Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 16-18, 2018

Preliminary Analysis of the Uncertainty Effect on Seismic Parameters and Frequency Spectrum for Nuclear Power Plants

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1. Introduction

After the Fukushima-Daiichi Nuclear Power Plants (NPPs) were disabled due to the massive earthquake and tsunami in Japan, the safety of the NPPs became one of the major social issues in Korea. Furthermore, the earthquakes that jolted Gyeongju in 2016 prompted and accelerated concerns about the safety of NPPs even though no NPP was damaged at that time.

To protect the safety related systems in NPP and NPP itself by preventing a badly damage caused by earthquakes in advance, the so-called seismic monitoring system was installed and is being currently operated for all the NPPs in Korea, and each seismic monitoring system is designed and operated to satisfy all the given requirements of both domestic guide and US NRC Regulatory Guide 1.12 rev.2 [1]. The Regulatory Guide has been recently revised to take the very high frequency range, i.e., 50 Hz ~ 100 Hz [2] into account for analyzing the structural damage caused by earthquakes. From this, it can be easily expected that the high frequency effect on various seismic parameters will be considered in seismic analyses of NPPs in the near future. It should be noted that the very high frequencies (>50 Hz) are currently filtered out and thus they aren’t used to analyze the structural damage. The other objective of the revision is related with the precise measurement of the seismic data because the measurement error or uncertainty may noticeably affect the prediction of the structural damage. From this reason, the new version of guide suggests that the acceleration sensors shall have a minimum dynamic range of 110 dB or 300,000:1 and the sensor should be able to record 4.0 g zero to peak. Nevertheless, it is very worthy to investigate the effect of the measurement error on seismic parameters related with the prediction of the structural damage because researches on effect of uncertainties that may be generated during measurements (or analyses) on analysis results have been rarely performed in Korea.

Our preceding paper focused on the uncertainty effect on frequency response spectrum to investigate the error propagation in the very high frequency range (50~100 Hz) using artificially generated seismic data [3]. In this work, the research continues to further investigate the uncertainty effect on various seismic parameters, such as Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV), Arias intensity (I_a), Characteristic Intensity (I_c), Cumulative Absolute Velocity (CAV), and frequency spectrum to evaluate or predict the damage caused by earthquake for NPPs. Especially, in the analysis of the frequency spectrum, the uncertainty effect caused by measurement errors is focused and mainly discussed.

In addition, an actual seismic data is applied to evaluate the five seismic parameters and spectrum mentioned above. Practically, to verify the effect of measurement error or uncertainty, a series of sensitivity analyses are performed using some ranges of randomly generated errors for evaluating the five seismic parameters and the frequency spectrum by employing the actual Gyeongju earthquake data measured in 2016.

2. Methodology

During the past few decades, lots of seismic parameters have been derived to evaluate the seismic effect on structure or building. For example, PGA, PGV, Peak Ground Displacement, I_a, I_c, CAV, Spectral Acceleration, Acceleration Spectrum Intensity, Velocity Spectrum Intensity, and Housner Intensity are widely used for correlation studies between seismic intensity and structural damage.

Among the seismic parameters, PGV, I_a, and I_c are known to have the strongest correlation with the structural (or seismic) damage [4], and thus the three seismic parameters were selected to investigate the effect of uncertainly in this work. PGA and CAV were also calculated by employing the uncertainty and compared with the original results without the uncertainty because they are currently used to design NPPs. PGA is highly related with the design basis earthquake for NPPs and CAV is used as one of inputs to assess the structural damage for NPPs Consequently, these five parameters, i.e., PGA, PGV, I_a, I_c, and CAV, were selected and calculated to investigate the uncertainty effect of the seismic data in the work.

It should be noted that the definitions of the five seismic parameters are as follows [4]:

$$\mathrm{PGA} = \max|a(t)|, \tag{1}$$

$$\mathrm{PGV} = \max|v(t)|, \tag{2}$$

$$I_a = \frac{\pi}{2g}\int_0^{t'} a(t)dt, \tag{3}$$

$$I_c = \left(\sqrt{\frac{1}{t'}\int_0^{t'} a(t)^2 dt}\right)^{2/3}\sqrt{t'}\,, \tag{4}$$

$$\mathrm{CAV} = \int_0^{t'}|a(t)|dt\,, \tag{5}$$

where t′ is the total duration of ground motion.

To investigate the uncertainty effects, the frequency response spectrum was also calculated using the so-called Fast Fourier transform (FFT) algorithm. FFT algorithm can be expressed as [3]:

$$F_k = (1/N)\left[\sum_{j=0}^{N/2-1} e^{2\pi ik(2j)/N} f_{2j} + \sum_{j=0}^{N/2-1} e^{2\pi ik(2j+1)/N} f_{2j+1}\right]$$
$$= (1/N)[F_k^e + W^k F_k^o]. \qquad (6)$$

3. Numerical Results

To verify the effect of measurement error on seismic parameters, the actual Gyeongju earthquake data measured in 2016 were used. In this work, the seismic data measured in Deokjeong-ri observatory (DKJ) were applied to evaluate the seismic parameters. The sampling period was 0.005 sec (i.e., 200 samples per second) and the data set consists of three individual sub-sets, i.e., North-South set, East-West set, and Vertical set. All the three sub-sets include a total of 50 seconds acceleration values. Among the three sub-sets, the data of North-South set was used to evaluate the effect of error or uncertainly on seismic parameters because it includes the biggest acceleration value.

3.1 Measurement Error Analyses

There are some measurement errors of a sensor such as the offset error, gain error, linearity error and so on. To analyze the effect of measurement errors on seismic parameters, five cases were defined in the aspects of error ranges, i.e., 0.01%, 0.05%, 0.1%, 0.5% and 1% of full detecting scale of the sensor. For example, the first case (0.01% error range) means 0.0004 g was added to the value at each time of the original data set. Note that the dynamic range of the sensor was assumed to 4.0 g [2]. As a first step, each seismic parameter was calculated with the original data set (Reference Case) and then the counterparts for the five cases were recalculated with the corresponding error range. Consequently, a total of six calculations were performed for obtaining each seismic parameter. The calculated values for the six calculations including the reference case of the five seismic parameters are listed in Tables I (for the effect of offset error) and II (for the effect of gain error).

Table I shows that the calculated values of the seismic parameters significantly increase as the given offset error increases. Especially, I_a, I_c and CAV increase rapidly, because calculated values of the parameters were accumulated as integral values. The PGA values of Cases IV and V are larger than the Operating Basis Earthquake (OBE, e.g., 0.1g) in NPPs. From this observation, it can be concluded that the offset error of a sensor gives misinformation to operators of NPPs. In other words, even though the OBE alarm shouldn't be occurred in this earthquake when the original data set was given (Reference Case), this error makes the OBE alarm (Cases IV and V).

Table II shows that calculated values of the seismic parameters increase in proportion to the corresponding gain error increments. It should be noted that the given gain errors for the five cases actually so small and thus seismic parameters including uncertainty effect were very similar with the counterpart of the reference case. For example, the calculated CAV with 1% gain error (Case V) is 0.07320 while it is 0.07248 with original raw data (Reference Case).

3.2 Uncertainty Analyses

To verify the effect of the uncertainty on response spectrum, the actual earthquake data were used to calculate the frequency spectrum. During the process of the calculation, the actual earthquake data were adjusted with randomly generated errors at each sampling point. Note that all the random errors are in -0.02% and +0.02% of full-scale of sensor range.

Fig. 1 shows the acceleration data with time history. Fig. 1.a and Fig.1.b are the original graph and adjusted graph reflecting the random errors at each time point, respectively.

Fig. 2 shows the response spectrums of original data (Fig.2.a) and of adjusted data (Fig.2.b). Note that Fig.2.a as well as Fig.2.b consist of three different spectrums evaluated using the first 10, 30, and whole data of the original data set, respectively. Since the value of the uncertainty considered was about 1.0e-5, one can easily find that the adjusted amplitude for all the frequency range was increased about a value of 1.0e-5. It can be easily found that the uncertainty has also produced noise, resulting in erroneous response spectrum in low-frequency regions of less than 1 Hz and high-frequency regions of more than 50 Hz, because the amplitude of these ranges is comparatively small. Since the raw data (original data) have only 200 samples per second and the dynamic range of sensor is less than 50 Hz, the exact response spectrum cannot be currently known for the very high frequency range (>50 Hz). Furthermore, the uncertainties about 0.02% can have incorrect consequences and therefore it should need to be measured more accurately in high-frequency regions.

From these observations, it can be concluded that the uncertainty effect on spectrum should be investigated and evaluated precisely, especially in high frequency region.

4. Conclusions

To investigate the effect of measurement error (or uncertainty) on the five seismic parameters, the seismic parameters were calculated and compared each other using the adjusted measured data by employing the various offset error and gain error at each sampling point. The frequency response spectrum was also calculated by considering the randomly generated uncertainties. The numerical results calculated with offset error say that the seismic sensor may misgauge and cause misanalysed seismic parameters. On the other hand, there are no significant changes when the gain errors were applied to the original data. Uncertainty of the sensor or measurement error also causes misanalysed response frequencies, and thus these misanalysed results may affect the other safety analyses and the corresponding follow-up actions in NPPs. Therefore, to avoid these misanalyses and to reduce the uncertainty effect, analyses reflecting the error of sensor need to be considered.

Acknowledge

This work is conducted with support of the Korea Institute of Energy Technology Evaluation and Planning (KETEP), which is under the Ministry of Trade, Industry and Energy (MOTIE). [No. 20171510101860]

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Table I: Effect of Offset Error on Seismic Parameters

	Reference (Raw Data)	Case I (0.01% Error)	Case II (0.05% Error)	Case III (0.1% Error)	Case IV (0.5% Error)	Case V (1% Error)
PGA	0.09244	0.09284	0.09444	0.09644	0.11244	0.13244
PGV	0.00045	0.00045	0.00046	0.00047	0.00055	0.00065
I_a	0.00234	0.00235	0.00264	0.00354	0.03220	0.12177
I_c	0.21741	0.21778	0.22629	0.24943	0.52085	0.81147
CAV	0.07248	0.07922	0.13690	0.22174	0.96329	1.90515

Table II: Effect of Gain Error on Seismic Parameters

	Reference (Raw Data)	Case I (0.01% Error)	Case II (0.05% Error)	Case III (0.1% Error)	Case IV (0.5% Error)	Case V (1% Error)
PGA	0.09244	0.09245	0.09249	0.09253	0.09290	0.09336
PGV	0.00045	0.00045	0.00045	0.00045	0.00045	0.00045
I_a	0.00234	0.00234	0.00234	0.00235	0.00237	0.00239
I_c	0.21741	0.21743	0.21749	0.21756	0.21814	0.21886
CAV	0.07248	0.07249	0.07251	0.07255	0.07284	0.07320

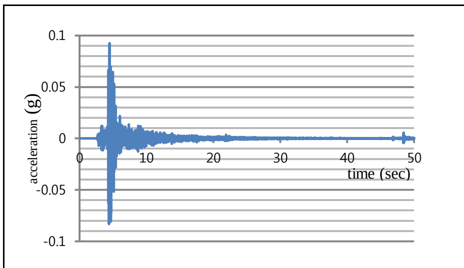

Fig. 1.a

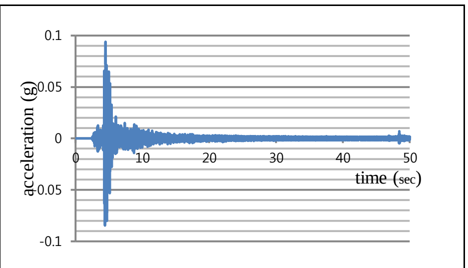

Fig. 1.b

Fig. 1: Acceleration-Time Graph

For 10 seconds	For 30 seconds	For 50 seconds
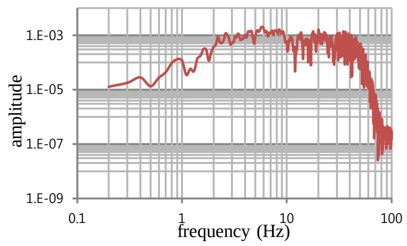	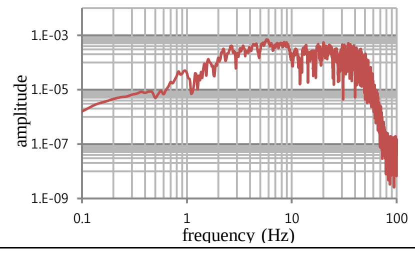	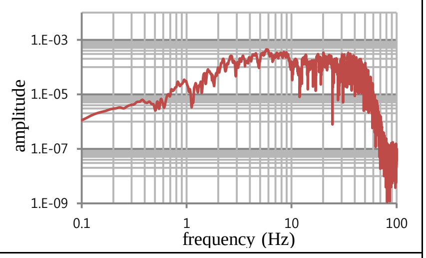
Fig. 2.a.1	Fig. 2.a.2	Fig. 2.a.3
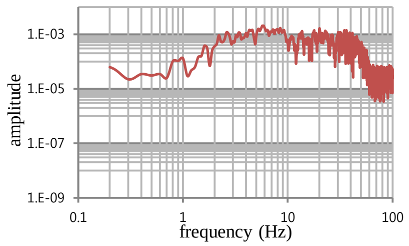	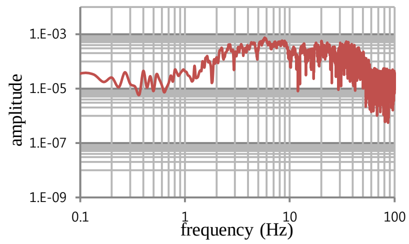	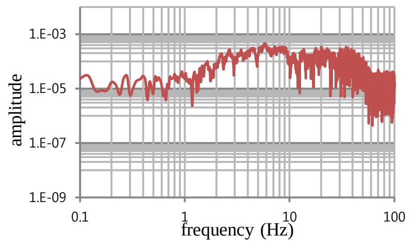
Fig. 2.b.1	Fig. 2.b.2	Fig. 2.b.3

Fig. 2: FFT Response Spectrum