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Dynamic Reliability Analysis of Large Span Isolated Structures Based on Extreme Distribution Theory

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Abstract. The reliability evaluation of the stochastic seismic responses of the large span isolated structure is studied based on the probability density evolution and extreme distribution theory. The method can accurately give the probability density and probability distribution of structural displacement extreme. According to the deformation limit, the dynamic reliability of each layer and roof can be obtained directly, and it's a feasible approach to the precise reliability analysis of large span isolated structures. The calculation results show that for the isolation layer is the most vulnerable part, and the grid roof takes second place, while the superstructure is relatively safe. The isolation layer and the grid roof should be enhanced in the design of large span isolated structures.
Keywords: Large span isolated structure; Probability density evolution method; Extreme distribution theory; Reliability

1. Introduction

The large span structures are generally very important public buildings which require high seismic performance. The reasonable utilization of seismic isolation technology can greatly improve its horizontal seismic performance, and is therefore of great significance in engineering. The seismic design and performance evaluation of the large span isolated structures are the basic problems that need to be solved, and one of the key points is structural vertical seismic response analysis. Earthquakes, which are disastrous activities, often have strong randomness in time, place and intensity of occurrence. Actual structures will go into a nonlinear state under the action of earthquakes, and the mechanical characteristics of structures themselves are random too. Therefore, it is necessary to carry out the nonlinear response and reliability analysis of complex and large structures subjected to random earthquake so as to ensure the safety of engineering structures.

Since the 1970s, structural reliability has become an important issue concerned by many scholars at home and abroad. Two methods, diffusion process theory (Zhu W.Q. 2003) and leapfrogging process theory (Crandall S. H. 1963), have been developed. It is found that the diffusion process theory is generally only applicable to single-degree-of-freedom systems, which means that the high-dimensional partial differential problems of multi-degree-of-freedom systems difficult to solve via the theory. The introduction of too many assumptions in the theory of leapfrogging process makes it difficult to guarantee the accuracy, and there are great difficulties in reliability analysis of multi-degree-of-freedom nonlinear systems. The probability density evolution method (PDEM) proposed by Li Jie's team (Li J. & Ai X.Q. 2006; Li J. & Chen J.B.2009) provides a new approach to structural reliability. On the basis of PDEM, the absorptive boundary condition is introduced to obtain the extreme value distribution of the response, and then the dynamic reliability of the structure can be obtained by numerical integration within a given safety limit. In this paper, the large span isolated structures are taken as the research objects to carry out the performance evaluation based on reliability on the basis of PDEM.

2. Reliability theory based on PDEM

Assume that the number of degrees of freedom of a large span isolated structure is *n*, and then the dynamic equilibrium equation of the system is as follows:

$$\boldsymbol{M}(\boldsymbol{\Theta})\ddot{Y} + \boldsymbol{C}(\boldsymbol{\Theta})\dot{Y} + \boldsymbol{f}(\boldsymbol{\Theta},\ Y) = \boldsymbol{F}(\boldsymbol{\Theta},\ t) \tag{1}$$

where $\boldsymbol{M}$=the mass matrix; $\boldsymbol{C}$=the damping matrix; $\boldsymbol{f}$ =the nonlinear response vector; $\boldsymbol{F}$=the excitation vector of ground motion. $\ddot{Y}$ =acceleration response vector; $\dot{Y}$ =velocity response vector; Y = displacement response vector; $\boldsymbol{\Theta}$ = the random vector which reflects the randomness of both structure itself and seismic excitation; t = arbitrary time.

The solution of $Y(t)$ depends only on the random parameter vector, $\boldsymbol{\Theta}$, and the probability density function of Y can be written as

$$p_Y(y,t) = \int_{\Omega_{\boldsymbol{\Theta}}} p_{Y\boldsymbol{\Theta}}(y,\theta,t)\mathrm{d}\theta \tag{2}$$

where Ω_Θ = the distribution area of the random parameter vector $\boldsymbol{\Theta}$.

The expression of structural dynamic reliability is

$$R = \int_0^{y_b} p_{Y_a}(y_a)\mathrm{d}y_a \tag{3}$$

where $p_{Y_a}(y_a)$ = probability density function of Y_a .

By using the above PDEM, the issue of structural dynamic reliability can be transformed into a problem of one-dimensional integral.

3. Dynamic Reliability Based on Extreme Distribution Theory

From the basic theory of probability density evolution, it can be concluded that the maximum displacement response of the large span isolated structure under random earthquakes becomes the truncated random variable of the constructed virtual random process. The probability density evolution equation of the large span isolated structure is established and solved. The probability distribution of the extreme value of the nonlinear random displacement response of the large span isolated structure is calculated. Finally, the dynamic reliability of the structure is obtained by integrating in the safety domain.

Firstly, a virtual stochastic process, $Z(\tau)$,is constructed where τ =the virtual time parameter. Combining the above density evolution theory, the joint probability density function of (Z,Θ), $p_{\mathbf{Z\Theta}}(z,\theta,\tau)$, can be obtained to satisfy the probability evolution equation:

$$\frac{\partial p_{\boldsymbol{Z\Theta}}(z,\boldsymbol{\theta},\tau)}{\partial t} + H(\boldsymbol{\Theta},T)\frac{\partial p_{\boldsymbol{Z\Theta}}(z,\boldsymbol{\theta},\tau)}{\partial z} = 0 \tag{4}$$

Combining the initial conditions, the dynamic reliability of the large span isolated structure can be obtained by solving the above partial differential equations with finite difference method:

$$R = \int_0^{y_b} p_Z(z,\ \tau{=}1)\mathrm{d}z \tag{5}$$

The large span isolated structure can be regarded as a series structure system. That is to say, assuming that there is no correlation between the displacement failure of each story, the dynamic reliability of the large span isolated structure system is:

$$P = P_u \cdot P_{IS} \tag{6}$$

$$P_u = \prod_{i=1}^{l} P_i \tag{7}$$

where P =the reliability of the structure system; P_{IS} =the reliability of isolation layer; P_u = the reliability of superstructure; P_i =the reliability of each floor of superstructure.

4. Numerical Example

4.1. Structure Survey

The model of large span isolated space truss is steel-concrete composite structure. The upper part is double-deck space steel structure, and the lower part is two-story concrete frame structure. The span of the structure is 90m (along the direction of seismic wave input), and the depth length is 45m. The height of the grid is 2.44m, and the height of the frame story is 5 m. The function of the second floor of the frame requires hollow without columns, and the grid roof is supported by the surrounding columns. The isolation layer is arranged between the foundation and the supporting columns. Seismic fortification intensity is 8 degrees (0.3g), and the site type is II.

4.2. Generation of Stochastic Ground Motion

Three random parameters of the site are selected, namely, frequency, damping ratio and input amplitude. The mean and coefficient of variation of random parameters are given in reference (Ou J.P. et al. 1991). By using he random ground motion model based on physical and synthesis technology based on Fourier spectrum (Ai X.Q. & Li J 2009), 202 seismic waves are generated artificially, and all the peak value of such ground motions are 510gal. Random ground motions synthesized above can show non-stationary characteristics of intensity. The synthesized results can simulate real ground motions well and can be used to analyze the response of large span isolated structures under random earthquakes.

4.3. Horizontal Displacement Extreme

Due to space limitation, Figure1 gives only the probability density curves of the extreme displacements of the isolation layer (The results of first layer, second layer and grid layer are ignored), as well as the curves obtained by conventional assumptions such as Rayleigh distribution, Normal distribution and lognormal distribution, where PDF means Probability Density Function. It can be seen from the graph that the maximum probability density value is the case that the extreme value of the interlayer displacement of the isolation layer is 0.25m. The probability density curve of the extreme value of the displacement response calculated by PDEM are the closest to the corresponding curve calculated by lognormal distribution, but are quite different form the results of Rayleigh distribution.

Figure 2 shows the probability distribution curve of the interlayer displacement extreme of the isolation layer of the large span isolated structure, where CDF means Cumulative Distribution Function. According to the China code, the probability that the interlayer displacement of isolation layer is less than 440 mm is 0.9584. The results show that the reliability of isolation layer is high in absolute sense.

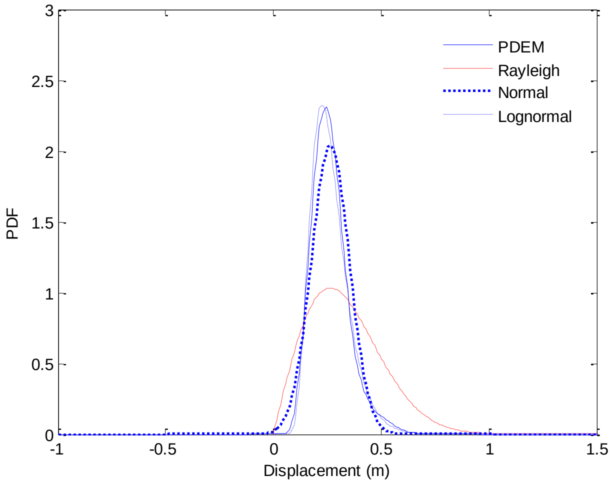

Figure 1. The PDF of isolation layer's displacement extreme

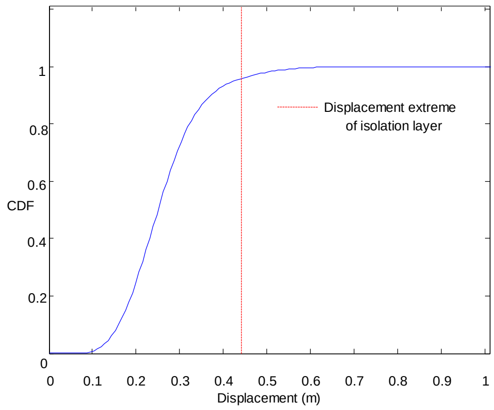

Figure 2. The CDF of isolation layer's displacement extreme

4.4. Vertical Displacement Extreme

For the large span isolated structure, if the grid layer deforms too much, it will not only affect the use of space, but also make people feel depressed. Therefore, it is necessary to study the reliability of the partial deflection of the grid. Figures 3 to 8 show the probability density curve and probability distribution curve of the vertical displacement extreme of the different points in the space truss layer of the large span isolated structure. From the graph, it can be seen that the probability density curve of the vertical displacement extremum of the grid layer nodes calculated is similar to both the normal distribution and the logarithmic normal distribution, but differs greatly from Rayleigh distribution.

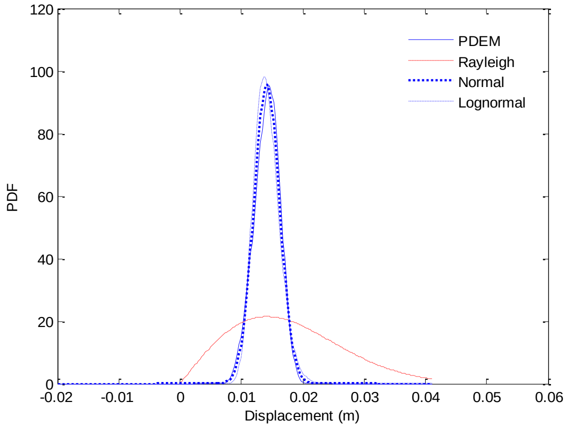

Figure 3. The PDF of grid layer's vertical displacement extreme

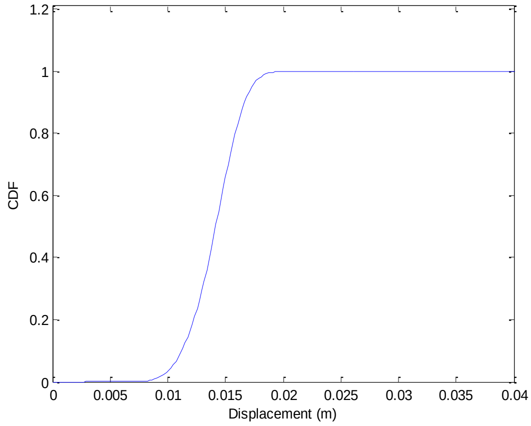

Figure 4. The CDF of grid layer's vertical displacement extreme

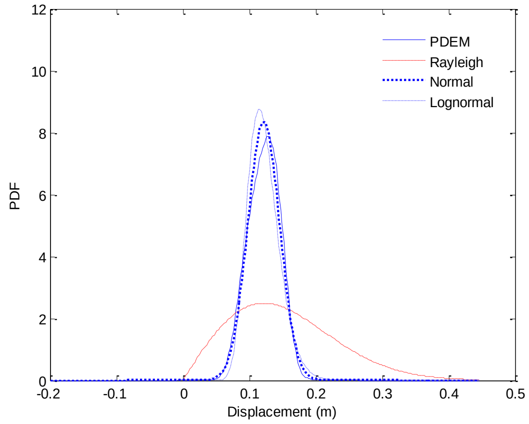

Figure 5. The PDF of grid layer's vertical displacement extreme

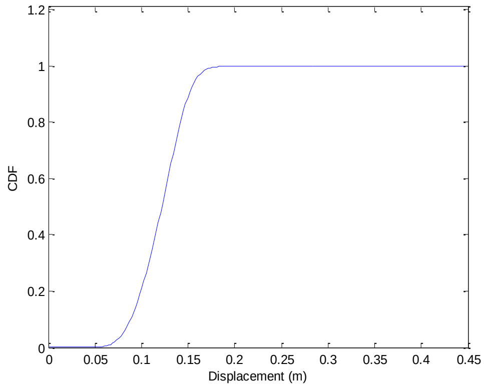

Figure 6. The CDF of grid layer's vertical displacement extreme

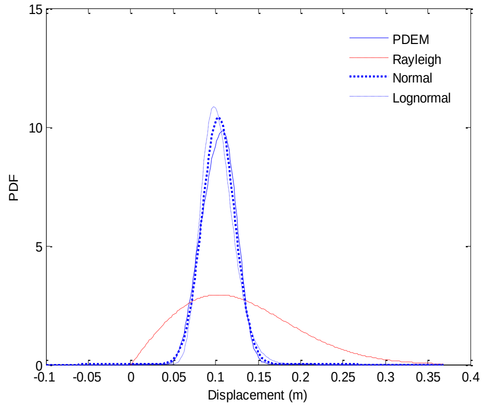

Figure 7. The PDF of grid layer's vertical displacement extreme

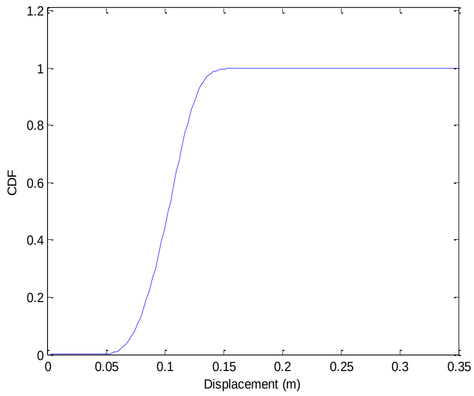

Figure 8. The CDF of grid layer's vertical displacement extreme

4.5. Reliability of Structure System

Research has long shown that the vertical vibration of truss roof can not be ignored for the large span structure. In this paper, the roof is divided into the upper chord layer and thelower chord layer. The failure probability at the corner points of the upper chord layer and the midpoints of the long side of the lower chord layer which should be paid more attention to in the design of the grid structure is one order of magnitude larger than that at other key nodes. Based on displacement index, the reliability of each node of the space truss is more than 0.99. Except for the nodes near the long side of the lower chord floor, the reliability of the whole roof reaches 0.9684, which indicates that the steel truss roof of the large span isolated structure can guarantee high reliability under 8.5 degree rare earthquake.

Table 1 shows the failure probability and dynamic reliability of each floor and the whole system of the large span isolated structure under rare random earthquake.

Table1. Dynamic reliability based on extreme distribution

Floor	Failure probability	Dynamic reliability
Second layer	0.0034	0.9966
First layer	0.0043	0.9957
Isolation layer	0.0416	0.9584
Superstructure	/	0.9923
Whole system	/	0.9510

From the table, it can be seen that the dynamic reliability of each layer of the superstructure is slightly less than 1.00, which indicates that the failure possibility of the first and second layers of the superstructure is very small after the isolation design of the large span structure. The failure probability of isolation layer under rare earthquake increases by an order of magnitude compared with the first and second stories of superstructure, which shows that isolation layer determines the system reliability of the large span isolated structure. Therefore, in the design process of the large span isolated structure, the emphasis should be placed on the isolation layer.

5. Conlusions

The main conclusions are as follows:

(1) The results of dynamic reliability of the large span isolated structure based on displacement index show that the reliability of isolation layer and space truss roof can reach high under rare earthquake. The superstructure will not fail and the reliability of structure system can reach 0.95. Therefore, it can be considered that the large span isolated structure has enough reliability under rare earthquakes.

(2) In the case of rare earthquake, the isolation layer of the large span isolated structure is the first place to fail, the lattice roof is the second place, and the superstructure is safer. In the design of the large span isolated structure, the above parts of isolation layer and lattice roof should be paid more attention and strengthened in order to improve the reliability of the whole structure.

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References

[1] Ai X.Q., Li J., “Synthesis method of non-stationary ground motion based on random Fourier spectra”, Journal of Earthquake Engineering and Engineering Vibration, Vol.29, No.2, 2009, PP 7-12.
[2] Crandall S. H., Mark W. D., Random vibration in mechanical systems,1963, New York: Academic Press.
[3] Li J., Ai X.Q., “Study on random model of earthquake ground motion based on physical process”, Earthquake Engineering and Engineering Vibration, Vol.26, No.5, 2006, PP 21-26.
[4] Li J., Chen J.B., Advances in theory and application of random vibration, 2009, Shanghai: Tongji University Press.
[5] Ou J.P., Niu D.T, Du X.L., “Random earthquake ground motion model and its parameters determination used in a seismic design”, Earthquake Engineering and Engineering Vibration, Vol.11, No.3, 1991, P45-53.
[6] Zhu W.Q., Nonlinear stochastic dynamics and control, 2003, Beijing: Science Press