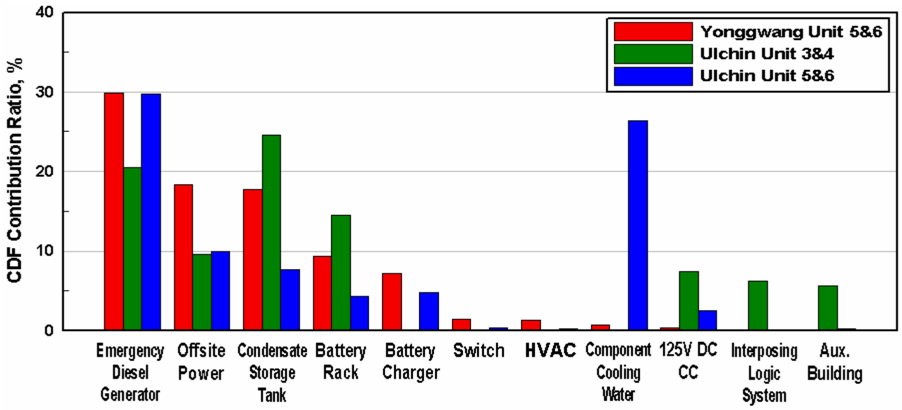


Fig. 1 CDF contribution ratios of the major equipment and components at Korean NPPs[10]

Table 1. Failure mode and HCLPF value

Nuclear Unit	Equipment/Components	Failure Mode	HCLPF (g)
Yonggwang Unit 5&6	Diesel Generator	Concrete Coning	0.38
	Offsite Power	Functional Failure	0.15
	Condensate Storage Tank	Structural Failure	0.41
	Battery Rack	Structural Failure	0.72
	Battery Charger	Functional Failure	0.41
		Structural Failure	0.52
Ulchin Unit 3&4	Diesel Generator	Concrete Coning	0.38
	Offsite Power	Functional Failure	0.15
	Condensate Storage Tank	Structural Failure	0.41
	Battery Rack	Structural Failure	0.43
Ulchin Unit 5&6	Diesel Generator	Concrete Coning	0.38
	Offsite Power	Functional Failure	0.15
	Condensate Storage Tank	Structural Failure	0.45
	ESW Pump	Anchorage	0.47
	CCW Surge Tank	Concrete Coning	0.47

EFFECTIVENESS OF A SEISMIC ISOLATION

For a base isolation of rotating equipment such as an EDG, especially, a coil spring-viscous damper system is suitable because a mechanical vibration in a vertical direction is generated during an operation and it is reduced by a coil spring with a low vertical stiffness[11]. Thus, a coil spring-viscous damper system has been adapted to vibrating machines to reduce their mechanical vibration during an operation as well as their seismic force during an earthquake. This study evaluates the seismic effectiveness of a coil spring-viscous damper system through a seismic test of a scaled model of a base-isolated EDG on a shaking table. As a prototype, an EDG set with a HANJUNG-SEMT Pielstick Engine 16PC2-5V 400 was chosen, which is identical to the EDG installed at Yonggwang Nuclear Unit 5&6, Wolsung 2, 3&4 and Ulchin Nuclear Unit 3&4, 5&6 of Korea, and the scaled model was designed to represent the seismic behavior of a prototype of an EDG set. The dynamic characteristics of the coil spring-viscous damper system were obtained by cyclic tests and the seismic responses of the base-isolated EDG model were obtained by shaking table tests.

EDG Test Model

The prototype of the EDG set consists of an engine unit, a generator unit, and a concrete mass. Net weights of the engine unit, the generator unit, and the concrete mass are 912 kN, 392 kN, and 2,474 kN, respectively, and the total weight is 3,779 kN. A 6-DOF seismic simulator with a table dimension of 2.5 m × 2.5 m was used for the model test. Test model was designed by considering the size of the shaking table of the simulator as shown in Figure 2, which consists of a concrete block of 2,300 mm × 800 mm × 450 mm, four steel blocks of 600 mm × 600 mm × 140 mm, and two steel plates of 1,500 mm × 300 mm × 30 mm. Total weight of the test model is 39 kN and the steel blocks were placed to have an equivalent mass center of the prototype.

For the seismic isolation of the EDG test model, a coil spring-viscous damper unit that consists of a combination of 2 coil springs and one viscous damper was adapted. The stiffnesses and the damping coefficients of the coil spring-viscous damper unit for the vertical and horizontal directions were determined by the seismic responses of the EDG test model for the input motion. The test model was supported by 4 coil spring-viscous damper units as shown in Figure 2.

Item		Properties
Load Capacity		15 kN
Height		410 mm
Stiffness	Vertical	0.144 kN/mm
	Horizontal	0.04 kN/mm
Damping Coefficient	Vertical	3.5 kNs/m
	Horizontal	4.0 kNs/m

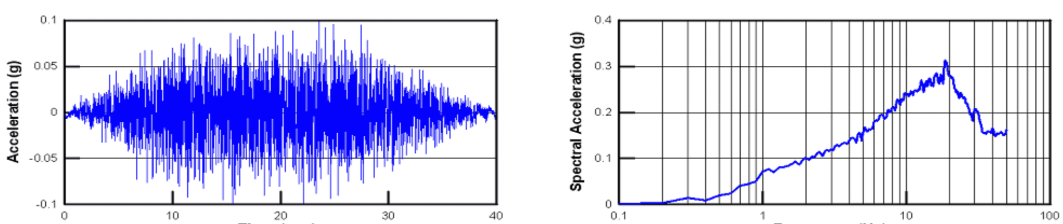
Fig. 2 EDG model with spring-damper units for the shaking table test

Shaking Table Test

An artificial time-history corresponding to the uniform hazard spectrum[12] was used and three peak acceleration levels of 0.1g, 0.2g, and 0.3g were applied for the input table motion. Seismic tests were carried out for one and three directional excitations. Identical input motions and peak acceleration levels were used in two horizontal directions and one vertical direction. Figure 3 shows the artificial time history and response spectrum of the input motion. The acceleration and displacement responses were measured by using two accelerometers and eight LVDTs.

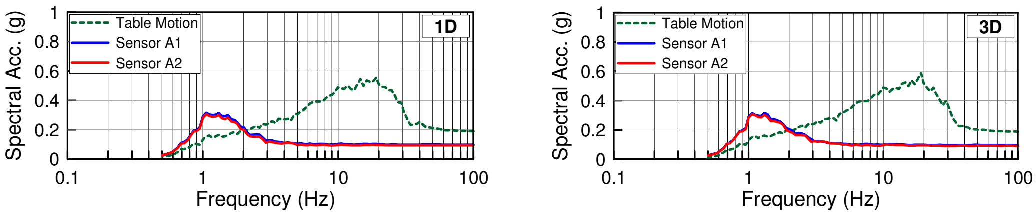
Test Results

Figure 4 shows the spectral accelerations for the peak acceleration level of 0.2g during one and three directional excitations together with the table motions. It is found that the spectral accelerations decrease significantly due to a shift



(a) Artificial time-history (b) Response spectrum

Fig. 3 Input motion for the shaking table tests of the predominant frequency from 20Hz to 1.0Hz, and the differences between the acceleration responses in the one horizontal excitation and the three directional excitations are very small. Figure 5 shows the horizontal and vertical acceleration response ratios, which are determined as a ratio of the peak acceleration response for the test model to the peak acceleration of the shaking table, for different acceleration levels and excitation directions. There was a small difference in the acceleration response ratios between the two accelerometers (A1, A2) because the mass center was not located at the center of the test model. The average response ratios for the horizontal and vertical directions are 0.5 and 0.7, respectively. This indicates that the coil spring-viscous damper system can reduce the seismic force transmitted to the EDG model from the table by up to 50 percent in the horizontal direction and 30 percent in the vertical direction, respectively. This result demonstrates that the seismic capacity of an EDG set can be effectively improved by using a base isolation system. The acceleration response ratios can be minimized by an optimum design of the base isolation system.



(a) One horizontal excitation (b) Three directional excitations

Fig. 4 Spectral accelerations for the peak acceleration of 0.2g

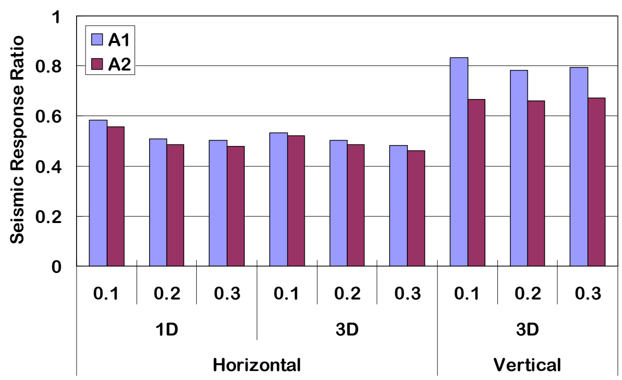


Fig. 5 Comparisons of acceleration response ratios for the isolated EDG model

FRAGILITY ANALYSIS

It is known that the major failure mode of an EDG is a concrete coning failure due to a pulling out of the anchor bolts as shown in Table 1. However, if applying the base isolation system to the EDG, the major failure mode will not be a concrete coning failure any more. The governing failure mode of the base-isolated EDG must be a failure of the isolation system. Thus, the fragility curves for a base-isolated EDG should be different from those for a conventional type. This study developed a fragility analysis method for a base-isolated structure and investigated the effect of a seismic isolation of an EDG set on its seismic fragility curve.

Fragility Analysis Method

A simple fragility analysis method which uses only one seismic input motion was proposed[13]. The proposed method uses a relation regarding the seismic response and input seismic motion. The probability of a structural failure regarding an input seismic motion is defined by Eq. (1).

$$F_A(A) = \int_0^\infty f_R(A, x_R)\left[\int_0^{x_R} f_C(x)dx\right]dx_R \tag{1}$$

where, f_R is a probability density function of a seismic response, and f_C is that of the capacity. Equation (1) can also be represented as Eq. (2).

$$F_A(A) = 1 - \Phi\left[\frac{\ell n C_m - \ell n R_m(A)}{\sqrt{\beta_C{}^2 + \beta_R(A)^2}}\right] \tag{2}$$

where, β_C and β_R are an uncertainty of capacity and response, respectively. A relation of the mean response and the median response can be given as in Eq. (3).

$$R_m(A) = \frac{\overline{R(A)}}{\sqrt{1+\left(\frac{\sigma_R}{\overline{R(A)}}\right)}} = \overline{R(A)} \cdot e^{-\frac{1}{2}\beta_R{}^2} \tag{3}$$

Using Eq. (3), Eq. (2) can be rewritten as Eq. (4).

$$F_A(A) = 1 - \Phi\left[\frac{\ell n C_m - \ell n \overline{R(A)} - \frac{1}{2}\beta_R{}^2(A)}{\sqrt{\beta_C{}^2 + \beta_R(A)^2}}\right] \tag{4}$$

where, $\ell n \overline{R(A)}$ is a logarithm of the mean response. The relation of $F_A(A)$ and A represents the probability of a failure.

Fragility Analysis

A fragility analysis was carried out for a base-isolation and non-isolation EDG set. Since the natural frequency of the EDG set is about 34Hz, its dynamic behavior is similar to a rigid body motion. Thus, a numerical model of a single degree of freedom system as shown in Figure 6 was used for the fragility analysis. The weight of the EDG is modeled as a lumped mass at the mid-height and spring elements which consist of two springs for the horizontal direction and one spring for the vertical direction are introduced at the base of the EDG in order to represent the behavior of the base isolation system. The identical input seismic motion used for the shaking table test was applied for the fragility analysis. The failure criterion for the fragility analyses were assumed as a maximum acceleration response of 1.2g and a maximum displacement limit of 5cm.

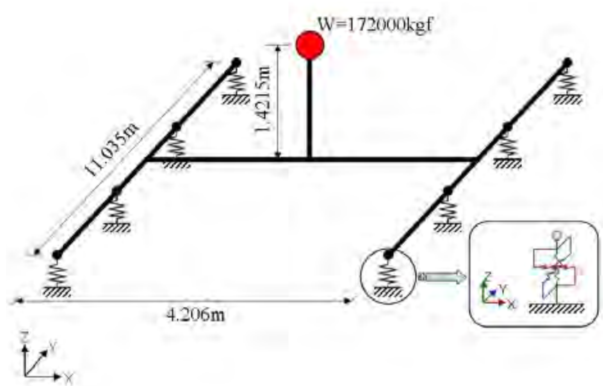
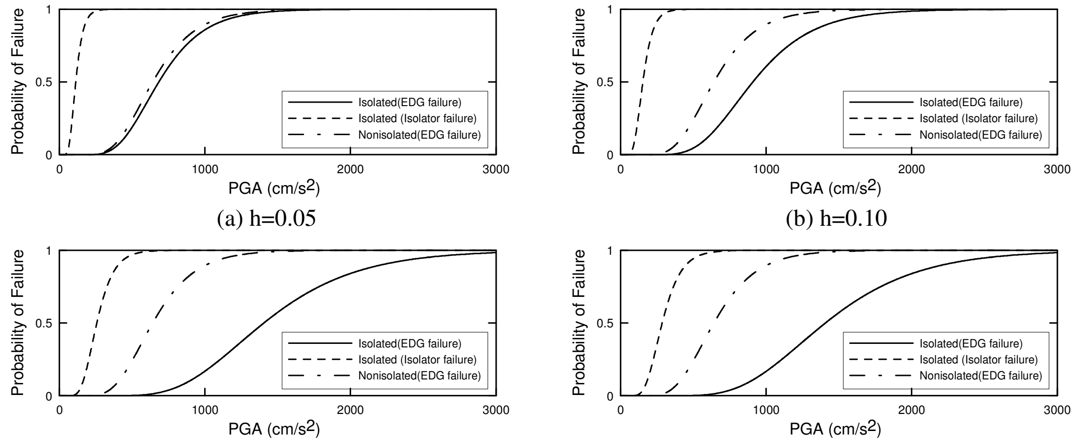


Fig. 6 Numerical model of a base-isolated EDG

The results of the fragility analysis for various damping coefficients are shown in Figure 7. The figure shows that when an EDG is supported by a base isolation system, the failure probability of the EDG body will be significantly decreased because the governing failure mode of an isolated EDG will be the failure of an isolator. The fragility curves are very sensitive to the damping value of an isolation system. For a larger damping value, the probability of a failure will be low. The HCLPF values of the base-isolated EDG set determined with the same parameters are shown in Figure 8. It is found that the failure of an isolator governs the probability of a failure of the isolated EDG set except with a damping ratio of over 10 percent and the probability of a failure of the isolated EDG set is dramatically decreased. As a result it can be said that the seismic safety of an EDG set is increased by using a base isolation system.

The fragility curves of the base-isolated EDG set for various failure criteria of the displacement of an isolator are shown in Figure 9. It is easily seen that the probability of a failure will be low for the limitation of a large displacement. The HCLPF values for various failure criteria of the displacement of an isolator are shown in Table 2. The HCLPF value



(a) h=0.05 (b) h=0.10

(c) h=0.25 (d) h=0.40

Fig. 7 Fragility curves of the isolated EDG set for different damping ratios

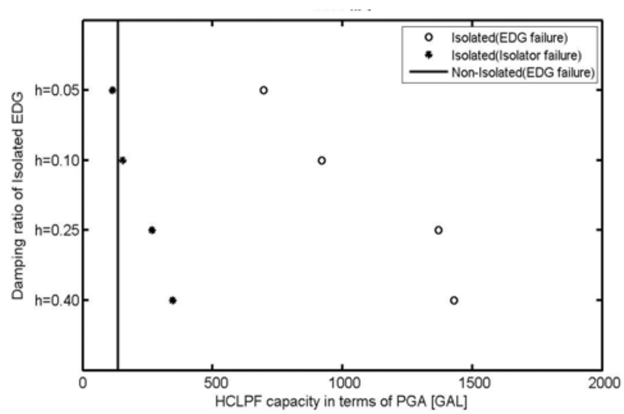


Fig. 8 HCLPF values of the isolated EDG set for different damping ratios

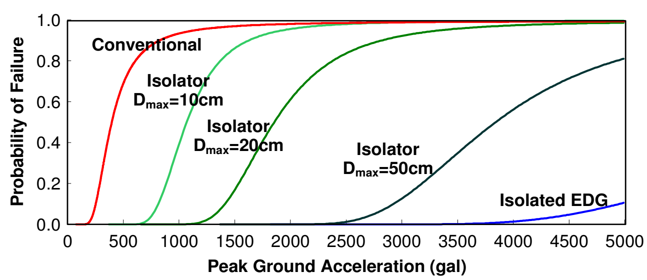


Fig. 9 Fragility curves of the isolated EDG set for displacement failure criteria

Table 2. HCLPF values for the displacement failure criteria

Type	HCLPF (gal)
Conventional EDG	192
Isolated, D_{max}=10 cm	687
Isolated, D_{max}=20 cm	1,192
Isolated, D_{max}=50 cm	2,470
Isolated, no failure at isolators	3,903

is very sensitive to the displacement failure criteria of an isolator, and the HCLPF value is significantly increased with an increase of an allowable displacement of an isolator. For instance, when the maximum displacement of the isolator is limited to 10 cm, the HCLPF value increases by 3.6 times the HCLPF value for a conventional EDG, and when the maximum displacement of the isolator is limited to 20 cm, the HCLPF value increases by 6.2 times the HCLPF value for a conventional EDG.

CORE DAMAGE FREQUENCY

Core damage frequencies were evaluated through a case study for Yonggwang Unit 5&6 when a base isolation system is introduced to an EDG set only. In general, a seismic-induced CDF is reduced with an increase of the seismic capacity of an EDG. However, there is a limitation in the reduction of the seismic-induced CDF. For a larger HCLPF value than an effective value, even though the seismic capacity increases, the seismic-induced CDF does not decrease any more as shown in Figure 10. For the EDG, it is found from Figure 10 that there is little decrease in the seismic-induced CDF for a HCLPF value greater than 0.84g.

A seismic-induced CDF and a total CDF for Yonggwang Unit 5&6 were originally calculated as 7.79E-06 and 1.76E-05, respectively. When the HCLPF value of the EDG reaches 0.84g by introducing a base isolation system, a seismic-induced CDF and a total CDF were calculated as 4.46E-06 and 1.42E-05 as shown in Table 3, respectively. This indicates that a reduction of 47 percent in a seismic-induced CDF can be achieved by the base isolation system, and finally a total CDF can be reduced by 19 percent.

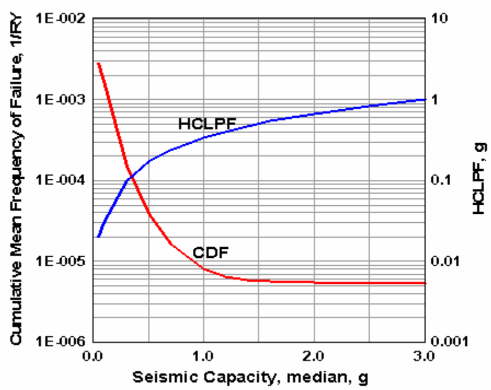


Fig. 10 Relations between the HCLPF of an EDG and the CDF[9]

Table 3. Comparison of the CDF between the non-isolated and isolated cases

Event	Non-Isolation	Base Isolation
Internal	7.43E-06	7.43E-06
Seismic	7.79E-06	4.46E-06
Fire	2.35E-06	2.35E-06
Total	1.76E-05	1.42E-05

CONCLUSION

This study evaluates a CDF of a nuclear power plant when a base isolation system is introduced to an EDG set. An EDG set reveals a high contribution to a seismic-induced CDF but its HCLPF value is not high. Thus, if one equipment item or component has to be selected for improving the seismic safety of a nuclear power plant, the first choice should be the EDG. Since the failure mode of the EDG is known as a concrete coning failure due to a pulling out of the anchor bolts, the use of a base isolation system instead of an anchor bolt will increase the seismic capacity of an EDG.

A base isolation system is very effective for an improvement of the seismic capacity of equipment or components. The effectiveness of the seismic isolation effect of a base isolation system for an EDG set was demonstrated through a shaking table test for a scaled EDG model by using a uniform hazard spectrum. The coil spring-viscous damper system for the EDG could reduce the seismic force transmitted to the EDG model from the table by up to 50 percent in the horizontal direction and 30 percent in the vertical direction, respectively. The seismic capacity of an EDG set can be effectively improved by using a base isolation system.

The seismic fragility curves for a base-isolated EDG will be different from those for a conventional type. The results of seismic fragility analyses by using a simple method proposed in this study showed that the fragility curves were very sensitive to the damping value of an isolation system and the HCLPF value was very sensitive to the displacement failure criteria of an isolation system. The probability of a failure will be low for a larger damping value and the HCLPF value is significantly increased with an increase of an allowable displacement of an isolation system. An introduction of a base isolation system to an EDG set will reduce its failure probability and increase its HCLPF value.

In general, a seismic-induced CDF is reduced with an increase of the seismic capacity of an EDG. However, for a larger HCLPF value than an effective value, even though the seismic capacity increases, the seismic-induced CDF does not decrease any more. The effective HCLPF value for the EDG in Yonggwang Unit 5&6 was determined as 0.84g. There is little decrease in the seismic-induced CDF for a HCLPF value of an EDG greater than 0.84g for Yonggwang Unit 5&6. When the HCLPF value of the EDG reaches 0.84g by introducing a base isolation system, a reduction of 47 percent in a seismic-induced CDF can be achieved, and finally a total CDF can be reduced by 19 percent.

A base isolation is a very powerful concept to improve the seismic safety of nuclear power plants through its introduction to their safety-related structures and components. A seismic-induced CDF and a total CDF could be significantly reduced by introducing a base isolation system to the facilities which reveal a high contribution to a seismic-induced CDF. A base isolation concept can be effectively applied to all nuclear facilities including buildings, liquid storage tanks, turbine and diesel generators, transformers, mechanical and electrical equipment, and secondary systems. Base isolation of individual components is especially beneficial in a situation where existing components and their supports have to be requalified for higher seismic loads. By using a base isolation, it may be possible to avoid an expensive retrofitting of a supporting facility and foundation.

ACKNOWLEDGEMENT

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