The Simulation of Spatially Unsteady Seismic Ground Motion

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Abstract. The simulation of spatially varying non-stationary seismic fields holds a crucial role in the fields of earthquake engineering and structural engineering. This simulation technique not only significantly enhances the safety of structural designs but also boosts multi-scale analysis capabilities, optimizes emergency management, and improves disaster response efficiency. By more accurately assessing the potential impacts of earthquakes, it notably advances the identification and precision of disaster management and brings revolutionary progress to the development of related scientific and technological fields. This simulation method has profound practical applications and theoretical value, making it a current research hotspot. This paper employs the Harmonic Synthesis Method to simulate the acceleration time histories of non-stationary seismic waves, innovatively incorporating the Fast Fourier Transform (FFT) algorithm to significantly enhance the efficiency and accuracy of the simulations. Additionally, the paper takes into account the unique structural characteristics of large-span bridges in mountainous areas, simulating not only the traveling wave effects of multiple-point excitation but also the spatial coherence between bridge piers. By using modulation functions for the non-stationary treatment of seismic waves, this study accurately reflects the dynamic variations of seismic waves at different locations, thereby more realistically simulating and predicting the response behavior of large structures during actual earthquakes. Moreover, the methods and results of this study not only have significant implications for engineering practice but also provide new ideas and tools for theoretical research in earthquake engineering, deepening our understanding of the complexities of earthquake dynamics. Through this efficient and innovative simulation method, we can better design and evaluate structural safety and emergency measures in the face of earthquake threats, thereby reducing losses during disasters and protecting human life and property.

Keywords :eismic ground; WASW; unsteady; spatial correlation

1 INTRODUCTION

The fact that seismic spatial changes significantly and have a great impact on the seismic differential response of long structures has been widely recognized by the

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engineering community. Even in the range of 50m, there are obvious differences in seismic motion, showing the complex form and distribution of spatial and space-time [1]. In structural seismic analysis, for the input mode of seismic motion, countries still use a simple model of homogeneous substrate input. In models that ignore the mass of the foundation, the amplitude and phase of seismic motion at each input point are the same. However, for the construction of deep mountain canyons, the assumption of bridge structures with large height differences is obviously inconsistent with the actual situation.

Li Y.M. et al. believe that it is superior to use the self-regressive sliding average model (ARMR) to describe the intensity and frequency time-varying characteristics of real seismic motion [2]; Wen and Gu use the Hilbert spectrum to describe the time-frequency non-stationary characteristics of seismic motion, and then synthesize seismic motions through the Hilbert spectrum envelope [3]. Some scholars have used other similar time-frequency digital transformation methods to describe the non-stationary characteristics of seismic motion, and have also obtained better results [4-8]. However, in general, although the above time spectrum has the resolution of time and frequency, which is suitable for the simulation and reproduction of specific records, the description of the binary function of time and frequency is too complicated and has many parameters, which is difficult to directly apply to engineering practice [9]. In order to facilitate engineering application, Yuetal. A simplified time-frequency envelope function model with statistical parameters is proposed, and in its subsequent research, the energy distribution in the time-frequency envelope function [10-11] has been further improved. These models not only have clear physical significance, but also well reflect the intensity and frequency non-stationary characteristics of seismic motion.

In summary, current research in earthquake field simulation, both domestically and internationally, largely overlooks the spatial distribution characteristics of long-span bridges. This oversight can lead to simulation results that do not accurately reflect the response characteristics of such structures in actual earthquakes, thereby impacting the safety and reliability of structural design. Due to their unique structural features, such as long spans and high flexibility, long-span bridges exhibit dynamic responses different from typical building structures under seismic activities. In the field of earthquake engineering, the unique spatial distribution and response characteristics of these bridges necessitate more refined and specialized simulation techniques. For instance, considerations such as the multiple-point excitation effects, travelling wave effects, and the interactions between different parts of the structure should be accounted for in simulations. Additionally, the variations in dynamic properties at different bridge locations, the activation of different vibration modes caused by earthquakes, and how these modes interact and affect the overall structural safety are critical factors that must be precisely considered during simulations. In this study, the Harmonic Synthesis Method combined with the Fast Fourier Transform (FFT) algorithm was used to simulate the acceleration time histories of non-stationary seismic waves, significantly enhancing the efficiency and accuracy of the simulations. Considering the special structural requirements of long-span bridges in mountainous areas, this thesis not only simulates the travelling wave effects under multi-point excitations but also takes into account the spatial coherence between bridge piers. By using modulation functions to handle the non-stationary characteristics of seismic waves, this research accurately portrays the dynamic changes at different locations, thereby more realistically simulating and predicting the response of large structures in real earthquake scenarios. Furthermore, the methods and results of this study provide important guidance for engineering practice and open new avenues and tools for theoretical development in earthquake engineering, deepening our understanding of the complexities of seismic dynamics. Through this efficient and innovative simulation technique, it is possible to more effectively design and assess structural safety and emergency response measures in the face of seismic threats, thus reducing losses and safeguarding human lives and property in the event of disasters.

2 POWER SPECTRUM MODEL OF SPATIAL CHANGE

2.1 Modulation Function

Engineering models of non-stationary random seismic motion can usually be expressed as

$$a(t) = g(t)\begin{Bmatrix} u_1(t) \\ \vdots \\ u_m(t) \end{Bmatrix} = g(t)\{u(t)\} \tag{1}$$

In the formula, $g(t)$ is a modulation function; $u_1(t),\cdots,u_m(t)$ is a m stationary random process.

The modulation function used in this paper is [5]

$$g(t) = \begin{cases} t/t_1 & 0 \le t < t_1 \\ 1 & t_1 \le t < t_2 \\ e^{-\beta(t-t_2)} & t_2 \le t \le t_3 \end{cases} \tag{2}$$

2.2 Spectrum Intensity

Kanei and Tajimi assume that the seismic movement of the bedrock is white noise, and put forward a stable stochastic process model with clear physical significance considering the site characteristics.

$$S(\omega) = \frac{1 + 4\xi_g^2 \dfrac{\omega^2}{\omega_g^2}}{(1 - \dfrac{\omega^2}{\omega_g^2})^2 + 4\xi_g^2 \dfrac{\omega^2}{\omega_g^2}} S_0 \tag{3}$$

In the formula, ω_g 、 ξ_g are the excellent frequency and damping ratio of the site soil respectively; S_0 is the white spectrum intensity.

However, this power spectral density function($T \ge 3.5s$)approximates an ideal white noise within a long period, so it inevitably causes a resonant response to the structure, which contradicts the conclusion that has been confirmed by theory and experiments that the long period has a good seismic isolation effect. In order to overcome the shortcomings of formula (3), the literature [12] gives a standardized unilateral power spectral density function consistent with China's seismic design specification revised over a long period of time.

$$S(\omega) = \frac{\frac{\omega}{\omega_g}}{(1-\frac{\omega^2}{\omega_g^2})^2 + 4\xi_g \frac{\omega^2}{\omega_g^2}} S_0 \tag{4}$$

Seismic waves propagate from the source to the surroundings. It can be roughly believed that a point on the site and the epicenter are the propagation direction of seismic waves. The mutual power spectrum between the two points i and k in a straight line along the direction of wave propagation $S_{jk}(i\omega)$ can be expressed as follows.

$$S_{jk}(\omega) = \sqrt{S_{jj}(\omega) S_{kk}(\omega)} \rho_{jk}(d,\omega) e^{-i\omega \frac{d}{V_a(\omega)}} \tag{5}$$

Among them, $S_{jj}(\omega)$ and $S_{kk}(\omega)$ are the self-power spectrum of j and k points; $\rho_{jk}(d,\omega)$ is the coherent function of two points; and $V_a(\omega)$ is the apparent speed. The corresponding expressions of the items in the expression (5) are as follows.

$$V_a(\omega) = C_1 + C_2 \ln(\omega / 2\pi) \tag{6}$$

$$\rho_{jk}(d,\omega) = e^{-a(\omega)\cdot d^{b(\omega)}} \tag{7}$$

$$a(\omega) = a_1\omega^2 + a_2 \tag{8}$$

$$b(\omega) = b_1\omega + b_2 \tag{9}$$

The literature [13] considers the change of the self-power spectrum at various points in the site. Through the detailed study of the seismic record of the SMART-1 array, the difference between the self-power spectrum parameters between the measuring points is fitted.

$$\Delta S_0 = 0.2571\Delta h - 0.0124\Delta x \tag{10}$$

In the formula, ΔS_0 is the difference between the self-power spectral parameters between the measuring points, and the unit is $cm^2/(rad \cdot s^2)$; Δh is the thickness of the soil between the two measuring points (from the bedrock to the surface), and the unit is m; Δx is the difference between the epicenter distance between the two measuring points, and the unit is m.

3 SIMULATION OF SMOOTHING PROCESS

3.1 Harmonic Synthesis Method

The harmonic synthesis method is used here. The harmonic synthesis method simulates stochastic process samples through the iteration of a series of triangular cosine functions. Consider the Gaussian stationary random process $u(t)$ of a one-dimensional m variable, whose mutual spectral density matrix is:

$$S(\omega)=\begin{bmatrix} s_{11}(\omega) & s_{12}(\omega) & \cdots & s_{1n}(\omega) \\ s_{21}(\omega) & s_{22}(\omega) & \cdots & s_{2n}(\omega) \\ \vdots & \vdots & \ddots & \vdots \\ s_{n1}(\omega) & s_{n2}(\omega) & \cdots & s_{nn}(\omega) \end{bmatrix} \tag{11}$$

$S(\omega)$ power spectral density function, $H_{jk}(\omega_l)$ is the element of the matrix $H(\omega)$, and $H(\omega)$ is the Cholesky decomposition of $S(\omega)$:

$$S(\omega)=H(\omega)H^{T^*}(\omega) \tag{12}$$

$$H(\omega)=\begin{bmatrix} H_{11}(\omega) & 0 & \cdots & 0 \\ H_{21}(\omega) & H_{22}(\omega) & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ H_{m1}(\omega) & H_{m2}(\omega) & \cdots & H_{mm}(\omega) \end{bmatrix} \tag{13}$$

Elements in matrix $H(\omega)$ can be represented by the following formula:

$$\begin{cases} H_{11}(\omega)=\sqrt{S_{11}(\omega)} & \\ H_{j1}(i\omega)=S_{j1}(i\omega)/H_{11}(i\omega) & j=2,3,\cdots,m \\ H_{jj}(\omega)=[S_{jj}(\omega)-\sum_{r=1}^{j-1}H_{jr}(i\omega)H_{jr}^{*}(i\omega)]^{\frac{1}{2}} & j=2,3,\cdots,m \\ H_{sj}(i\omega)=\dfrac{S_{sj}(i\omega)-\sum_{r=1}^{j-1}H_{sr}(i\omega)H_{jr}^{*}(i\omega)}{H_{jj}(\omega)} & s=j+1,\cdots,m \end{cases} \tag{14}$$

$$H_{jj}(\omega)=H_{jj}(-\omega)\,,\quad j=1,\cdots,m \tag{15}$$

$$H_{jk}(\omega)=\left|H_{jk}(\omega)\right|e^{i\theta jk(\omega)},j=2,\cdots,m;k=1,\cdots,m-1;j>k \tag{16}$$

Among them, $\theta_{jk}(\omega)$ is the amplitude and angle of $H_{jk}(\omega)$:

$$\theta_{jk}=\tan^{-1}\left\{\frac{\mathrm{Im}\left[H_{jk}(\omega)\right]}{\mathrm{Re}\left[H_{jk}(\omega)\right]}\right\} \tag{17}$$

In order to avoid distortion of simulation results, the time interval should meet:

$$\Delta t\le\frac{2\pi}{2\omega_u} \tag{18}$$

The simulated random process period is:

$$T_0 = m\frac{2\pi}{\Delta\omega} = mN\frac{2\pi}{\omega_u} \tag{19}$$

Thus, the random process can be simulated by the following formula:

$$u_j(t) = \sqrt{2}\sum_{k=1}^{j}\sum_{l=1}^{N}\left|H_{jk}(\omega_l)\right|\sqrt{\Delta\omega}\cos\left[\omega_l t + \theta_{jk} + \phi_{kl}\right], j = 1,\cdots,m \tag{20}$$

ϕ_{kl} is a random phase angle, take the uniformly distributed random number in [0, 2π],

ω_l index frequency: $\omega_l = (l-1)\Delta\omega$, ω_u is the cut-off frequency

N is the sampling frequency point. In theory $N \to \infty$, it is only necessary to take a sufficiently large integer in the actual calculation. In order to use FFT technology, $N = 2^{\mu}$, μ is a positive integer.

3.2 FFT Technology

Rewrite the formula (20) as:

$$u_j(p\Delta t) = \mathrm{Re}\left\{\sum_{k=1}^{j} h_{jk}(p\Delta t)\right\} \tag{21}$$

$$j = 1,\cdots,m, \qquad p = 0,\cdots,2N\times m-1$$

Among

$$\begin{aligned} h_{jk}(p\Delta t) &= \sum_{l=0}^{2N-1} B_{jk}(l\Delta\omega)\exp(il\Delta\omega p\Delta t) \\ &= \sum_{l=0}^{2N-1} B_{jk}(l\Delta\omega)\exp(ilp\frac{\pi}{N}) \end{aligned} \tag{22}$$

$$B_{jk}(l\Delta\omega) = \begin{cases} \sqrt{2\Delta\omega}H_{jk}(l\Delta\omega)\exp(i\phi_{kl} + i\theta_{jk}), & 0 \le l < N \\ 0 \quad , & N \le l \le 2N \end{cases} \tag{23}$$

Rewrite the formula (21) to read:

$$u_j(p\Delta t) = \mathrm{Re}\left\{\sum_{k=1}^{j} h_{jk}(q\Delta t)\right\} \tag{24}$$

$j = 1,\cdots,m,$ $\quad p = 0,\cdots,2N\times m-1,$ the remainder of q to $p/2N$

Among

$$h_{jk}(q\Delta t) = \sum_{l=0}^{2N-1} B_{jk}(l\Delta\omega)\exp(ilq\frac{\pi}{N}) \tag{25}$$

Obviously, $h_{jk}(q\Delta t)$ is the discrete Fourier transform of $B_{jk}(l\Delta\omega)$, which can be analyzed by FFT technology.

4 SYNTHETIC EXAMPLES

In this paper, the piers free field of Class II sites in China's seismic specification are simulated. Seismic analysis requires simulating the seismic time range of 7 points. The seismic source is located on the left side of the bridge, with a design intensity of 7 degrees. The positions of each point are shown in Figure 1. The parameters in the simulation are shown in Table 1-Table 3, and the simulation results are shown in Figure 2-Figure 8.

Table 1. parameter of different pier position

Index	1	2	3	4	5	6	7
X(m)	0	145	405	665	925	1185	1330
H(m)	240	160	68	0	66	190	240

Table 2. parameter of seismic simulation

Cut-off frequency	sampling isometric	sampling time distance	simulated sampling points,	seismic spectrum
20 π	1024	0.02s	8192	Standardized single-sided power spectrum [1]

Table 3. parameter of power density [13][14]

ω_g	ξ_g	S_0	c_1	c_2	a_1	a_2	b_1	b_2	β	t_1	t_2	t_3
15.7	0.6	23.5	2401	1211	1.7e-5	1.2e-3	-5.5e-3	0.767	0.16	6s	12s	20s

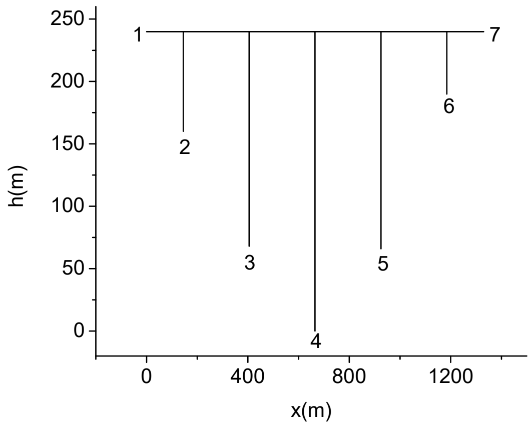

Fig. 1. The position of piers

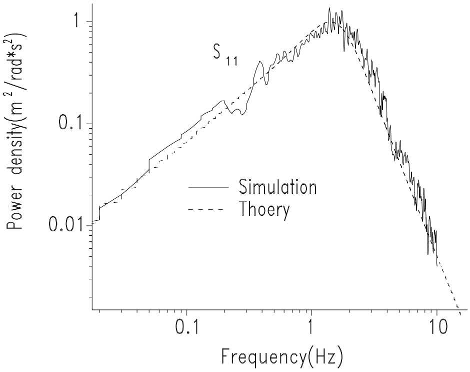

Fig. 2. Comparison of spectral density at 1#(In logarithmic scale)

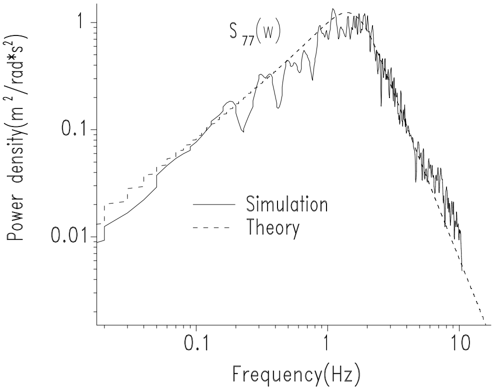

Fig. 3. Comparison of spectral density at 7#

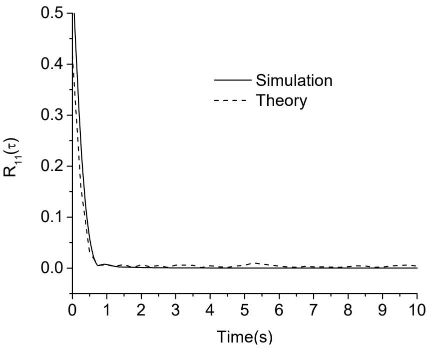

Fig. 4. Comparison of correlation functions at 1# (In logarithmic scale)

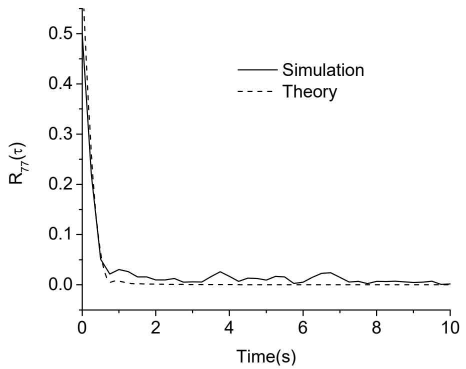

Fig. 5. Comparison of correlation functions at 7#

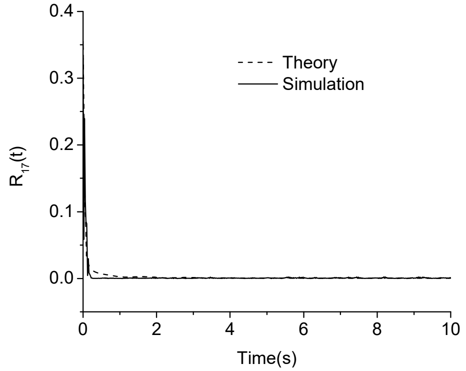

Fig. 6. Comparison of correlation functions

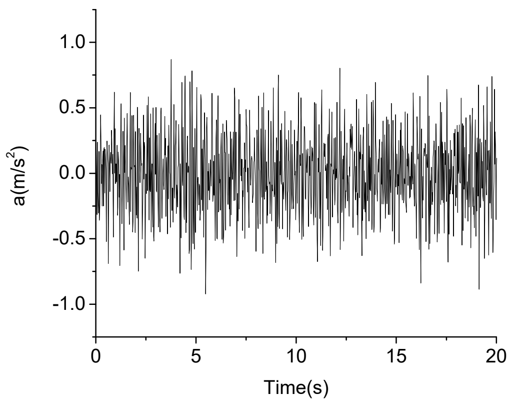

Fig. 7. The history of steady acceleration

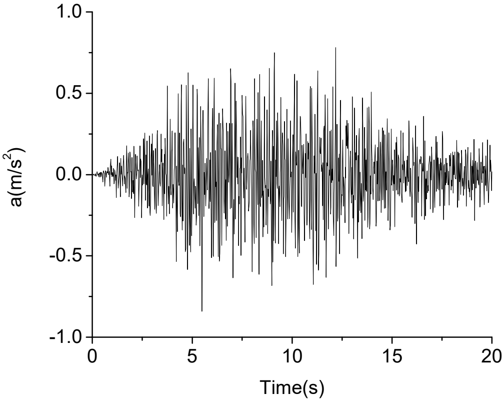

Fig. 8. The history of unsteady acceleration

In the study of seismic wave simulation, the Fourier transform is a commonly used mathematical tool for converting time-domain signals into frequency-domain signals. This step is crucial for understanding and analyzing the frequency characteristics of seismic waves. In this research, the Fourier transform was applied to the simulated seismic wave time history results, and the rectangular filtering method was used to extract the power density spectrum. This method effectively isolates and analyzes the energy distribution within specific frequency ranges.

Figures 2 and 3 display the power density spectra obtained from experimental and theoretical calculations, showing good agreement between them. This consistency indicates that the simulation process can accurately reproduce the frequency characteristics of seismic waves, thereby validating the effectiveness and accuracy of the simulation method.

Further, Figures 4, 5, and 6 explore the autocorrelation functions and cross-correlation functions between different points. The autocorrelation function measures the similarity of seismic waveforms at different times at the same location, while the cross-correlation function assesses the similarity of seismic waves at two different locations. These figures show a comparison between theoretical calculations and simulation results, demonstrating that the simulated seismic waves maintain good correlation between different points. This finding provides strong evidence for understanding the coherence and interactions of seismic waves during ground propagation.

Figures 7 and 8 respectively provide the time history curves for stationary and non-stationary seismic waves. Stationary seismic waves refer to those whose statistical characteristics, such as mean and variance, remain constant over time, while non-stationary seismic waves display varying statistical characteristics over time. The time history curves of these two types of seismic waves help to better understand and distinguish the behaviors and responses of seismic waves under different conditions. Through detailed analysis of these two different types of seismic waves, a deeper study and simulation of the impact of earthquakes on building structures can be conducted, especially under different geological and environmental conditions.

5 CONCLUSIONS

The spatial variability of seismic activity is of critical importance to the seismic safety of large-span structures, and research in this area aids in enhancing the design and seismic resilience of critical infrastructure such as bridges. Particularly in unique geological settings like river valleys, the study of seismic input modes becomes a key factor. In recent years, as research into the effects of valley seismic input modes on bridge seismic responses has deepened, this field has drawn increasing attention from the engineering community. The significance of this research lies in its ability to help engineers more accurately predict and assess the seismic risks that structures might encounter in specific geographic environments.

In this study, we derived simulation formulas using the FFT algorithm and successfully simulated non-stationary seismic fields with spatial variability using the harmonic synthesis method. Moreover, our model considers not only the traveling wave effects of multi-point excitation but also the spatial coherence of seismic motions. These factors are crucial in affecting the seismic response of large-span bridges, and traditional seismic simulation methods often overlook these complex interactions.

The simulation results, displayed from Figures 2 to 6, not only verify the feasibility of the proposed method but also reveal its high accuracy and practicality. The successful application of this simulation technique demonstrates that it can serve as a powerful tool in seismic engineering, particularly when analyzing the seismic response of complex structures like large-span bridges. Additionally, this study provides new theoretical foundations and practical approaches for the field of seismic engineering, aiding in the optimization of seismic design standards and construction practices.

In conclusion, the simulation method proposed in this paper not only expands our understanding of seismic field simulation techniques but also offers new perspectives and tools for understanding and implementing more effective seismic risk assessment and management strategies. Future work will explore how these simulation techniques can be more broadly applied to different types of structural designs to enhance their seismic performance and safety.

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