Forest Chemicals Revew
www.forestchemicalsreview.com
ISSN: 1520-0191
July-August 2021 Page No. 1935-1948
Article History: Received: 12 May 2021 Revised: 25 June 2021 Accepted: 22 July 2021 Publication: 31 August 2021

The Stochastic Seismic Response Analysis and Reliability Research on Nonlinear Pile-Soil-Structure Interaction System with Uncertain Parameters

Zhiguang Li[1,2,3,*], Aihong Zhou[2,3,*], Ying Yuan[2,3], Yuanjie Zhao[1]
[1]Hebei Normal University, Shijiazhuang, 050024, China
[2]Hebei Technology Innovation Center for Intelligent Development and Control of Underground Built Environment, Hebei GEO University, Shijiazhuang, 050031, China
[3]Hebei Center for Ecological and Environmental Geology Research, Hebei GEO University, Shijiazhuang, 050031, China
*Corresponding author

Abstract:

A new approach is presented to analyze the seismic response of nonlinear pile-soil-structure interaction (PSSI) systems with uncertain parameters subject to the stochastic earthquake. First, the pseudo-excitation approach transforms the stochastic seismic analysis to an accurate analysis of the deterministic harmonic vibration. Second, a small parameter perturbation method is adopted to deal with the uncertain material parameters, while a direct interpolation equivalent linearization model is deduced for simulating the material nonlinearity. Then, the impacts of the variation of shear modulus, damping ratio, density, and Poisson's ratio on the PSSI system's stochastic seismic response are verified. Finally, according to the characteristics of the earthquake damage for the PSSI system, an anti-seismic approach is employed to take similar reliability for both pile foundation and structure. In addition, the stochastic seismic response analysis is employed to perform the stochastic dynamic reliability of the PSSI system with uncertain parameters based on the dual design guideline of strength and deformation. According to the results, the response's variation coefficients and the inputted material parameters have the same magnitude, while the effects of the variation of material parameters on the response magnitude should be considered. The control indexes, i.e., settlement, shear force, and a bending moment of the pile foundation, inter-storey displacement, and inter-storey shear force of structure, decrease while increasing the failure probability.

Keywords: *Stochastic seismic response, Reliability, System with uncertain parameter, Perturbation method, Pseudo-excitation method, Nonlinear*

Forest Chemicals Revew
www.forestchemicalsreview.com
ISSN: 1520-0191
July-August 2021 Page No. 1935-1948
Article History: Received: 12 May 2021 Revised: 25 June 2021 Accepted: 22 July 2021 Publication: 31 August 2021

I. INTRODUCTION

Earthquake motion has obvious randomness. The change factors of soil material parameters are much larger than those of steel and concrete. In recent years, the point of view that all kinds of random factors should be considered in the structural analysis and structural design is gradually under observation by researchers and engineers [1-3]. So the study of stochastic seismic analysis of stochastic structure has become one of hot issues in the field of structural analysis. Under strong earthquake, the dynamic interaction among pile, soil, structure is widespread and soil presents obvious nonlinear [4-8]. Therefore, the stochastic vibration analysis and reliability research considering the random earthquake, the variability and nonlinearity of soil materials, the dynamic interaction among pile, soil, structure is more reasonable and has a practical significance [2,5-11].

However, due to the complexity of the seismic problem itself and the influence of random load, stochastic seismic analysis of structures with uncertain parameters, also called combined stochastic seismic analysis, is very complicated. The research on combined stochastic seismic analysis is still in the exploratory stage at present. The combined stochastic seismic analysis methods can be divided into three categories: Monte Carlo simulation approach, orthogonal decomposition method, and the perturbation method.

Monte Carlo simulation method can approach arbitrary precision as long as enough samples can be obtained in theory, which is often used to test the numerical results of other methods. But the computation efficiency is very low in combined stochastic seismic analysis for large and complex structure. In order to improve the computation efficiency, the Neumann series expansion was introduced into Monte Carlo simulations [1].

Orthogonal decomposition method decomposes the response into orthogonal polynomial and then the statistical characteristics of response are calculated. When random factors are many or variation coefficients are great, the terms of polynomial increase significantly. The orthogonal decomposition method is improved by Li jie [3].

Perturbation method assumes that the known or unknown variable can be expanded to power series of small parameters. Combined the perturbation method with the frequency domain transfer function method or the pseudo-excitation method, many combined stochastic seismic problems can be solved.

Under strong earthquake, the soil presents obvious nonlinear. The nonlinear stochastic seismic analysis methods include accurate analysis method, numerical simulation method and

Forest Chemicals Revew
www.forestchemicalsreview.com
ISSN: 1520-0191
July-August 2021 Page No. 1935-1948
Article History: Received: 12 May 2021 Revised: 25 June 2021 Accepted: 22 July 2021 Publication: 31 August 2021

practical approximation method. Accurate analysis method at present is mainly Fokker-Planck-Kolmogorov method which is based on Markova process to solve the exact solution of probability distribution of the system response and has made great progress in the exact stationary solution for the FPK equation in recent 30 years. Numerical simulation method is characterized by Monte Carlo method. From the view of engineering application, a variety of practical approximate methods mainly include the equivalent linearization method, stochastic finite element method [2], Markov state equation construction method, semi-implicit integration method, and improved perturbation method, etc., in which the equivalent linearization method is used more widely.

Stochastic seismic analysis is different from the definite seismic analysis in soil, in which the shear strain in the soil layer is random. Iwan proposed the arithmetic average equivalent linearization method and Wu Zaiguang proposed the probabilistic average equivalent linearization method and the improved direct interpolation equivalent linearization method.

The pseudo-excitation approach is presented to transform the stochastic seismic analysis to an accurate analysis of definite harmonic vibration that considers the coupled impacts of the randomness with both material parameters and external loads. Author proposed a stochastic seismic analysis method combined the pseudo-excitation approach with deterministic dynamic finite element approach. Taking the homogeneous soil as an example, use direct acceleration method to input seismic load, investigate the effects of different equivalent shear strains on seismic response by ANSYS software, and compare with the theoretical solutions. The results show that different equivalent shear strain values have great effects on seismic response; the results calculated by the probabilistic average method and direct interpolation method is close. Those two methods have clear physical significance, but direct interpolation method is more concise and can be adopted to obtain the linear equivalent in the stochastic seismic analysis.

Based on the stochastic seismic analysis, the reliability research is carried on. Different uncertainties can be quantitatively characterized through the reliability analysis approach, and failure probability can be employed as a unified criterion for safety evaluation. The reliability design was extensively utilized to design the structure under the static load, indicating the appropriate and inevitable use of the dynamic reliability analysis approach in the anti-seismic design of pile foundation structure under stochastic earthquake. Due to the difficulty of the study on stochastic dynamic reliability of the PSSI system with structural parameter variation, as an essential issue in earthquake engineering, it has rarely been studied in the literature. Thus, it is crucial and meaningful and is beneficial for designing the pile foundation anti-seismic.

The earthquake can damage the pile foundation and structure. The structure destruction

Forest Chemicals Revew
www.forestchemicalsreview.com
ISSN: 1520-0191
July-August 2021 Page No. 1935-1948
Article History: Received: 12 May 2021 Revised: 25 June 2021 Accepted: 22 July 2021 Publication: 31 August 2021

often resulted from the pile foundation damage to some extent. Moreover, although the pile foundation was usually good, the structure was damaged. The mentioned cases were not expected to be seen. Therefore, according to the characteristics of the earthquake damage for the pile-soil-structure interaction (PSSI) system, the anti-seismic design approach of considering similar reliability for pile foundation and structure is employed. The presented approach is straightforward and can be employed to perform nonlinear combined stochastic response analysis and reliability research, compatible with the current earthquake engineering growth level.

II. PSEUDO-EXCITATION METHOD FOR STOCHASTIC RESPONSE ANALYSIS OF LINEAR SYSTEM

2.1 The Realization Form of the Finite Element Software in Stationary Random Vibration Pseudo-Excitation Method

Structure can produce cycle response by continuous load cycle. The module of harmonic response in finite element software, such us ABAQUS and ANSYS, can be utilized to obtain the linear structure's steady state response, which suffered the load for the sine law of the change.

$$M\ddot{y}(\mathrm{t}) + \mathrm{C}\dot{y}(\mathrm{t}) + \mathrm{Ky}(\mathrm{t}) = \mathrm{EF}_0 \sin \omega t \tag{1}$$

Among them, E is indicated to the force of the column vector, ω is the excitation frequency range (To which input in the Software is a series of discrete frequency points), F_0 is the amplitude of the excitation. The result which can be get is the changing curve of the response amplitude and the frequency, and the phase angle of peak displacement which occurred and so on.

2.2 A linear Structural Response under Stationary Random Excitation

The monophyletic of the since power spectrum which named $S_{ff}(\omega)$ and the phase stationary random excitation which named $\mathrm{f(t)}$ both are acted on the linear structure. The virtual incentive $\tilde{F}(\mathrm{t}) = \mathrm{p}\sqrt{S_{ff}(\omega)}e^{i\omega}$ is constructed, plugging in Euler's formula $e^{i\omega} = \cos \omega t + i \sin \omega t$, which get

$$\tilde{F}(\mathrm{t}) = \mathrm{p}\sqrt{S_{ff}(\omega)}(\cos \omega t + i \sin \omega t) \tag{2}$$

Forest Chemicals Revew
www.forestchemicalsreview.com
ISSN: 1520-0191
July-August 2021 Page No. 1935-1948
Article History: Received: 12 May 2021 Revised: 25 June 2021 Accepted: 22 July 2021 Publication: 31 August 2021

Through the pseudo-excitation method, the random excitation is become to the simple harmonic excitation. By using the analysis module of the finite element software harmonic response, considering the respective harmonic response analysis of the $\cos\omega t$ and $\sin\omega t$, the displacement response of any one degree of freedom can be get. Be shown as follows,

$$y_{\cos}(\omega,\mathrm{t})=\mathrm{B}(\omega)\sin(\omega\mathrm{t}+\varphi+\pi/2) \tag{3}$$

$$y_{\sin}(\omega,\mathrm{t})=\mathrm{B}(\omega)\sin(\omega\mathrm{t}+\varphi) \tag{4}$$

Among them, $\mathrm{B}(\omega)$ is the amplitude function, φ is the phase Angle. The degrees of freedom to this virtual response is

$$\tilde{\mathrm{y}}(\omega,\mathrm{t})=\sqrt{S_{ff}(\omega)}[\mathrm{B}(\omega)\sin(\omega\mathrm{t}+\varphi+\pi/2)+\mathrm{iB}(\omega)\sin(\omega\mathrm{t}+\varphi)] \tag{5}$$

According to the pseudo-excitation method, the above type can be put into $\mathrm{S}_{yy}(\omega)=\tilde{\mathrm{y}}^*(\omega,\mathrm{t})\cdot\tilde{\mathrm{y}}^T(\omega,\mathrm{t})$ after finishing it,

$$\mathrm{S}_{yy}(\omega)=B^2(\omega)S_{ff}(\omega) \tag{6}$$

Among them, $\mathrm{S}_{yy}(\omega)$ is the displacement response spectrum of this degree of freedom. It only depends on the incentive power spectrum $S_{ff}(\omega)$ and the amplitude of harmonic response $\mathrm{B}(\omega)$.

The motivate power spectrum $S_{ff}(\omega)$ in the corresponding frequency points is discrete. The amplitude function $\mathrm{B}(\omega)$ is extracted after analyzing the structure of harmonic response. Then the response power spectrum is get when plugged in type (6). It is efficient and convenient to realize the pseudo-excitation method in finite element software.

2.3 The Structural Dynamic Response of Acceleration Excitation in Consistent Stationary Random Ground

The structural equations of motion in stationary random acceleration excitation is

$$M\dot{y}(t)+C\dot{y}(t)+Ky(t)=m\ddot{x}(t)p \tag{7}$$

Among them, $\ddot{\mathrm{x}}(\mathrm{t})$ is the incentive acceleration, p is the Order vector, m is the main quality of the incentive. When $\mathrm{m}\ddot{\mathrm{x}}(\mathrm{t})\mathrm{p}=F(\mathrm{t})$, the acceleration excitation will become to the random

Forest Chemicals Revew
www.forestchemicalsreview.com
ISSN: 1520-0191
July-August 2021 Page No. 1935-1948
Article History: Received: 12 May 2021 Revised: 25 June 2021 Accepted: 22 July 2021 Publication: 31 August 2021

force excitation. The method of the calculating can be followed by which has introduced in section 2.1. As can be seen, the linear structures which under stationary random earthquake ground excitation can be achieved the seismic response of the structure which is only analyzed in real number field. In this paper, this kind of method is called the real domain pseudo-excitation method, which is distinguished by the complex domain of random seismic analysis method.

III. EQUIVALENT LINEARIZATION OF NONLINEAR SYSTEM

Stochastic seismic analysis was converted to a series of harmonic vibrations according to pseudo-excitation method. Firstly, suppose initial shear modulus and initial damping ratio and carry out the stochastic response analysis of linear system. Secondly, through equation (8), obtain variance of shear strain σ_γ, shear strain speed $\sigma_{\dot{\gamma}}$, and shear strain acceleration $\sigma_{\ddot{\gamma}}$, through equation (9), obtain bandwidth parameter β, through equation (10), and obtain equivalent shear strain γ_{eq}. Thirdly, through equation (11), obtain the new equivalent shear modulus and equivalent damping ratio. Finally, Replace the old value with the new value and iterate until the results satisfy the given accuracy. The used equations are as follows,

$$\sigma_\gamma^2 = \int_0^\infty G_\gamma(\omega)d\omega \,, \quad \sigma_{\ddot{\gamma}}^2 = \int_0^\infty \omega^4 G_\gamma\left(\omega\right)d\omega \,, \quad \sigma_{\dot{\gamma}}^2 = \int_0^\infty \omega^2 G_\gamma\left(\omega\right)d\omega \tag{8}$$

$$\beta = \sigma_{\dot{\gamma}}^2 / \sigma_\gamma \sigma_{\ddot{\gamma}} \tag{9}$$

$$\gamma_{eq} = \sqrt{2/\pi}\sigma_\gamma + \beta\left(\sqrt{\pi/2}\sigma_\gamma - \sqrt{2/\pi}\sigma_\gamma\right) \tag{10}$$

$$G_{eq} = G\left(\gamma_{eq}\right) = \frac{1}{1+\left|\gamma_{eq}/\gamma_r\right|}G_{\max}, \xi_{eq} = \xi\left(\gamma_{eq}\right) = \frac{\left|\gamma_{eq}/\gamma_r\right|}{1+\left|\gamma_{eq}/\gamma_r\right|}\xi_{\max} \tag{11}$$

IV. THE COMBINED STOCHASTIC SEISMIC RESPONSE ANALYSIS APPROACH OF LINEAR SYSTEM

Soil features are more challenging and have more significant variation compared with structures like steel and concrete structures. The variation of soil material parameters is assumed as the stochastic vector $\{b\} = \{G, \xi, \mu, \rho\}$ that comprises a simple time-independent random variable. Here, G stands for the shear modulus; ξ denotes the damping ratio; μ denotes the Poisson's ratio; ρ stands for the density. All random variables have similar expressions. For instance, G is represented as $G = G_{\mathrm{m}} + \varepsilon G_r$, in which G_m stands for the

Forest Chemicals Revew
www.forestchemicalsreview.com
ISSN: 1520-0191
July-August 2021 Page No. 1935-1948
Article History: Received: 12 May 2021 Revised: 25 June 2021 Accepted: 22 July 2021 Publication: 31 August 2021

average value reflecting the definite part; ε denotes a small parameter; G_r stands for the random part compatible with the standard normal distribution.

$$E[G]=E[G_{\mathrm{m}}]+\varepsilon E[G_r]=E[G_m]=G_m \tag{12}$$

$$D[G]=E[G^2]-(E[G])^2=E[G_m^2]+\varepsilon^2 E[G_r^2]-(E[G])^2=\varepsilon^2 E[G_r^2] \tag{13}$$

The material parameters' randomness causes the response's randomness and can be described with a normal distribution based on the central limit theorem. The response magnitude is described as

$$\{R\}=\{R_m\}+\varepsilon\{R_r\} \tag{14}$$

where $\{R_m\}$ is the average response component that is definite; $\{R_r\}$ is the random response component caused by soil material parameters' random component.

$\{R_r\}$ can be expanded in series of G, ξ, μ, ρ and is described as,

$$\{R_r\}=\left\{R_{,G}\right\}G_r+\left\{R_{,\xi}\right\}\xi_r+\left\{R_{,\mu}\right\}\mu_r+\left\{R_{,\rho}\right\}\rho_r \tag{15}$$

where $\{R_{,G}\}=\{R_{m,G}\}+\varepsilon\{R_{r,G}\}$.

Stochastic component is relatively smaller than the mean component. Therefore, $\{R_{,G}\}=\dfrac{\partial\{R\}}{\partial G}\approx\dfrac{\partial\{R_m\}}{\partial G}$.

The covariance function of $\{R\}$ is described as

$$\mathrm{cov}(\{R\},\{R\})=E[(\{R\}-\{R_d\})(\{R\}-\{R_d\})^T]=E[\{R_r\}\{R_r\}^T]\varepsilon^2 \tag{16}$$

The variation coefficient of response $\{R\}$ is defined as

$$\zeta_R=\sigma_R/R_d \tag{17}$$

The variation coefficient of response $\{R\}$ induced by the variation of shear modulus G is described as the following,

Forest Chemicals Revew
www.forestchemicalsreview.com
ISSN: 1520-0191
July-August 2021 Page No. 1935-1948
Article History: Received: 12 May 2021 Revised: 25 June 2021 Accepted: 22 July 2021 Publication: 31 August 2021

$$\zeta_{RG} = (\frac{\partial R_m}{\partial G} \sigma_G) \Big/ R_m \tag{18}$$

Consider that two random parameters are uncorrelated, then we have

$$\zeta_R^2 = \zeta_{RG}^2 + \zeta_{R\xi}^2 + \zeta_{R\mu}^2 + \zeta_{R\rho}^2 \tag{19}$$

The variation coefficient of the root-mean-square response is obtained for the PSSI system through the above approach. The detailed stochastic seismic response analysis approach on the employed nonlinear pile-soil interaction system was illustrated in the literature.

V. THE STOCHASTIC SEISMIC RELIABILITY ANALYSIS APPROACH FOR STRUCTURES WITH UNCERTAIN PARAMETERS

Response variance can be obtained through stochastic seismic analysis, which is helpful to understand the average amplitude of the random process. However, the structural damage is generally due to the maximum structural dynamic response, which can be described with a random variable according to the maximum theory.

The maximum response x_m is described as,

$$x_m = R_x \sigma_x \tag{20}$$

where R_x stands for the peak value, which is a random variable; σ_x is variance.

The mean and variance values of the maximum response in the interval $[0, T]$ can be described as

$$E[x_m] = E[R_x] \cdot E[\sigma_x] \tag{21}$$

$$V[x_m] = V[R_x]V[\sigma_x] + (E[R_x])^2 V[\sigma_x] + V[R_x](E[\sigma_x])^2 \tag{22}$$

$$E[R_x] = \sqrt{2\ln(\nu T)} + \frac{0.5772}{\sqrt{2\ln(\nu T)}} \tag{23}$$

$$V[R_x] = \frac{\pi^2}{6} \frac{1}{2\ln \nu T} \tag{24}$$

Forest Chemicals Revew
www.forestchemicalsreview.com
ISSN: 1520-0191
July-August 2021 Page No. 1935-1948
Article History: Received: 12 May 2021 Revised: 25 June 2021 Accepted: 22 July 2021 Publication: 31 August 2021

$$E[\sigma_x] = \sqrt{E[\sigma_x^2]} \tag{25}$$

$$V[\sigma_x] = \frac{V[\sigma_x^2]}{4E[\sigma_x^2]} \tag{26}$$

The maximum response distribution is compatible with the extreme value I distribution, which can be expressed as,

$$F_{x_m}(x) = \exp\{-\exp[-(x-a)/b]\} \tag{27}$$

where a stands for the location parameter and b describes the scale parameter obtained from the mean and variance of the maximum response.

$$a = E\left[X_m\right] - 0.5772b \tag{28}$$

$$b = \sqrt{V\left[X_m\right]} / 1.2825 \tag{29}$$

The failure probability p_f for a set of threshold value x_0 is expressed as,

$$p_f = 1 - F_{x_m}(x_0) \tag{30}$$

VI. CALCULATION MODEL AND CALCULATION PARAMETERS

The pile takes 1.0m in diameter and $20m$ in length, $3m \times 3m$ square symmetrically arranged, pile spacing 3m. Pile cap is rigid, whose dimension is 8m×8m×1m, and is fixed with pile. The pile is made of the reinforced concrete with the elastic modulus $E_p = 30GP_a$, Poisson's ratio $\nu_p = 0.167$, mass density $\rho_p = 2500kg/m^3$, and damping ratio 5%. The structure is five-storey with $3m$ in storey height and 200 ton of mass. Each floor makes dislocated deformation only at transverse vibration and the stiffness are 242×10^6, 211×10^6, 177×10^6, 145×10^6 and 97×10^6 from the bottom to the top respectively.

Considering the nonlinearity under strong earthquake, the maximum shear modulus of soil is 72Mpa, the maximum damping ratio is 0.28, the density is $1800kg/m^3$, Poisson's ratio is 0.35, the variation coefficient is 10%, and the reference shear train is 2.5×10^{-4}.

Suppose that the stochastic earthquake process model satisfies the KANAI-TAJIMI

Forest Chemicals Revew
www.forestchemicalsreview.com
ISSN: 1520-0191
July-August 2021 Page No. 1935-1948
Article History: Received: 12 May 2021 Revised: 25 June 2021 Accepted: 22 July 2021 Publication: 31 August 2021

spectrum, where its spectrum parameters are $\omega_g = 17.9 rad/s$, $\xi_g = 0.46$, the spectrum intensity is $G_0 = 1.463 \times 10^3 m^2/s^3$ and the duration is 16s.

Figure 1 shows the calculation model of the PSSI system. Structure is simulated as a multi-degree-of-freedom system, pile cap as rigid block, pile as beam element, and soil as plane strain element, respectively. In order to avoid the outward wave within the calculation area reflected back from the position of truncated boundary, the viscous-spring boundary is adopted, which can also model the elastic restoring performance of foundation.

The normal viscous-spring boundary can be expressed as,

$$K_{fi} = \frac{2G_i}{r} A_i \text{,} C_{fi} = \rho_i c_{pi} A_i \tag{31}$$

Tangential viscous-spring boundary can be expressed as,

$$K_{qi} = \frac{3G_i}{2r_i} A_i \text{,} C_{qi} = \rho_i c_{si} A_i \tag{32}$$

Where, K_i, C_i is spring coefficient and damping coefficient respectively; G_i, c_{pi}, c_{si} is shear modulus, longitudinal wave velocity and transverse wave velocity respectively; A_i represents the area that the boundary node i shared; r_i denotes the distance from the wave source to the boundary node i.

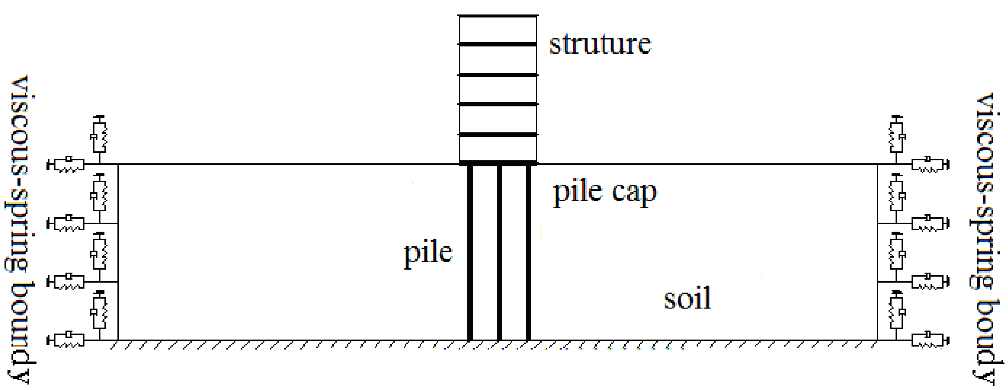

Fig. 1 Calculation model of the PSSI system

Forest Chemicals Revew
www.forestchemicalsreview.com
ISSN: 1520-0191
July-August 2021 Page No. 1935-1948
Article History: Received: 12 May 2021 Revised: 25 June 2021 Accepted: 22 July 2021 Publication: 31 August 2021

VII. CALCULATION RESULTS

The earthquake damage observation and survey analysis showed that pile foundation's common failure modes have bending moment, shear force and crack failure, or failure caused by the extreme deformation; while the failure usually occurs in pile top nearby. Thus, displacement, bending moment, and shear force at the pile top are derived for pile foundation, as presented in Table I and Table II.

TABLE I. Variation coefficients for different random parameters (%)

random parameter / variation coefficient	shear modulus	damping ratio	Poisson's ratio	density
displacement	9.17	1.02	1.92	3.85
bending moment	7.93	1.05	3.73	1.61
shear force	5.30	1.04	4.92	0.86

TABLE II. Total variation coefficients for all random parameters (%)

displacement	bending moment	shear force
10.18	8.98	7.35

As shown in Table I and Table II, among four factors, the shear modulus has the most significant impact on the responses' variation coefficients, while the damping ratio has the minimum impact. The displacement has the maximum variation coefficient among the three responses, while the maximum variation coefficients are greater than than 10%.

The superstructure's failure is mainly because the inter-storey shear force exceeds its corresponding bearing capacity or inter-storey displacement exceeds the permissible deformation. Therefore, the stochastic seismic responses of inter-storey displacement and inter-storey shear force are displayed in Fig. 2, Fig. 3, and Table III.

Forest Chemicals Revew
www.forestchemicalsreview.com
ISSN: 1520-0191
July-August 2021 Page No. 1935-1948
Article History: Received: 12 May 2021 Revised: 25 June 2021 Accepted: 22 July 2021 Publication: 31 August 2021

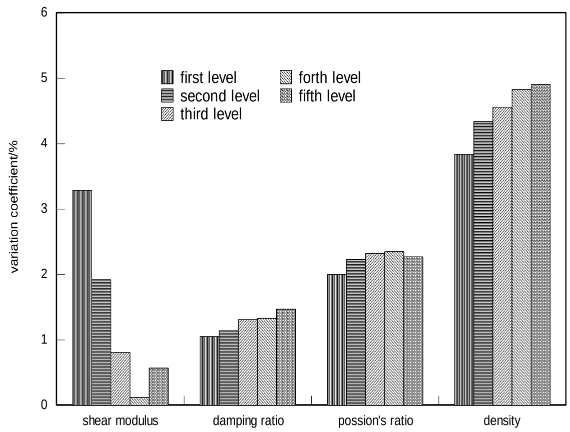

Fig. 2 The inter-storey shear force's variation coefficients for different random parameters

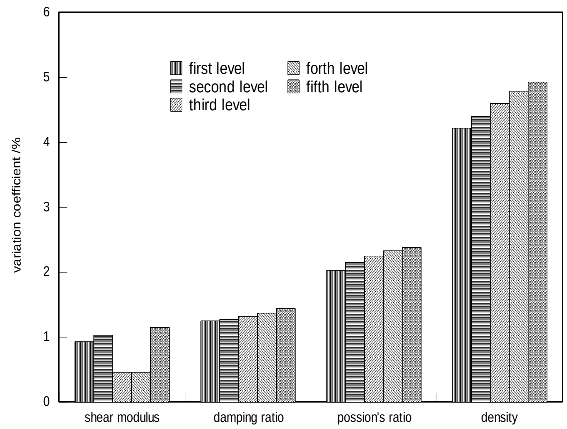

Fig. 3 The inter-storey displacement's variation coefficients for different random parameters

TABLE III. The obtained total variation coefficients for all random parameters (%)

floor level	**1**	**2**	**3**	**4**	**5**
Total variation coefficients of the inter-storey displacement	5.54	5.37	5.34	5.53	5.63
Total variation coefficients of the inter-storey shear force	4.94	5.16	5.31	5.52	5.78

As depicted in Fig. 2, Fig. 3, and Table III, among four factors, the density has the more significant impact on the responses' variation coefficients, while their magnitudes depend on the floor level, and the maximum is greater than 5%.

Table IV shows the response for pile foundation and structure on the same reliability. Based on Table IV, pile foundation and structure control indices decrease while increasing the failure probability.

TABLE IV. Responses for various probabilities of exceedance

Probability of exceedance (%) / **response**	**10**	**20**
displacement of pile top (mm)	8.3	7.6
shear force of pile top (kN)	103.279	94.050

bending momoent of pile top (kN*m)		140.337	127.410
inter-storey displacement (mm)	1	10.1	9.3
	2	10.8	9.9
	3	11.1	10.1
	4	10.2	9.3
	5	8.4	7.7
inter-storey shear force (kN)	1	1246.415	1140.959
	2	1213.072	1110.217
	3	1158.373	1060.253
	4	1045.194	956.759
	5	809.782	741.269

VIII. CONCLUSION

The upcoming conclusions are drawn through the above analysis:

1) The variation coefficients of the response and the inputted material parameters have similar magnitudes, while the variation of material parameters cannot significantly affect the response magnitude;

2) The presented approach in this paper can be employed to perform the combined stochastic vibration analysis for the PSSI system;

3) The control indices of the pile foundation and structure decrease while increasing the failure probability.

ACKNOWLEDGEMENTS

The research of this project is supported by the National Science Foundation of China (Grant No.41301015 & No.41807231) and the Teaching Reform Research and practice project of Hebei GEO University (Grant No.2020J36 & No.2020J33) and the Funding for the Science and Technology Innovation Team Project of Hebei GEO University (Grant No.KJCXTD-2021-08) and Higher Education Teaching Reform and practice project in Hebei Province (Grant No.2019GJJG294).

REFERENCES

Forest Chemicals Revew
www.forestchemicalsreview.com
ISSN: 1520-0191
July-August 2021 Page No. 1935-1948
Article History: Received: 12 May 2021 Revised: 25 June 2021 Accepted: 22 July 2021 Publication: 31 August 2021

[1] Jinping Yang, Zheng Lu, Peizhen Li. Large-scale shaking table test on tall buildings with viscous dampers considering pile-soil-structure interaction. Engineering Structures, 2020, 220(220).
[2] Raheem Shehata E Abdel, Aal Elsayed M. Abdel, AbdelShafy Aly G.A., Fahmy Mohamed F.M., Mansour Mahmoud H. Pile-soil-structure interaction effect on structural response of piled jacket-supported offshore platform through in-place analysis. Earthquakes and Structures, 2020, 18(4).
[3] Yunfei Xie, Shichun Chi, Maohua Wang, José Domingo Álvarez. Influence of Variable Rigidity Design of Piled Raft Foundation on Seismic Performance of Buildings. Mathematical Problems in Engineering, 2020, 2020(2020).
[4] F.D. Konstandakopoulou, K.I. Evangelinos, I.E. Nikolaou, G.A. Papagiannopoulos, N.G. Pnevmatikos. Seismic analysis of offshore platforms subjected to pulse-type ground motions compatible with European Standards. Soil Dynamics and Earthquake Engineering, 2020, 129(129).
[5] Limin Sun, Wen Xie. Evaluation of pile-soil-structure interaction effects on the seismic responses of a super long-span cable-stayed bridge in the transverse direction: A shaking table investigation. Soil Dynamics and Earthquake Engineering, 2019, 125(125).
[6] Sun Yong Kwon, Mintaek Yoo. Evaluation of Dynamic Soil-Pile-Structure Interactive Behavior in Dry Sand by 3D Numerical Simulation. Applied Sciences, 2019, 9(13).
[7] Pasin Plodpradit, Van Nguyen Dinh, Ki-Du Kim. Tripod-Supported Offshore Wind Turbines: Modal and Coupled Analysis and a Parametric Study Using X-SEA and FAST. Journal of Marine Science and Engineering, 2019, 7(6).
[8] Pasin Plodpradit, Van Nguyen Dinh, Ki-Du Kim. Coupled Analysis of Offshore Wind Turbine Jacket Structures with Pile-Soil-Structure Interaction Using FAST v8 and X-SEA. Applied Sciences, 2019, 9(8).
[9] Zhang Zhi, Li Xiaojun, Lan Riqing, Song Chenning. Shaking table tests and numerical simulations of a small radius curved bridge considering SSI effect. Soil Dynamics and Earthquake Engineering, 2019, 118(118).
[10] A. Ajamy, B. Asgarian, C.E. Ventura, M.R. Zolfaghari. Seismic fragility analysis of jacket type offshore platforms considering soil-pile-structure interaction. Engineering Structures, 2018, 174(174).
[11] Md. Shajib Ullah, Hiroki Yamamoto, Chandra Shekhar Goit, Masato Saitoh. On the verification of superposition method of kinematic interaction and inertial interaction in dynamic response analysis of soil-pile-structure systems. Soil Dynamics and Earthquake Engineering, 2018, 113(113).