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Research on the attribution evaluating methods of dynamic effects of various parameter uncertainties on the in-structure floor response spectra of nuclear power plant

Li Jianbo[1,2†], Lin Gao[1‡], Liu Jun[1§] and Li Zhiyuan[1§]

1. *State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, Dalian 116024, China*
2. *Ocean Engineering Joint Research Center of DUT-UWA, Dalian University of Technology, Dalian 116024, China*

Abstract: Consideration of the dynamic effects of the site and structural parameter uncertainty is required by the standards for nuclear power plants (NPPs) in most countries. The anti-seismic standards provide two basic methods to analyze parameter uncertainty. Directly manually dealing with the calculated floor response spectra (FRS) values of deterministic approaches is the first method. The second method is to perform probability statistical analysis of the FRS results on the basis of the Monte Carlo method. The two methods can only reflect the overall effects of the uncertain parameters, and the results cannot be screened for a certain parameter's influence and contribution. In this study, based on the dynamic analyses of the floor response spectra of NPPs, a comprehensive index of the assessed impact for various uncertain parameters is presented and recommended, including the correlation coefficient, the regression slope coefficient and Tornado swing. To compensate for the lack of guidance in the NPP seismic standards, the proposed method can effectively be used to evaluate the contributions of various parameters from the aspects of sensitivity, acuity and statistical swing correlations. Finally, examples are provided to verify the set of indicators from systematic and intuitive perspectives, such as the uncertainty of the impact of the structure parameters and the contribution to the FRS of NPPs. The index is sensitive to different types of parameters, which provides a new technique for evaluating the anti-seismic parameters required for NPPs.

Keywords: uncertain parameter; floor response spectra (FRS); soil-structure interaction (SSI); seismic analysis and structural design; nuclear power plant (NPP)

1 Introduction

Nuclear power will play a vital role in the future plan of China's energy development (Kong and Lin, 2013). However, due to the serious damage and disastrous consequences of nuclear accidents, the security problems of nuclear power have always been a concern. A multi-earthquake country, the seismic safety of nuclear power plant structures (NPPs) has attracted significant attention in China. In addition to the uncertainty of the seismic disturbance, the dynamic effects of various parameter uncertainties also have direct relationships with the resulting reliability in structural aseismic evaluation. Furthermore, because the floor response spectrum (FRS) is an important basis for anti-seismic analysis, especially for the NPP's equipment, the corresponding seismic design codes both at home and abroad require the dynamic effect of the parameter uncertainties, focusing on the FRS of nuclear power plants (ASCE 4-98, 2000; ASCE/SEI 43-05, 2005; ASCE, 1980).

Performing the sensitivity analysis to sort the influence degrees of various random parameters is a common method in many other areas. Ibrahim reviewed the different impacts on the structural dynamic properties of parameter uncertainties, which included the results of experimental investigations, the phenomenon of normal modes localization, the mistuning effects of turbomachinery blades, and even the forced response characteristics (Ibrahim, 1987). Porter *et al*. analyzed the sensitivity of seismic loss to parameters, including uncertain structural parameters, uncertain seismic load, and unit repair cost (Porter *et al*., 2002). Yin

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Correspondence to: Li Jianbo, Institute of Earthquake Engineering, State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, Dalian, Liaoning, 116024, China
Tel: +86-411-84709552
E-mail: jianboli@dlut.edu.cn
†Associate Professor; ‡Professor; §PhD

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studied uncertain parameter sensitivities for structural seismic responses using the first-order second-moment method (Yin, 2011). Pang *et al*. used the probability design module (PDS) analysis function of ANSYS to analyze parameter sensitivity for the structure-dynamic response (Pang, 2010; Jiang *et al.*, 2007). Few parameter uncertainty studies are found in the NPP seismic analysis area on the basis of the modern dynamic soil-structure interaction (SSI) method.

Due to the manufacturing environment and characteristics of the materials, nuclear power plant structures and equipment are enormous in size and well-made in structure, as well as random in terms of the material properties of the different structures and foundation positions. Nuclear power plants are extremely complex and stochastic structural systems, among which the primary uncertain parameters in engineering include the structure's elastic modulus and the foundation's shear wave velocity (Morante *et al.*, 2011; Porter *et al.*, 2002). Because of the complexity of time-history SSI analyses, it is difficult to obtain a normal intuitive conclusion to confirm the extent of parameter change in the final FRS response (Wolf, 1994; Bhaumik and Raychowdhury, 2013).

Currently, two approaches are suggested by the seismic design codes of nuclear power plants for the uncertainty analysis. First, as presented in related literature and research results, ASCE4-98 states that it is acceptable to process the floor spectrum using deterministic methods in an indeterminate manner (ASCE 4-98, 2000; ASCE/SEI 43-05, 2005). The other approach is to consider the complexity of nuclear power structures, and ASCE4-98 suggests performing a probability statistical analysis with different assurance rates on sets of structural sample response results, for which Monte Carlo simulation is commonly applied as the main computational method with the sample space of the appointed random parameters. However, neither method can determine the extent of the impact or the amount of uncertainty, and there are no effective means to analyze these aspects. Certainly, in the relevant literature, many studies focus on how to develop the Monte Carlo method or how to develop the SSI method (Gu, 2010). For example, Lin *et al*. (2012) apply the Monte Carlo method to describe the probabilistic dynamic effect on the nuclear power plant at runtime. Li *et al*. (2006) study the effects of single changes in the shear modulus of foundation under soft and hard soil conditions, which is considered on the bases of SSI analysis. There is no clear study explaining how to measure the contributions of one type of uncertain parameter (Li *et al*., 2011; ASCE 4-98, 2000). Determining the extent of impact and the impact of every type of uncertainty factor on specific, important control factors, such as FRS, is instructive.

This study combines China's desire for developing seismic safety assessment methods of nuclear power structures with the authors' practical experience of evaluating the uncertainty effects in the Hong Yanhe nuclear power plant and the Yang Jiang nuclear power plant. To develop a set of overall indicators for assessing the uncertain parameters' sensibility, the attributes of various random parameters are discussed herein from a statistical standpoint, in which correlation coefficients are used to describe the contributions of the parameters' sensitivity, the regression slopes are used to describe the contribution of the parameters' susceptibility, and the Tornado amplitude is applied to describe the variations and trends in the results. With the comprehensive application of this indicator system, it is possible to consider the floor response spectrum as a measured variable and to use it to intuitively analyze the dynamic impact of all types of indeterminate parameters from a statistical perspective. Then, the priority of the parameters' sensitivity can be determined under certain site conditions, and it is possible to discriminate among them.

The content of this study is arranged as follows. First, some theoretical bases of the uncertainty evaluation index are presented in detail. The second part focuses on the numerical implementation of how to use such indexes, mainly including the calculation of the floor response spectrum and the characteristic frequencies. Finally, to compare the different contributions to the floor response spectrum of various uncertain parameters, the new presented evaluation indexes are applied and validated with practical numerical examples.

2 Theoretical basis of the uncertainty evaluation index

From the view of probability and statistics, there is a rigorous mathematical proof of the influence of parameter uncertainty. Therefore, by selecting an appropriate evaluation index, probability statistics can be used as the basis to evaluate the nuclear power engineering structure and seismic equipment. Such indexes establish the connection between the mathematical model and the physical meaning of the anti-seismic uncertain parameters.

2.1 Correlation coefficient

The sign and value of the correlation coefficient reflect the degree of data discretization and the relativity (sensitivity) of the result to the parameter, which is embodied by the size of the covariance in probability statistics. To examine the correlation coefficient of x and y, the first step is to determine the covariance of two such groups of random variables (Pang, 2010). The definition is as follows:

$$r_{\mathrm{p}} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}} \tag{1}$$

where n is the number of Monte Carlo simulations, x is an uncertain input parameter of the nuclear power engineering structure, and y is the calculated FRS value corresponding to the parameter sample of x. By comparing the absolute values of different types of uncertainty parameters of the correlation coefficient (r_{p}), the sensitivity of these parameters to the floor response spectrum can be measured. Such sensitivity is often visualized by a pie chart or bar chart. A positive or negative sign of r_{p} represents the change trend with the same sign or the opposite sign in the uncertain input parameter and FRS results, respectively.

If Eq. (1) is to be used to solve the correlation coefficient r_{p} of the two FRS curves, the correlation of these two curves is equivalent to the correlation of two discrete data series under the condition of equal frequency intervals in FRS curves. In such a case, x_i, y_i in Eq.(1) represent two data series of the considered FRS, and $\bar{x}$, $\bar{y}$ in Eq.(1) represent the average values of two discrete data series.

2.2 Regression slope

A correlation coefficient reflects the intensity of two variables' sensitivity to one another but cannot reveal how much a change in one quantity affects the other quantity, which can be called the acuity. The regression slope can be used to promulgate this acuity by artificially fitting the regression equation. The regression slope shows that changing the input parameter, X, by one unit leads to the change in the result, Y. Based on a least–squares approximation at a frequency point, one can suppose that the following equation describes the relationship between the structural FRS and a random input parameter:

$$Y = a + bX + \varepsilon \tag{2}$$

where X represents the uncertain parameter, Y is the floor spectrum, a is the regression line's intercept, b is the regression slope, and ε is the analytical error. Using regression analysis, the relation between the acuity and the sensitivity can be determined by checking the relationship between the FRS phototonus and the uncertainty parameter. The best-fit regression trend line can be drawn on the scatter diagram. In general, the more the distribution of the scattered point samples is concentrated, the better the regression trend will fit. In this case, the sensitivity of this parameter on the FRS phototonus will increase. At the same time, the absolute value of the trend line's slope will increase, and the regression slope (acuity) will also increase.

2.3 Tornado amplitude

The input random parameters and the corresponding FRS results usually do not show a specific trend and cannot be determined in advance. Therefore, it is difficult to use a direct method to analyze the impact of parameter uncertainty. From the view of probability and statistics, a Tornado amplitude figure provides a basic analysis method for decision-making in this field. This model is also used to show the statistical characteristics of FRS in the form of a swing chart, usually with the 90% and 10% guarantee rates. From top to bottom, the amplitude is arranged from wide to narrow. Therefore, for a particular frequency in FRS, the difference between the highest and lowest limit values in the Gantt chart is defined as the swing. This chart is clear and direct. It is useful not only for analyzing the statistical characteristics of the effects on FRS due to random changes of some parameters but also for reflecting the difference between the trend of the changes in the statistical characteristics of the FRS results and the deterministic results.

3 Calculation of the floor response spectrum and selection of the characteristic frequency

To determine the FRS of nuclear engineering structures, a dynamic analysis of the soil-structure interaction is one of the fundamental requirements of the seismic safety regulations for nuclear power plants. Such SSI dynamic analysis needs to represent the basic algorithm in the deterministic analyses and impact analyses of parameter uncertainty.

Obtained through deterministic analysis, the structural FRS usually changes drastically when the frequency varies and is generally not smooth with many peaks and valleys. Based on Monte Carlo simulations that include the parameter uncertainties, the floor response spectra obtained by probability statistics with a specified guaranteed rate of 90% are relatively smoother. Compared with the deterministic results, these spectra have reduced and extended peaks, which is consistent with nuclear power specifications.

This study focuses on the nuclear power floor response spectrum's sensitivity to one specific uncertainty factor and discriminates random factors with greater impacts by ranking the spectrum's sensitivity to each factor. Due to the correlation of the floor spectrum's frequencies, it is necessary to select a characteristic frequency in the spectrum results, such as the peak points or the extended broadest points. During concrete operation, two typical peak frequencies are taken as the characteristic frequencies herein to ensure the comprehensive analysis for the overall dynamic influences of all uncertain input parameters.

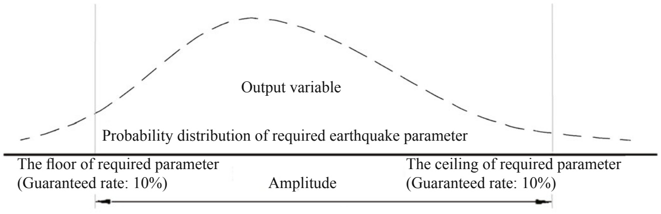


Fig. 1 Schematic of the parameter swing analysis of the tornado amplitude

4 Example and numerical analysis

As shown in Fig. 2(a), for a million-kilowatt reactor building, the material parameters involved in the analysis of deterministic dynamic interactions include: the concrete density (2500 kg/m^3), dynamic elastic modulus (40 GPa), Poisson's ratio (0.2), damping ratio (7%), foundation rock mass density (2659 kg/m^3), Poisson's ratio (0.31), and damping ratio (5%). Because of the highly weathered condition of the rock site, the shear wave velocity is set to 800 m/s, and the RG1.60 seismic wave (as shown in Fig. 2(b)) is applied as the input with the design ground motion of 0.3 g. Following the suggestions of the ASCE4-98 standard, this study focuses on six types of uncertainties in the input parameters, which include the foundation's shear modulus G, the elastic modulus of the concrete E, the damping ratio of the concrete ξ, the shear area of a structural beam element S_a, the moment of inertia of a beam element I, and the node quality of the structural mass.

4.1 Effect of parameter uncertainty on the FRS at the characteristic frequency

According to the conventional Monte Carlo method and the uncertainty effect of the floor response spectrum, the result of analyzing the uncertainty effects on the FRS at a guaranteed rate of 90% is shown in Fig. 3. In the figure, the uncertainty of the floor response spectrum has obvious extension and reduction peaks. According to the principle described in Section 2, 3.15 Hz and 2.9 Hz are taken as the characteristic frequencies of these peaks.

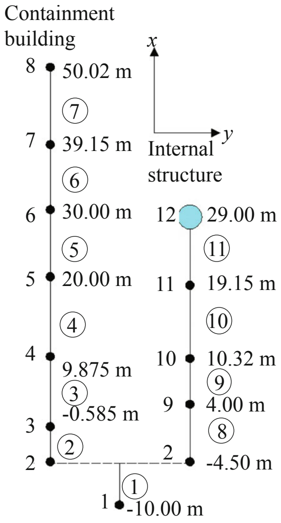


Fig. 2(a) Dynamic numerical model of a 1000 MW nuclear power plant

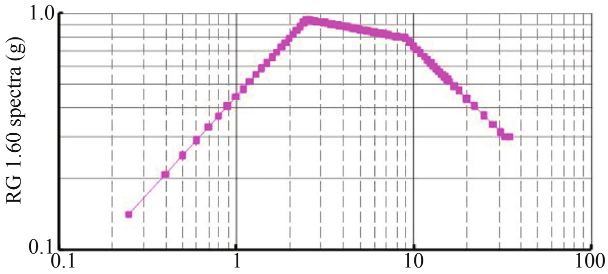


Fig. 2(b) Input RG1.60 seismic spectrum

Corresponding to the FRS values with a frequency of ω_i in Fig. 3, the numerical method of Monte Carlo simulation can be used to solve the statistical FRS results on the condition of a predefined reliability level. The random FRS discrete values constitute a whole set of statistical data. By assuming that these discrete data are normally distributed, the data mean σ and data standard deviation μ can be directly calculated. Then, in the normal distribution function table, the reliability level of 90% requires 1.28 times the standard deviation. In other words, the value of $\sigma + 1.28\ \mu$ is the statistical FRS result with a 90% assurance rate.

4.2 Analysis of the correlation coefficients

Table 1 lists the values of the correlation coefficients for six random parameters to the floor response spectrum, which were calculated using the proposed method. For the sake of a convenient comparison, Fig. 4 depicts these results in bar and pie charts.

Through many attempts to determine the effect of a random sample number, 300 samples are used in the Monte-Carlo numerical simulation to calculate the correlation coefficients.

As seen from Fig. 4, at the peak frequency, the system's susceptibility to the damping ratio of concrete is significant and is somewhat susceptible to the foundation shear modulus and node quality. The remaining parameters are less relevant. At the extension peak's characteristic frequency, the susceptibilities of the system to the six random parameters are similar. In addition, at the two characteristic frequencies, the damping ratio of concrete, the elastic modulus of concrete, the moment of inertia of a beam element, and the shear area of a structural beam are negatively correlated with the FRS's correlation coefficients. Generally, the damping ratio, the node quality and the foundation's shear modulus are susceptible to changes in the floor response spectrum.

As seen in Fig. 4, when the correlation coefficients are negative, the residual linear fitting slopes are also negative. In such cases, the change tendencies are different between the input random parameters and the

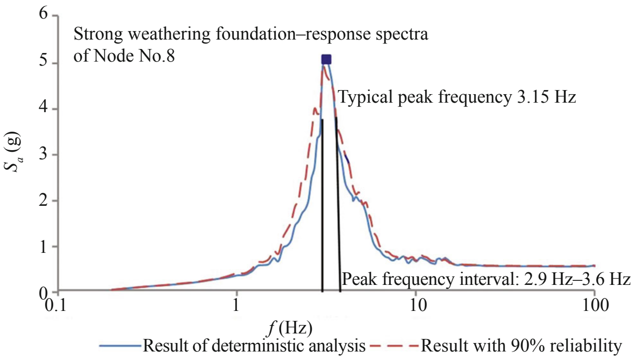
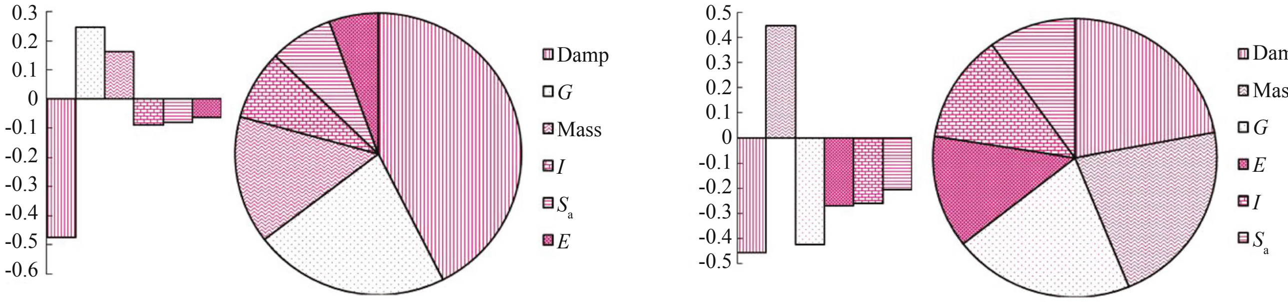


Fig. 3 Floor response spectra for the uncertainty analysis

Table 1 Correlation coefficients for six random parameters to the floor response spectrum

Random parameter	G	E	damp	mass	S_a	I
Peak frequency (3.15 Hz)	0.246	-0.062	-0.474	0.163	-0.08	-0.089
Peak extension frequency (2.9 Hz)	-0.424	-0.268	-0.454	0.446	-0.204	-0.259



(a) Peak frequency (3.15 Hz) (b) Typical extension peak frequency (2.9 Hz)

Fig. 4 Correlation coefficients for the uncertainty parameters to FRS at characteristic frequencies

FRS results. In other words, when the input parameter increases, the FRS result decreases.

4.3 Analysis of the regression slope

Table 2 presents the floor response spectra determined using the proposed method for the linear regression slope of six random parameters. The damping ratio, the node quality, and the foundation's shear modulus are relatively susceptible to changes in the peak frequency of the floor response spectrum. In comparison with the correlation coefficients, the peak floor response spectrum is also susceptible to changes in these parameters. In general, the correlation coefficient and linear regression slope have the same sign.

The two characteristic frequencies are drawn in conjunction with a scatter plot. The regression trend lines are shown in Fig. 5 from the largest to smallest regression slope.

The above figure normalizes the abscissa with deterministic parameters. The larger the regression coefficient, the more susceptible these parameters are to the floor response spectrum. The scatter plot also shows that the intensive dispersion of dots and the characterization of the susceptibility correlation coefficients have similar characteristics.

4.4 Tornado-swing analysis

From a statistical point of view, a Tornado-swing analysis can show the characteristic trend of the change amounts in the floor response spectrum affected by some uncertain stochastic parameters.

If the peak frequency of the uncertainty characteristics for various parameters leads to the value of the floor response spectrum with a 90% guaranteed rate, which is less than the result of the deterministic analysis, then it is one of the phenomena associated with the reduction peak. The swing width reflects the degree of sensitivity to changes in the floor response spectrum when different parameters vary. However, at the extension peak's characteristic frequency, the peak extension phenomenon shown in the Tornado-swing figure is significantly different.

4.5 Comprehensive evaluation of the impacts of parameter uncertainties

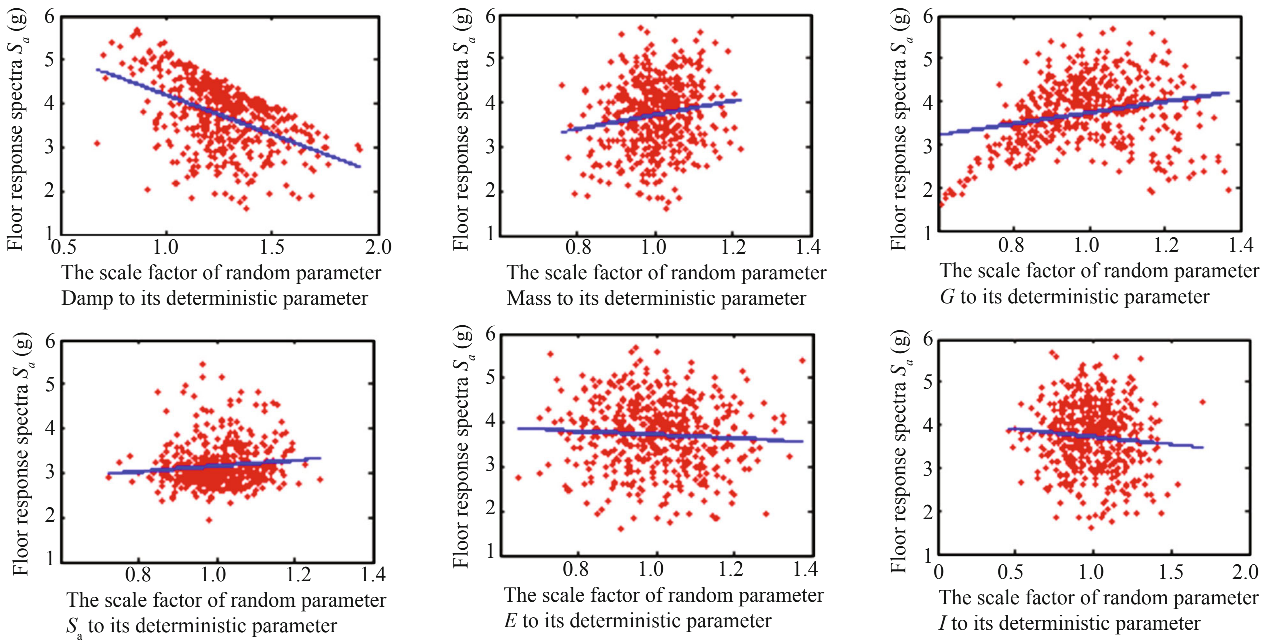
Based on these three types of analysis, a comprehensive evaluation of the effects of parameter uncertainties at the extension peak and peak frequencies can be performed, and the contribution of each factor can be determined.

The correlation coefficients, the regression slope and the Tornado-swing analysis complement each other. To better reflect how changes in random parameters affect the floor response spectrum, the correlation coefficient can be graphed against the frequency, as shown in Fig. 7, which reflects the increases in susceptibility to a coefficient as the frequency changes.

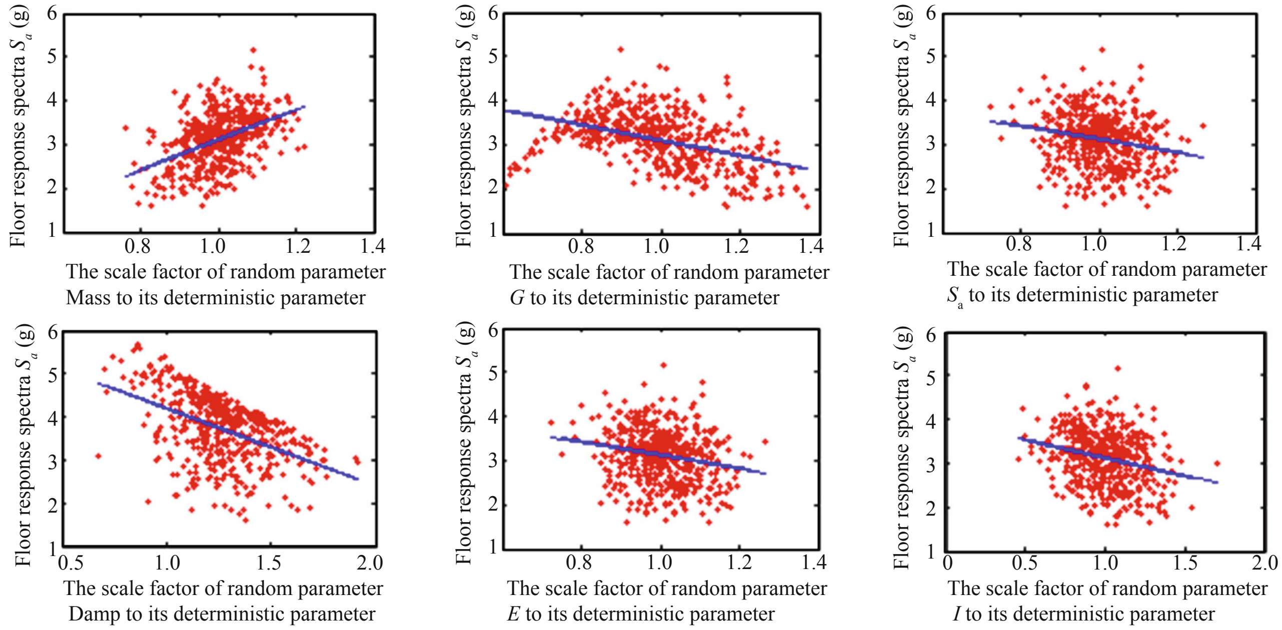
The susceptibility of some parameters to the frequency varies. The range of all types of parameter susceptibilities appears as a small ripple at the peak, whereas the curve representation is stable at relatively low and high frequencies. In general, the susceptibility of most input parameters varies significantly with the

Table 2 Linear regression slope

Random parameter	G	E	Damp	Mass	S_a	I
Peak frequency (3.15 Hz)	1.278	-0.389	-1.805	1.600	-0.748	-0.359
Peak extension frequency (2.9 Hz)	-1.737	-1.322	-1.36	3.446	-1.501	-0.821

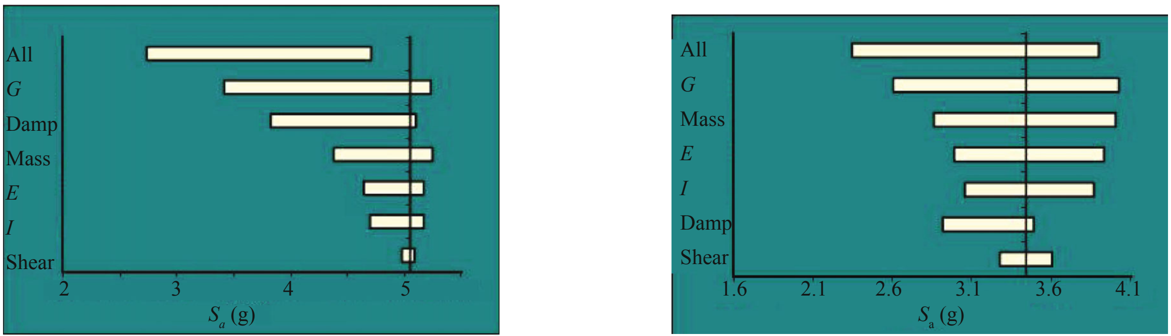


(a) Typical peak frequency (3.15 Hz)



(b) Typical extension peak frequency (2.9 Hz)

Fig. 5 Scatter plots of the FRS and random parameters at typical frequencies



(a) Typical peak frequency (3.15 Hz)

(b) Typical extension peak frequency (2.9 Hz)

Fig. 6 Amplitude chart of the tornado-swing analysis

Table 3 Width of the floor response spectrum's amplitude between the 10% and 90% guaranteed rates

Random parameter	G	E	Damp	Mass	S_a	I
Peak frequency (3.15 Hz)	1.811	0.525	1.271	0.866	0.110	1.271
Peak extension frequency (2.9 Hz)	1.416	0.941	0.571	1.141	0.327	0.907

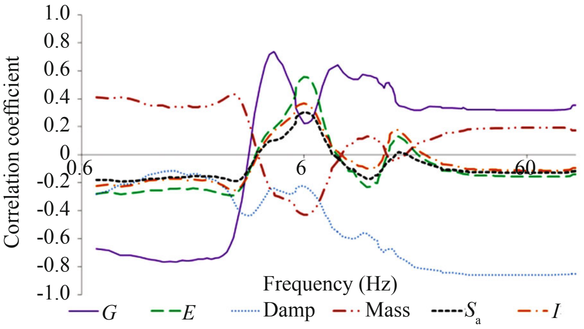


Fig. 7 Correlation coefficient versus the frequency

frequency. For example, the shear modulus of soil has always been a strongly susceptible parameter, and its susceptibility coefficient varies more in the plus or minus direction. As shown in Fig. 7, the shear modulus of soil is negatively correlated below the peak frequency, whereas it becomes generally positively correlated in the higher frequency bands. Additionally, the correlation coefficient of the concrete damping and the FRS is negative for all of the frequency bands, which is consistent with our traditional understanding. Based on the absolute value, the susceptibility of the damping of concrete is larger at high frequencies than low frequencies.

5 Conclusions

Parameter uncertainties are significant for the seismic and safety evaluations of nuclear structures. However, there is no direct index system for identifying the degree of influence of a class of uncertain factors and their proportions. In this study, based on a summary of engineering practices combined with China's need for a test of the seismic safety of nuclear power facilities, a comprehensive index is created using the sensitivity, accuracy and influence of the statistical swing from different perspectives. Practical examples verify the engineering applicability and internal relations of the proposed method. It is a common method. The six random parameters selected for the analysis were used as an example to validate the new index and method. The random input parameters are not limited to six types. The proposed index and method are suited for other parameters. The largest impact factors that require more attention in the structural design, such as the shear modulus of soil are quantified and determined. Then, action can be taken to reduce the random variations of some important parameters to decrease the adverse effects. The results enhance the understanding of the effects of uncertain parameters on the FRS, particularly as they relate to the phenomena of peak reduction and FRS extension, from which the major influence factors can be identified among different input parameters. This application will provide an important technique for the seismic design of nuclear structures.

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