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Peak-Broadening of Floor Response Spectra for Base Isolated Nuclear Structures

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1. Introduction

Nuclear structures should be designed to ensure the safety of equipment and components mounted on their floors. However, coupled analysis of a structure and components is complex, so equipment is separately analyzed using floor response spectra (FRS). FRS calculated from dynamic analysis of structural model should be modified to create floor design response spectra (FDRS), the input for seismic design of equipment. For nuclear structures, smoothing and broadening peaks of FRS is required to account for uncertainties owing to material properties of structures, soil, modeling techniques, and others [1]. The peak broadening method proposed for fixed based structures may not be appropriate for base-isolated structures because of additional uncertainties in the property of isolation bearings.

In this paper, uncertainties in developing FRS are explained first. Then FDRS of a fixed structure is computed using a conventional method as an example. Lastly FRS of a base-isolated structure is computed and suitability of current peak-broadening method is examined.

2. Uncertainties in developing FRS

2.1 Uncertainties in fixed-based structures

FRS generated from floor response of mathematical model of a structure cannot account for uncertainties, which should be considered in FDRS.

Uncertainties in developing FRS come from various factors. Firstly, approximation of a real structure is inevitable to develop a structural model needed to obtain responses. Also, the input values of the structural properties could be different from the real values; it could be due to the measurement error or the variation in the material property values. Analysis method, on whether it is direct integration method or modal superposition method, also makes different results. Therefore, simulation of a real structure of which result is exactly same with the real value cannot be realized. Material properties and modelling technique of soil are another important factor that produce uncertainties in FRS. Generally, soil parameter has the most substantial effect on FRS.

In case of nuclear structures uncertainties in the FRS could be significantly reduced because nuclear power plants are mostly built on a hard rock foundation, which enables the uncertainty due to the soil be ruled out.

2.2 Uncertainties in base-isolated structures

For a base-isolated structure, additional uncertainties due to the isolation devices are added. Variation in isolators comes from manufacturing process, temperature, and aging effects, and others. Property variation in the isolator is restricted when it is applied to a nuclear structure. ASCE provisions for seismic isolation of safety-related nuclear structures states that the mechanical properties of isolators shall not vary over the lifespan by more than 20% from the values used for the analysis and design, with 95% probability [2]. Aging of isolators constitutes a considerable portion of this variation limit 20%, and the initial variation of isolators is guessed to be around 10%. The uncertainties due to aging cannot be reduced, but the initial uncertainties can be decreased by quality control at manufacturing process.

3. Floor design response spectra for conventional structures

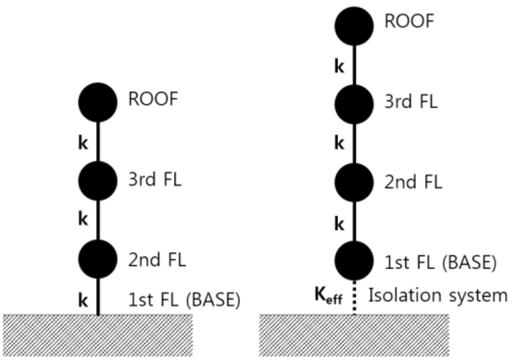
3.1 Conventional peak-broadening method

Uncertainties in FRS mentioned above are considered using peak-broadening when developing FDRS. Regulatory Guide 1.122 is the only guideline for peak broadening of FRS as of now. The guide states peaks of spectrum at frequency f should be broadened by a frequency, $\pm\Delta f$, where Δf is calculated with a procedure considering the variation in the frequency due to variation in significant parameters. If the procedure is not used, 15% of peak broadening ratio is commonly used and recommended because quantification of parameter variation is difficult.

3.2 Application of peak-broadening of FRS to a fixed structure

To investigate variation of structural property that allow the corresponding FRS to be enveloped in a 15%-broadened-FRS, stiffness was selected as variation property. Other factors related to the FRS are assumed to be negligible.

A beam-stick model representing a three-storied-fixed building was used in the analysis as shown in the left side of Fig. 1. The degree of freedom has been limited to x-direction (horizontal) for the simple analysis. The stiffness of the beam representing each wall is k.



(a) Fixed case (b) Isolated case

Fig. 1. Fixed and base isolated models.

To figure out how much the maximum variability of the structure stiffness would be, k were changed by -50% to +50%. For each variation model, time history analyses with 30 earthquake motions were implemented. The input motions were matched to regulatory guide 1.60 spectrum scaled to 0.5 g [3]. FRS were computed at the top of the structure as there will yield the largest response.

FRS are plotted in the Fig. 2. The grey and bold dot-and-dash line represents broadened spectrum of the no-variation model by 15% of the peak frequency. It is shown that around 30% of increase or decrease of the structural stiffness yield the FRS that are enveloped by the broadened spectrum. That is, the allowable stiffness variation range of fixed structures is around 30% when assuming that there is not any other factor influencing a change of spectra.

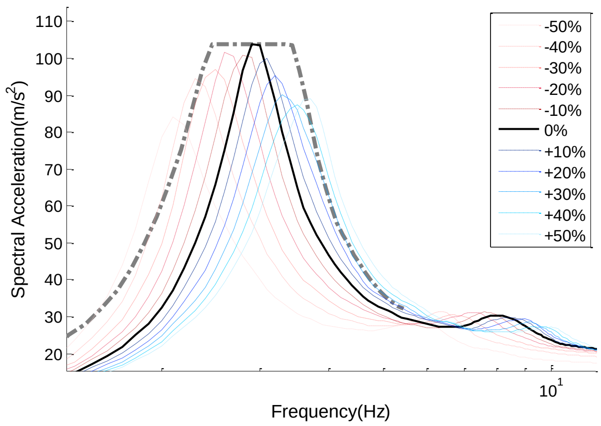


Fig. 2. FRS of fixed structure.

4. Evaluation of FRS for base-isolated structures

4.1 Uncertainty of superstructure property

To figure out the effect of variations of structural stiffness on FRS of base-isolated structures, the same observation has been carried out for an isolated model. The isolated model has been modelled attaching an isolator below the fixed structure as shown in the right side of Fig. 1. The isolator acts as natural rubber with a stiffness k_{eff}. The isolation stiffness were determined so as to have the isolation period 1.0, 1.5, 2.0, and 2.5 seconds. With four different periods of isolated model, the effect of structural stiffness k on FRS has been investigated. Linear time history analyses were conducted.

The result of the 2.5-sec model is plotted in the Figs. 3 and 4. Models with other isolation periods had results in the same vein. Fig. 3 represents time history response of displacement and acceleration at the top of the structure. Both response of different superstructure are almost same between each other. The time history response coincide with the FRS as represented in the Fig. 4, showing the insignificant difference between the varied superstructures. This could draw a conclusion that uncertainties coming from superstructure can be ignored when generating a FDRS of a base-isolated structure.

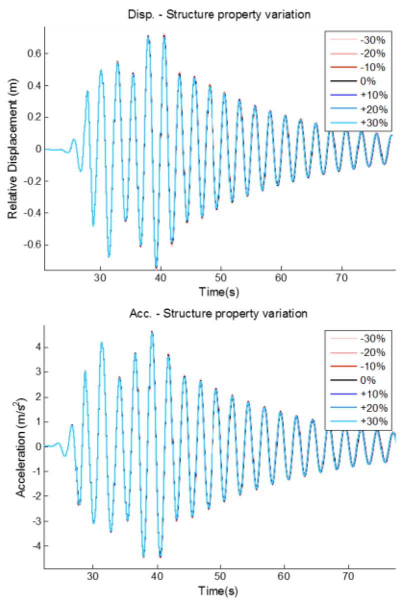


Fig. 3. Time history response for variation of structure property (2.5-sec model).

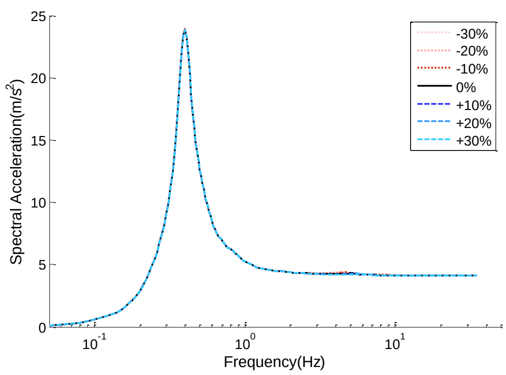


Fig. 4. FRS with 5% damping for variation of structure property (2.5-sec model).

4.2 Uncertainty of base-isolation property

Analyses were implemented with the assumption that the isolator stiffness is the only parameter related to the spectra. Isolator stiffness, k_{eff}, were changed by -30% to +30%, and the time history response and the spectra results are shown in the Figs. 5 and 6. The figures compare the response of 2.5sec-models with variation in their isolator stiffness. Results of other models also have the similar tendency with that of the 2.5sec-model.

Response of the model with lower stiffness of isolator is larger and has longer periods in both displacements and acceleration. As the isolator property changes, peak of FRS is shifted and zero-period-response changes. Shifted peaks are the only interest herein because the shift of peaks are dominant change in the spectrum. The broadened spectrum, grey dot-and-dash line in the Fig. 6, envelops the spectrum of the model of which isolator property is changed by -30% to over +20%.

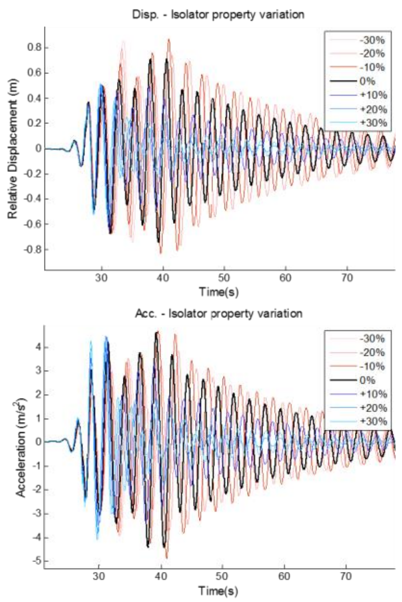


Fig. 5. Time history response for variation of isolator property (2.5-sec model).

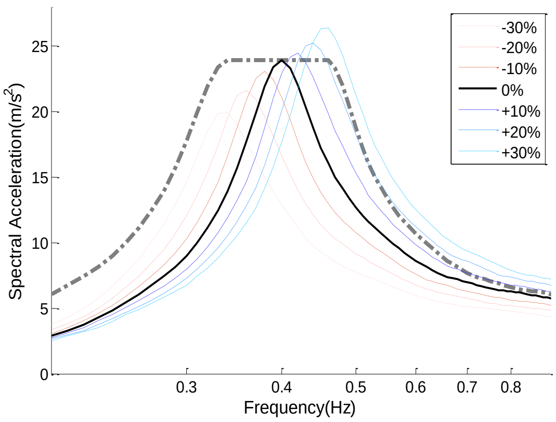


Fig. 6. FRS with 5% damping for variation of isolator property (2.5-sec model).

To see more in detail, change rate of peak spectral values and required broadening ratios for each variation models were calculated and shown in the Tables I and II. Change rate of peak spectral values represents the percentage of change in spectral acceleration value at the peak as the isolator stiffness changes from the raw model. Required broadening ratios represent how much the raw spectrum should be broadened from the peak to envelop the changed spectrum.

Table I: Change Rate of Spectral Peak Amplitude

Isolator variation (%)	Isolation period (sec)			
	1.0	1.5	2.0	2.5
-20	-7.82	-5.53	-11.69	-9.67
-15	-5.36	-2.07	-8.25	-6.58
-10	-2.79	-1.44	-5.97	-3.61
-5	-0.57	-1.90	-2.96	-1.74
+5	-0.15	+1.98	+2.83	+1.38
+10	+1.72	+7.53	+5.01	+2.15
+15	+5.22	+12.58	+6.48	+3.33
+20	+8.88	+17.58	+6.58	+5.56

Table II: Required Broadening Ratio

Isolator variation (%)	Isolation period (sec)			
	1.0	1.5	2.0	2.5
-20	-6.83	-10.23	-8.56	-9.86
-15	-5.93	-8.92	-7.52	-8.17
-10	-4.24	-7.22	-5.79	-6.49
-5	-3.04	-4.09	-3.72	-4.49
+5	+2.08	+5.11	+4.77	+3.72
+10	+7.10	+9.81	+8.38	+6.90
+15	+11.26	+13.88	+11.03	+10.62
+20	+14.51	+17.28	+13.79	+14.25

As shown in the Table I, the maximum change rate of the peak amplitude for variation with 20% is +17.58 % of 1.5-sec model and other models have less than 10% of change rate of peak amplitude. The spectrum of base isolated structure do not have to be amplified for consideration of increased spectral values; because the peak is very narrow, having little energy at the tip, which could make the amplified peak value be negligible in generation of design spectrum.

Table II shows that the increase of the isolator stiffness brings larger change of the spectrum than the decrease of the isolator. The largest required broadening ratio is +17.28% of 1.5-sec model for isolator variation of 20%. This exceeds 15%, the conventional broadening ratio, but the calculation of required broadening ratio here is based on the spectral ordinate of the peak of the raw spectrum as seen in the Fig. 7, so 15% of broadening ratio virtually envelops the +20% variation of 1.5-sec model.

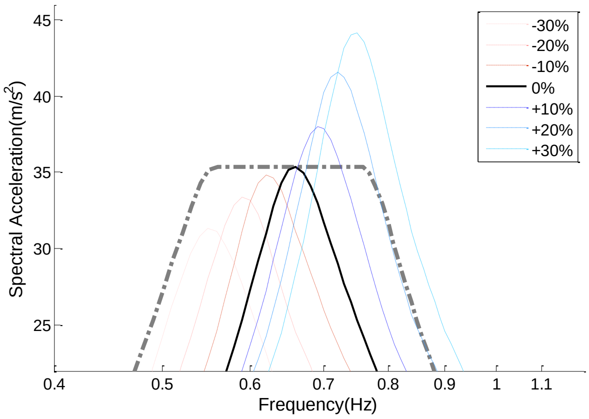


Fig. 7. FRS with 5% damping for variation of isolator property (1.5-sec model).

As the maximum variation of isolation device is restricted to 20%, FRS broadening ratio 15% would be sufficient for base-isolated nuclear plants.

20% of change is the extreme case and variability of isolation system at the time of design would be around 10%. Within the variation range of 10%, the maximum required broadening ratio is 7.10, 9.81, 8.38, 6.90% for 1.0, 1.5. 2.0, 2.5-sec model. Broadening ratio of every model is less than 10%.

5. Conclusion

Uncertainties in the material property of structure influence FRS of fixed structures significantly, but their effect on FRS of base-isolated structures is negligible. For base-isolated structures, mechanical property of isolator plays a dominant role on the change of FRS.

As base-isolated nuclear plants should meet the ASCE provisions, uncertainty in the isolation system would be around 10%. For the base isolated 3-storied beam model with 2.5-sec isolation period, 6.9% of broadening ratio was enough for development of FDRS at the required variation condition. Also for the models with various isolation periods, less than 10% of broadening ratio was sufficient. Thus, conventional peak-broadening ratio could be reduced to under 10% for base-isolated nuclear structures.

Acknowledgement

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