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Original Article

Seismic performance of emergency diesel generator for high frequency motions

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ABSTRACT

The nuclear power plants in South Korea have been designed in accordance with the U.S. Regulatory Guide 1.60 (R.G 1.60) design spectrum of which the peak frequency range is 2–10 Hz. The characteristics of the earthquakes at the Korea nuclear power plant sites were observed to be closer to that of Central and Eastern United States (CEUS) than the R.G 1.60, which is a lower amplification in a low frequency range, and a higher amplification in a high frequency range. The possibility of failure for sensitive power plant components in the high frequency range has been considered and evaluated. In this study, in order to improve the reliability of nuclear plant and administrative control procedures, seismic tests of an emergency diesel generator (EDG) were conducted using a shaking table under both high and low frequency ranges. From the tests, oil/lubricant leaks from the bolt connections, the fuel filter and the fuel inlet were observed. Therefore, the check list of nuclear plant components after an earthquake should include bolt connections of EDG as well as anchor bolts.

1. Introduction

The risk posed by seismic events to nuclear power plants (NPPs) operating in the United States has been the subject of several studies conducted over the past three decades. The prerequisite for the seismic risk study is the determination of the seismic hazard associated with a given plant site. Recent seismic hazard studies for the operating plant sites in the CEUS have concluded that an increased number of seismic motions at these sites had higher frequencies compared to the original safe shutdown earthquake (SSE) response spectrum used for the design of many plants [1]. Gyeongju earthquakes occurred in South Korea in 2016 with the magnitudes of 5.1 and 5.8 were also high frequency motions [2].

Equipment items important to the safety of operating NPPs were originally qualified for the in-structure or in-cabinet seismic motions consistent with the SSE defined for each plant. The SSE ground motions, did not typically include significant frequency contents above 10 Hz. To provide the guidance of hazard-consistent ground motions, the CEUS had maximum spectral values occurring in the 20–30 Hz range in the late 1980s [3]. It was reported that high-frequency motions were in general, non-damaging to components and structures that have strain- or stress-based potential failures modes [4–6]. On the other hand, components such as relays and other devices subject to electrical functionality failure modes have unknown acceleration sensitivity for frequencies greater than 16 Hz.

EDGs have been installed in many industrial and public facilities such as plants, buildings and hospitals, to ensure the safety and to maintain the functionality of the facilities after severe earthquake events. In nuclear power plants, AC power to Class 1E power systems and equipment must have uninterruptable power source. EDGs are used when the main turbine generator and offsite power source are not available. The Fukushima accident, power supply system failure due to post earthquake tsunami flooding, resulted in more robust requirements for electrical systems important to safety.

Emergency diesel generators with a capacity of 1750 kW–8800 kW have been installed for large-size medium-speed diesel engines at the South Korea nuclear power plants. Though the seismic performance of the real size EDGs was not evaluated because of the limited capacity of the shaking tables in South Korea, a small-scale model study was conducted to evaluate the seismic safety by isolation system based on the similitude law [7,8]. The study was conducted on a shaking table with a low frequency, and the effect of high frequency on the seismic performance of an emergency diesel generator was not evaluated [9–11].

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Table 1
Failure mode of EDG under standby condition in NPP(%) [12–14].

Degree of damage	GRS	IRSN	U.S.NRC	IAEA
Potential failure	32	53.7	27.8	51
Complete failure	57	43.5	33.0	49
Degraded ability	11	2.7	39.1	–

Table 3
Failure mode of EDG by earthquake [16].

Un-start	Failure to start				Total
	Equipment failure	Fuel poverty	Tsunami	Unknown	
17	60	125	24	7	233

In this study, a shaking table test of an emergency diesel generator was conducted to improve the reliability of the seismic performance of nuclear plants and the administrative control procedure. A seismic input motion was simulated based on the R.G 1.60 design spectrum and the Korean Nuclear Power Plant site specific Uniform Hazard Spectrum (UHS). The UHS motion was selected for the evaluation of high frequency effects. To investigate the EDG after seismic tests, a functional test and visual inspection were conducted after each seismic test. The changes of the voltage, frequency, and temperature of the EDG from standby condition were also measured and compared for the acceptable limits.

2. Failure mode of EDG and fragility analysis of components at NPP

The failure of an emergency diesel generator should be considered as both structural and functional failures. A structural failure mode with component of EDG system should be considered as bending or shear. In the case of an anchor bolt failure, breakout, tension and shear failures should be considered. A functional failure mode should be considered as the frequency and voltage within acceptable limits.

2.1. Failure mode of EDG under standby condition in NPP

In order to classify the failure modes in standby conditions, the NPP EDG maintenance and overhaul records of the following databases were evaluated from GRS(Gesellschaft für Anlagen- und Reaktorsicherheit), IRSN(Institut de Radioprotection et de Sûreté Nucléaire), IAEA(International Atomic Energy Agency), and U.S. NRC(United States Nuclear Regulatory Commission) [12–14]. In total, 676 events related to EDG failures are summarized in Table 1 and Table 2.

2.2. EDG failure by earthquake in industrial and public facilities

Infrastructures such as hospitals and public facilities need uninterruptible power supplies to ensure their services. Most of the failures of occur in engine, exhaust, and cooling systems [15]. It is similar to the failure mode of diesel engine generator in NPP. In the failure of an engine system, supports made of rubber mounts or spring mounts, used for reducing the engine vibration were damaged, as well as the flexible pipes attached to the engine. Also, the pipeline systems failed due to uneven settling of the foundation and the fuel supply stoppage. Thus, the amount of fuel was limited as a precaution against fire.

In total, 4,811 EDGs in the regions of 6.0 or higher magnitude earthquakes that were investigated are summarized in Table 3. There was no damage to the mechanical parts but there were some electrical issues. The biggest problem however, was the fuel supply for the generators. It was impossible to store more than 1000 L of fuel due to legal restrictions. When the fuel was used, it could not be replenished because traffic was disrupted in the emergency following the earthquake and the power was interrupted for a week [16].

2.3. Fragility analysis of components at NPP

The fragility study results of Ulchin 5 and 6 NPP in South Korea are summarized in Table 4 according to the type of structures and components [17]. A_m represents a median seismic capacity, β_r and β_u are randomness and uncertainty values of failure probability, respectively. HCLPF stands for high confidence and low probability of failure. The definition of HCLPF is 95% confidence and 5% probability of exceedance. The resonant frequency of the EDG was evaluated at 10 Hz, and the median capacity of EDG concerning functional and structural failure was evaluated at 0.92 g. The HCLPF value concerning functional and structural failure of this EDG was evaluated as 0.40 g.

3. Test specimens and test conditions

3.1. Test specimen

An EDG system mainly consists of a diesel engine, a generator and a radiator mounted on a skid frame as well as the support systems such as lubricating oil, fuel oil, starting air, turbo air, cooling and ventilation.

The generator is an AC synchronous, single bearing bracketed, and foot mounted unit with a rating of 1000 kW, 1600 RPM and a weight of about 29.0 kN, as shown in Fig. 1(a). The diesel engine is a 12cylinder, 175 mm stroke, open combustion system with an electro-hydraulic governor and a weight of about 46.2 kN. The radiator consists of a radiator assembly housing and a single engine cooling water fan driven by a diesel engine. The skid frame consists

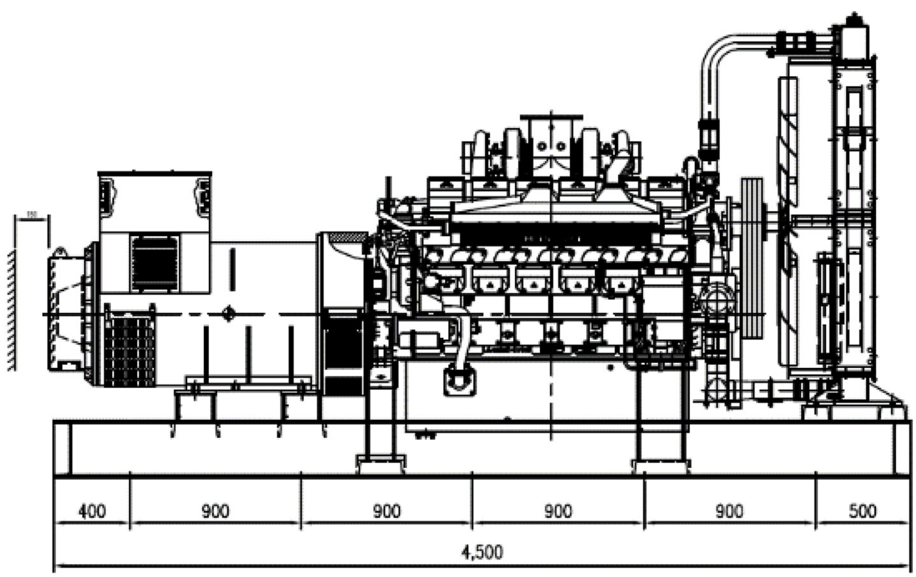
Table 2
Percentage of Failure of EDG components/systems [12–14].

System and component		GRS	IRSN	U.S.NRC	IAEA
Engine and mechanical systems	Engine	17	11.4	4.3	14
	Cooling system	10	21.2	13.0	22
	Fuel system	16	15.7	14.8	6
	Starting system	17	5.9	3.5	5
	Exhaust system	6	0.4	2.6	–
	Lubrication system	6	4.3	4.3	8
Generator and electrical-control system and other		28	41.1	57.5	45

Table 4
Fragility result of Ulchin 5 and 6 NPP in South Korea [17].

Structure or components	Resonant frequency (Hz)	Failure modes[a]	A_m	β_r	β_u	HCLPF (g)
Off-site power	–	GF	0.30	0.22	0.20	0.15
Emergency diesel Generator	10	S&F	0.92	0.30	0.20	0.40
4.16 kV SWGR	5	F	1.33	0.33	0.29	0.48
Battery Charger	N/A	S	1.35	0.29	0.31	0.50
Inverter	14.07	S	1.43	0.29	0.30	0.54
125V DC control center	15.08	S	1.12	0.29	0.30	0.42

[a] GF-Generic function, S-Structure, F-Function, S&F-Structure and function.



(a)

(b)

Fig. 1. Dimension and shape of tested EDG (unit: mm): (a) dimension of EDG, (b) test set up.

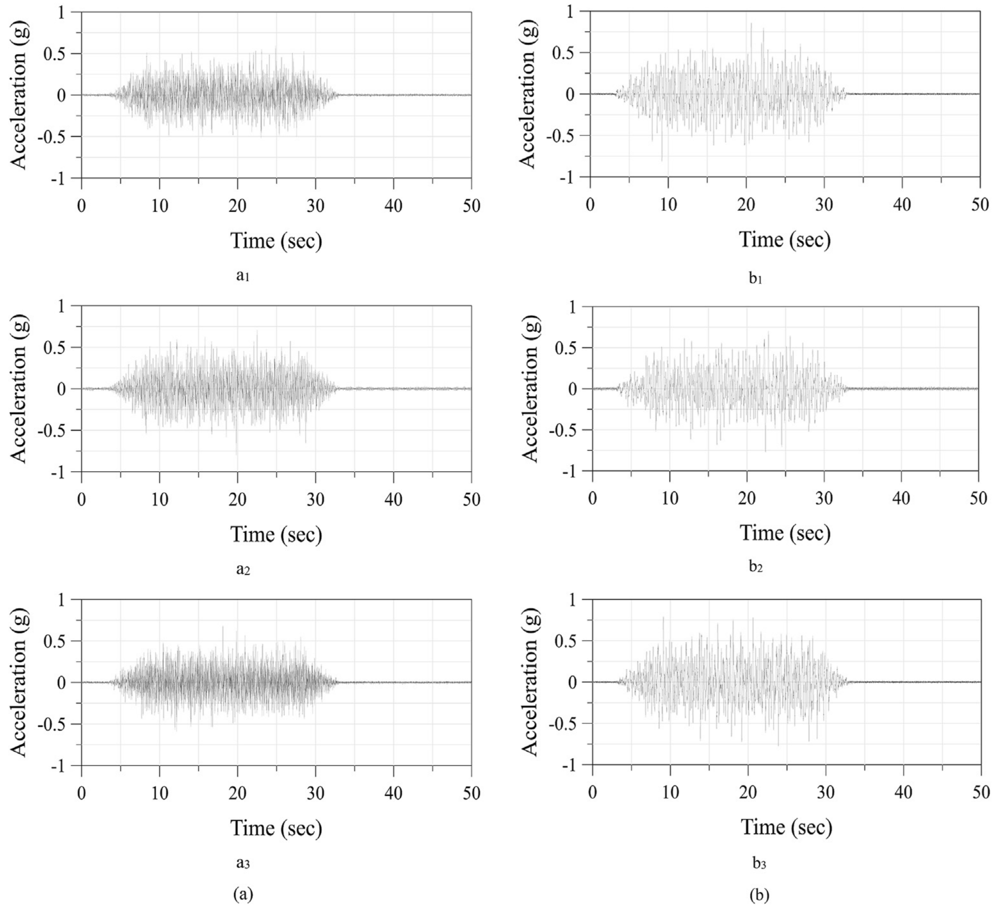


Fig. 2. Acceleration time history of UHS and RG 1.60 motions: (a) seismic motion of UHS(a_1: X direction, a_2: Y direction, a_3: Z direction), (b) Seismic motion of R.G 1.60(b_1:X direction, b_2: Y direction, b_3: Z direction).

of two C-channels that run the length and are stiffened by cross beams and ribs at various locations. The engine, the generator and the radiator are bolted down to the top flanges of the C-channels. The bottom flanges of the C-channels are anchored to the floor at several locations on each side, as shown in Fig. 1(b).

Seismic qualifications of the different components of an EDG system may be accomplished by analysis, test or a combination of approaches. Seismic testing can be used to determine accurate equipment capacity, obtain in-equipment response spectra and demonstrate functionality as well as detect contact chattering.

3.2. Seismic test conditions

To evaluate the seismic performance of the EDG system, two seismic input motions were used. The first one was a low frequency motion based on the R.G 1.60 design spectrum, and the second one was a high frequency motion based on the Korean Nuclear Power Plant site specific UHS in Uljin [18]. The UHS motion was selected to evaluate high frequency effect on the EDG, and the acceleration time histories of the two motions are shown in Fig. 2.

Table 5
Seismic test sequence.

Test No.	Input motion	Remarks
1	Random wave	Resonant frequency search
2	RG 1.60	3D 200%, 225%, 250%, 275%, 300%, 325%, 350%
3	Random wave	Resonant frequency search
4	Random wave	Resonant frequency search
5	UHS	3D 200%, 225%, 250%, 275%, 300%, 325%, 350%
6	Random wave	Resonant frequency search

Table 6
Summary of resonant frequency test results.

Test No.	Resonant frequency (Hz)								
	Radiator			Engine			Generator		
	X	Y	Z	X	Y	Z	X	Y	Z
1	6.25	9.00	21.50	16.50	12.50	24.00	16.50	12.00	24.00
3	5.50	8.75	21.50	16.50	11.50	24.50	16.50	11.50	24.50
4	6.00	9.00	21.50	16.50	12.00	23.50	16.50	11.75	23.50
6	5.75	8.75	21.25	15.50	11.00	21.25	15.00	10.75	23.25

The shaking table tests were performed on a three dimensional shaking table for a 0.3 g PGA (Peak Ground Acceleration) level following the sequence shown in Table 5. The seismic test of the EDG was carried out to in 25% increments from 200% to 350% in accordance with IEEE 344 [19] and IEEE 323 [20], and the resonant frequency tests were conducted for 30 s with random wave up to root mean square of 0.1 g and frequency range of 0.5 Hz–60.0 Hz. However, the seismic test was limited by the shake table capacity and structural and functional failure information could not be generated from the seismic test. After the seismic tests, visual inspection and functional test were conducted.

3.3. Functional test and visual inspection

A number of operating plants without offsite power supplies, experienced shutdown of station power. A substantial amount of electricity is required to run the safety system of the plant components and the control and instrument devices at any time. Thus, the EDG must operate with an auto-start signal from the standby condition in such way that the required voltage and frequency are within the acceptable limits of 10 s under the Loss of Offside Power (LOOP) and the Safety Injection Actuation Signal (SIAS) requirements. A functional test and visual inspection were conducted after each seismic excitation to investigate the effect of an earthquake on the function of EDG. The voltage, frequency, and temperature were measured in accordance with the IEEE 287 standard [21].

4. Test results

4.1. Resonant frequency test

To evaluate the dynamic characteristics of the EDG components, resonant frequency test was performed before and after the seismic tests. The resonant frequency tests were conducted in the order of X, Y and Z directions by installing accelerometers on the radiator, engine and generator. The test results are summarized in Table 6.

4.2. Seismic test

The acceleration response spectrum was computed from the measured acceleration time histories and a 3% damping level was adopted. The acceleration response spectra for the different input seismic motions are compared in Fig. 3. The test response spectrum (TRS) shows higher acceleration values than the required response spectrum (RRS). Those are measured acceleration response at the radiator, engine, and generator in X-direction are shown in Fig. 4.

Since EDGs are connected to the foundation concrete by anchor bolts, seismic capacity of the anchor bolts is important to prevent earthquake damage. In this study, pull-out force of M30 anchor bolts was evaluated for different peak ground accelerations and input motion spectra, and the results are shown in Fig. 5. The pull-out force for the RG 1.60 spectrum increased rapidly with increasing PGA and was larger than that for UHS spectrum for the same PGA, which increased gradually with increasing PGA. Using these results, the design strength of the anchor bolts was calculated and found to be within the acceptable values of bolt failure based on ACI 318 [22].

4.3. Results of functional test and visual inspection

With the safety injection signal and the loss of voltage signal, the EDG should be started and be ready to shut down the nuclear reactor safely. Though reliability of the EDG is important for the safety of the NPP, several NPP sites have experienced leaks in the piping for fuel oil, lubricating oil, or water [23]. Many of these leaks resulted from fatigue cracks in welded joints, induced by normal engine vibration.

Fig. 6 shows the voltage of the EDG after the seismic tests with R.G 1.60 at 350% and UHS at 325%. The EDG ordinarily operated in spite of fuel filter leakage. The results of the functional test and the visual inspection are summarized in Table 7, which shows that performance of the EDG was acceptable without any structural damage.

4.4. Comparison of test results for R.G 1.60 earthquake and UHS earthquake

Resonant frequencies at the radiator, engine and generator were similar before and after seismic test under both R.G 1.60 and UHS input motions. The pull-out force of anchor bolt was shown to be below the acceptable values without bolt failure. However, the increase of pull-out force under R.G 1.60 was greater than that corresponding to UHS. This result implies that the qualification requirement for anchor bolt by design spectrum (R.G 1.60) is severe

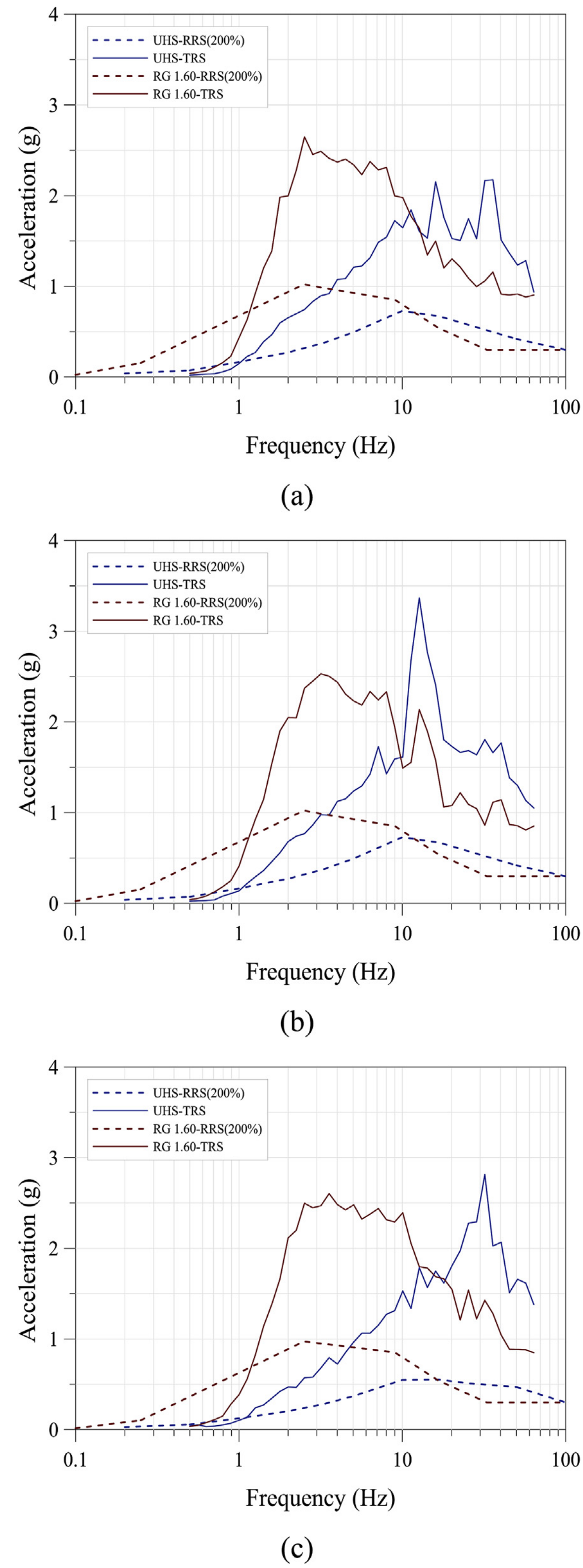


Fig. 3. Acceleration response spectrum with 3% damping ratio: (a) X direction, (b) Y direction, (c) Z direction.

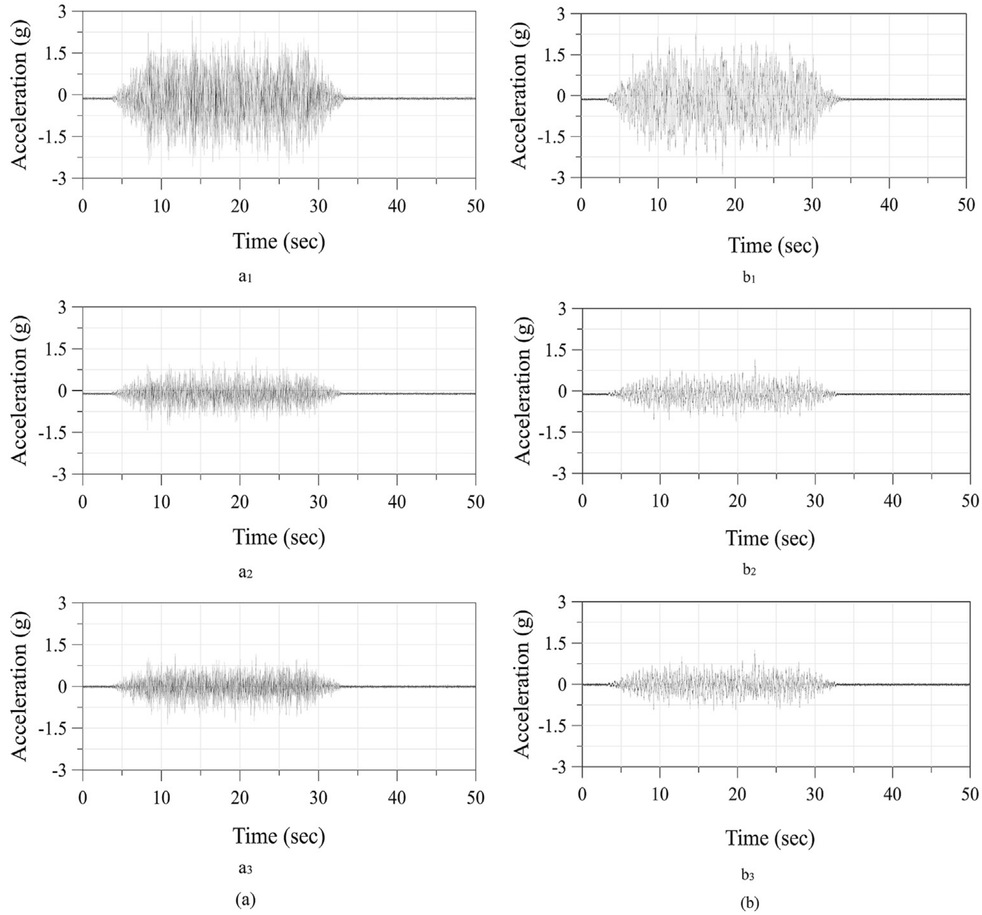


Fig. 4. Acceleration response of EDG components: (a) acceleration time history of X direction on UHS(a_1: radiator, a_2: engine, a_3: generator), (b) acceleration time history of X direction on R.G 1.60(b_1: radiator, b_2: engine, b_3: generator).

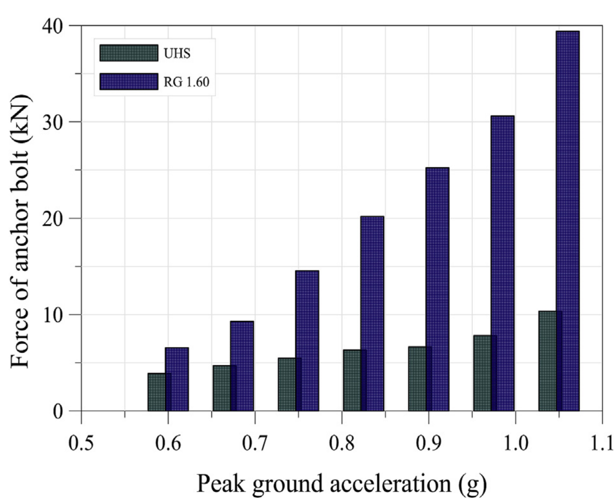


Fig. 5. Pull-out force of anchor bolt depending on input motion spectra.

in comparison with that of the UHS spectrum. The fuel filter leakage and lubricant leakage of bolt joint for engine occurred at similar PGA levels of the two input motions. However, leakage of bolt joint occurred earlier under UHS input motion. The operation of the EDG was maintained in spite of fuel filter.

5. Conclusion

In this study, a shaking table test of an emergency diesel generator was conducted in order to improve the reliability of nuclear plant and administrative control procedures. To evaluate the seismic performance of the EDG system, seismic motions were simulated based on the R.G 1.60 design spectrum and the Korean Nuclear Power Plant site specific UHS. From the seismic tests, leaks at the fuel inlet bolt connection and fuel filter were observed. However, the functional test and visual inspection showed that the EDG operated normally despite the leaks. The pull-out force of the anchor bolt with the RG 1.60 spectrum was larger than that for the UHS spectrum for the same PGA. The measured pull-out force was lower than the design strength of the anchor bolt based on ACI 318. Therefore, the check list of nuclear plant components after an earthquake should include bolt connections of EDG as well as anchor bolts.

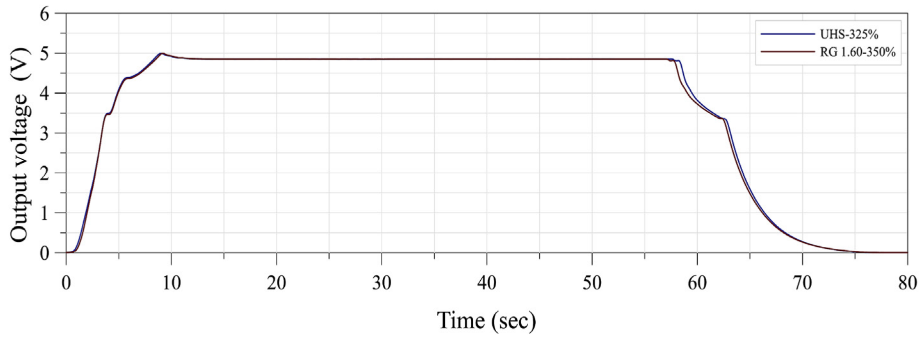


Fig. 6. The functional test results after seismic test with R.G 1.60 at 350% and UHS at 325%.

Table 7
Results of function test and visual inspection.

Test No.	Input motion	Results		Remarks
		Function	Inspection	
2	R.G. 1.60 200%	O.K.	O.K.	
	R.G. 1.60 225%	O.K.	O.K.	
	R.G. 1.60 250%	O.K.	O.K.	
	R.G. 1.60 275%	O.K.	O.K.	
	R.G. 1.60 300%	O.K.	O.K.	
	R.G. 1.60 325%	O.K.	O.K.	
	R.G. 1.60 350%	O.K.	Fuel filter leaking	Test progressed after re-clamp of the fuel filter
5	UHS 200%	O.K.	O.K.	
	UHS 225%	O.K.	O.K.	
	UHS 250%	O.K.	O.K.	
	UHS 275%	O.K.	O.K.	
	UHS 300%	O.K.	O.K.	
	UHS 325%	O.K.	Fuel filter leaking	Test progress after re-clamp for fuel filter
	UHS 350%	O.K.	Fuel filter leaking	Test progress after re-clamp for fuel filter

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.net.2019.03.012.

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