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Building Design Using Site Specific Response Spectra to Resist At Earth Quake

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Abstract

Earthquake is undoubtedly one of the greatest natural disasters that can induce serious structural damage and huge losses of properties and lives. The resulting destructive consequences not only have made structural seismic analysis and design much more important but have impelled the necessity of more realistic representation of ground motions, such as inclusion of ground motion spatial variations in earthquake modeling and seismic analysis and design of structures.

Recorded seismic ground motions exhibit spatial variations in their amplitudes and phases, and the spatial variability's have an important effect on the responses of structures extended in space, such as long span bridges. Because of the multi-parametric nature and the complexity of the problems, the development of specific design provisions on spatial variability's of ground motions in modern seismic codes has been impeded. Euro code 8 is currently the only seismic standard worldwide that gives a set of detailed guidelines to explicitly tackle spatial variability's of ground motions in bridge design, providing both a simplified design scheme and an analytical approach. However, there is gap between the code-specified provisions in Euro code 8 and the realistic representation of spatially varying ground motions (SVGM) and the corresponding stochastic vibration analysis (SVA) approaches. This study is devoted to bridge this gap on modeling of SVGM and development of SVA approaches for structures extended in space under SVGM.

A complete and realistic SVGM representation approach is developed by accounting for the **Nozeer, M.Tech** Assistant Professor Tudi Narasimha Reddy Institute of Technology and Sciences.

incoherence effect, wave-passage effect, site-response motion nonstationarity, effect, ground tridirectionality, and spectra-compatibility. This effort brings together various aspects regarding rational seismic scenarios determination, comprehensive methods of accounting for varying site effects, conditional modeling of SVGM nonstationarity, and code-specified ground motion spectra-compatibility.

A comprehensive, systematic, and efficient SVA methodology is derived for long span structures under tridirectional nonstationary SVGM.An absolute-response-oriented scheme of pseudoexcitation method and an improved high precision direct integration method are proposed to reduce the enormous computational effort of conventional nonstationary SVA.

A scheme accounting for tridirectional varying siteresponse effect is incorporated in the nonstationary SVA scheme systematically. The proposed highly efficient and accurate SVA approach is implemented and verified in a general finite element analysis platform to make it readily applicable in SVA of complex structures. Based on the proposed SVA approach, parametric studies of two practical long span bridges under SVGM are conducted.

To account for spatial randomness and variability of soil properties in soil-structure interaction analysis of structures under SVGM, a meshfree-Galerkin approach is proposed within the Karhunen-Loève expansion scheme for representation of spatial soil properties modelled as a random field. The mesh free shape functions are proposed as a set of basis functions in the Galerkin scheme to solve integral



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equation of Karhunen-Loève expansion, with a proposed optimization scheme in treating the compatibility between the target and analytical covariance models. The accuracy and validity of the meshfree-Galerkin scheme are assessed and demonstrated by representation of covariance models for various homogeneous and non homogeneous spatial fields.

The developed modelling approaches of SVGM and the derived analytical SVA approaches can be applied to provide more refined solutions for quantitatively assessing code-specified design provisions and developing new design provisions. The proposed meshfree-Galerkin approach can be used to account for spatial randomness and variability of soil properties in soil-structure interaction analysis.

Introduction

Earthquake is undoubtedly regarded as one of the greatest destructive natural disasters that can induce serious damage of structures, thereby causing huge economic losses, including lives and properties. The spatial variation of seismic ground motions has an important effect on the response of long structures, e.g., long span bridges (Zerva, 2009). Thus, structural seismic analysis and design, as the most effective approach in mitigating the consequences of earthquakes, become much more crucial for these long structures (Housner and Jennings, 1977).

In Section 1.1, a general overview of this thesis is presented, along with the scope and motivation of this study. Following the background introduced in Sections 1.1, the objec-tives of this study are presented in Section 1.2, and the organization of this thesis is then described in Section 1.3.

1.1 Motivation and Background

In the past several decades, a large number of destructive earthquakes have caused catas-trophical damage to bridge structures and tremendous losses of casualties and property (see Figure 1.1), such as 1906 San Francisco, 1976 Tangshan, 1979 Imperial Valley,

1994 Northridge, 1995 Kobe, 1999 Chi-Chi, 2008 Sichuan, 2010 Haiti, and 2011 Tohoku earth-quakes. These earthquakes not only have made structural seismic analysis and design much more essential, but impelled the necessity of more realistic representation of ground Motions, e.g., inclusion of ground motion spatial variations in earthquake modelling and seismic analysis and design of structures.



(a) 1994 Northridge



(b) 1995 Kobe



(c) 1999 Chi-Chi

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(d) 2008 Sichuan Figure 1.1 Collapse of bridges in the past earthquakes

Modelling of SVGM: (I) Seismic Scenarios Determination and Varying Site Effect

The recorded seismic ground motions are observed to exhibit spatial variations because of the incoherence, wave-passage, and site-response effects. Due to the scarcity of these earthquakes recorded at closely spaced seismographic stations and wide ranges of practical structure dimensions, response history analysis (RHA) of multiply supported structures must rely on the synthetic spatially varying ground motions (SVGM). In this chapter, the seismic scenarios determination and local site effect in simulating SVGM are studied.

2.1 Introduction

As discussed in Section 1.1.2, almost all of the techniques of simulating SVGM can be generally grouped as spectral representation method (SRM), where the approximate ground motion "power" models, e.g., the empirical Kanai-Tajimi spectrum or Clough-Penzien spectrum, are usually used. However, these approximate spectrum fail to accurately account for wave motions transmitted from the earthquake source through the medium. Hence, a physically consistent and refined model using seismological spectra, which can account for effects of the fault rupture and the transmission of waves from the fault through the media to the ground surface, is desired. Furthermore, seismic hazard of these seismic

Modelling of SVGM: (II) Nonstationarity and Spectra-compatibility

The synthetic spatially varying ground motions (SVGM), used in response history analysis (RHA), are usually desired to be spatially correlated, site reflected, nonstationary, and com-patible with target design response spectra. In addition to seismic scenarios determination and varying site effect considered in Chapter 2, modelling of SVGM nonstationarity and spectra-compatibility are studied in this chapter.

3.1 Introduction

Studies have revealed that nonstationarity of a specific ground motion, with proper dispersive characteristics and realistic wave arrival times, is largely determined by its phase difference spectrum (PDS) (Trifunac, 1971; Ohsaki, 1979). The PDS method has been used to capture nonstationarity of a time history. Most of the stochastic modelling procedures of strong motions still assume phase angles to be independent and uniformly distributed, from which only the stationary ground motions can be obtained. Nonstationary ground motions can be simulated using phase contents of ground motions that are uniquely ob-tained through phase difference model. Several statistical distributions were proposed to fit phase differences using Fourier analysis or wavelet technique (Montaldo et al., 2003;

Stochastic Seismic Analysis of Bridges under SVGM:

(I) Theoretical Methodology

Because seismic motions are random (stochastic) in nature (Housner, 1947), spatial effects of long span bridges can be analyzed using stochastic vibration analysis (SVA). In this chapter, a comprehensive, systematic, and efficient SVA methodology is developed for bridge structures under spatially varying ground motions (SVGM).

4.1 Introduction

SVA is a theoretically advanced, efficient, and effective tool providing stable and physically compliant structural response results; it has been adopted by bridge seismic design standards (CEN,



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2005b; MCPRC, 2008) in dealing with effect of ground motion spatial variations. In SVA of bridges under SVGM, spatial variations (commonly known as the incoherence, wave-passage, and local site effects), nonstationarity, and tridirectionality of SVGM should be accounted for.

Earthquake motions are in essence nonstationary and they are usually treated as uniformly modulated random processes in most of the response history analysis (RHA) or SVA of large structures under SVGM (Zhang et al., 2012a). In SVA, it is better to model earthquake motions as nonuniformly modulated seismic excitations, because substantial high frequency components of ground acceleration, which emerge in the early stages of an earthquake, decay much faster than the low frequency components that the ground acceleration involves only low frequency components eventually. This nonstationary pattern of frequency components of an earthquake cannot be characterized by the uniformly modulated evolutionary random process. Numerical analysis of structural responses to such nonuniformly modulated evolutionary random seismic excitations is very rare in the literature, let alone being included in stochastic seismic analysis of spatially extended structures under tridirectional SVGM.

4.2 PEM IN SEISMIC ANALYSIS OF STRUCTURESUNDER TRIDIRECTIONAL NONSTATIONARY SPATIAL MOTIONS

Since PEM is very effective and accurate in SVA of complex structures with a large number of DoF, it is natural to integrate (implement) on general finite element analysis (FEA) platforms, which have powerful modelling and analysis tools for seismic analysis of complex structures, so that engineers can readily access PEM. In addition, the implementation can improve and resolve drawbacks of some selfdeveloped PEM programs without good computational efficiencies and powerful modelling and analysis techniques. As discussed in Section 1.1.3, the conventional indirect approach for solving equations of motion of structures under SVGM can result in massive computations on static influence matrix and inverse of structure stiffness matrix. Furthermore, it is also prevented from possible ex-tension to the nonlinear SVA used for performance-based earthquake engineering (PBEE) because of the linear superposition treatment.

4.3 Modelling of Tridirectional Nonstationary Spatial Motions at Varying Sites

The SVGM, exhibiting variabilities in space, should be modelled by considering the coherence effect, wavepassage effect, and local site effect. The modelling of tridirectional spatial earthquake motions by accounting for the varying site conditions beneath every support of the structures is presented in this section. Properties of these SVGM with different site conditions should be reflected in the input pseudo-forces of the PEM. The spectral representation method (SRM) given in Section 2.2 is used in modelling spatial ground motions and determining the pseudo-forces.

4.6 Summary and Conclusions

In this chapter, a comprehensive, systematic, and efficient stochastic seismic analysis approach is derived for long span structures under tridirectional nonstationary spatial mo tions, considering ground motion incoherence effect, wave-passage effect, tridirectional local site effect (uniform and nonuniform site conditions), nonstationarity, and tridirectionality, which includes

1. An absolute-response-oriented scheme of PEM (in time domain) is developed to re-duce the enormous computational effort of the conventional indirect nonstationary SVA (in frequency domain) in solving equations of motion of structures under non-stationarity tridirectional SVGM.

2. A scheme in accounting for tridirectional varying site-response effect is incorporated in the nonstationary SVA scheme systematically.

3. The proposed SVA approach is implemented and verified in the general FEA platform to make it readily applicable in stochastic seismic analysis of complex structures.

4. This analytical SVA approach is more attractive for



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nonstationary stochastic seismic analysis of practical long span structures under tridirectional SVGM.

4.6 SUMMARY AND CONCLUSIONS



Figure 4.2 PSD of displacements ($\omega = 0.5 \text{ rad/s}$)





Figure 4.4 PSD of displacements (a = 15 rad/s)

Stochastic Seismic Analysis of Bridges under SVGM:

(II) Practical Applications

Based on the theoretical stochastic vibration analysis (SVA) methodology in Chapter 4, two practical bridges, a concrete-filled steel tubular (CFST) arch bridge and a high-pier railway bridge, are analyzed in details in this chapter.

5.1 Introduction

During the past two decades, responses of bridges to spatially varying ground motions (SVGM) have been studied extensively on various types of long span bridge structures, such as suspension bridges (Harichandran et al., 1996; Wang, 1999), cable-stayed bridges (Nazmy and Abdel-Ghaffar, 1992; Dumanoglu and Soyluk, 2003; Soyluk, 2004a), and arch bridges (Hao, 1993; Zanardo et al., 2004), and bridge pounding and isolation (Ates et al., 2005) under SVGM. In these works, SVA has been widely used (Zerva, 1990; Hao, 1993; Harichandran et al., 1996; Dumanoglu and Soyluk, 2003; Soyluk, 2004a; Ates et al., 2006; Zhang et al., 2009).



(a) FEA model of the high-pier railway bridge in ANSYS

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5.3 EXAMPLE II: A LONG SPAN HIGH-PIER RAILWAY BRIDGE



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(b) Modal frequencies and mode shapes Figure 5.10 FEA model and mode parameters of the high-pier railway bridge



Figure 5.12 PSD functions of nonstationary structural responses under site #1: F-F-F-F



Figure 5.13 PSD functions of nonstationary structural responses under site #2: M-M-M-M



Figure 5.14 PSD functions of nonstationary structural responses under site #3: S-S-S-S



Figure 5.15 Nonstationary seismic responses at key positions of the bridge under site group #A

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Figure 5.16 Nonstationary seismic responses at key positions of the bridge under site group #B



Summary and Conclusions

From the parametric studies of the CFST arch bridge and the high-pier railway bridge under SVGM, conclusions are drawn below.

The Long Span Arch Bridge

1. The conventionally used uniform input motions by neglecting both the phase shifts and the coherency losses might greatly underestimate or overestimate the responses. The wave-passage effect is more significant than the effect of coherence loss on struc-tural responses, and the wave-passage effect becomes more significant for structures with larger spans.

2. Variabilities of transverse and vertical ground motions can decrease responses of the half-through CFST arch bridge, while spatially correlated longitudinal excitations can increase structural responses. Hence, the uniform vertical and transverse input ground

Stochastic Seismic Analysis of Bridges under SVGM:

(III) A Highly Efficient and Accurate Scheme

The pseudo-excitation method (PEM) scheme developed in Chapter 4 can transform the nonstationary stochastic vibration analysis (SVA) in the frequency domain to determin-istic dynamic response problems in time domain, where the direct dynamic integration methods are required to solve the transient analyses. However, these direct dynamic integration methods usually require rather small integration time steps that are dependent on the natural periods of structures to ensure sufficient computational precision and stable response results, thereby increasing the computational effort. To resolve this problem, the high precision direct integration method (HPDIM) is studied in this chapter to improve the computation efficiency.

6.1 Introduction

The HPDIM, which can use larger time step and is not subjected to any limitation from the natural periods of structures, was proposed by Zhong and Williams



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(1994) in stationary/nonstationary random response analysis, reducing the computation time considerably (Lin et al., 1997a).

Because of good computational efficiency of PEM and HPDIM, these two methods can be combined to make nonstationary SVA, whether for uniformly or nonuniformly mod-ulated evolutionary random excitations, much easier and much more efficient. However, the combined scheme is generally still very time consuming and costly, because the time step of HPDIM still has to be small enough to simulate varying pseudo loadings properly, recursively especially for nonuniformly modulated nonstationary pseudo loadings (the limi-tation of assumption of loading form between two adjacent time steps, e.g., linear loading form, sinusoidal loading form). This becomes the bottle-neck problem in the application of HPDIM in nonstationary random response analysis (Lin et al., 1997a). To resolve the bottle-neck problem, the HPDIM parallel algorithm, in conjunction with PEM, was used to solve the independent structural equations of motion subjected to deterministic pseudo loadings at each frequency step (Lin et al., 1997b). However, the parallel algorithm improves the efficiency of computation utilizing the parallel capability of computer hardware, rather than improving on the algorithms of HPDIM.

To resolve the bottle-neck problem in the application of HPDIM in solving structure equations of motion, an improved high precision direct integration method (I-HPDIM), in conjunction with the absolute-responseoriented scheme of PEM in Section 4.2.2, is proposed in Section 6.2. It reduces significantly the number of transient analyses, without requiring small time step to maintain accurate approximation of forms of pseudo loadings between two adjacent time steps. The proposed I-HPDIM, combined with the absoluteresponse-oriented scheme of PEM, can greatly improve the computational efficiencies of both PEM and conventional HPDIM, and it becomes more attractive for engineering pur-poses, particularly in the SVA of some large yet complex structures under tridirectional nonstationary spatially varying ground motions (SVGM).

To demonstrate the proposed SVA scheme, a seismic pounding analysis of a high-pier railway bridge under tridirectional nonuniformly modulated SVGM is conducted in Section 6.2 using the proposed absoluteresponse-oriented scheme of PEM combined with the I-

6.2 THEORETICAL BASIS: SCHEME OF I-HPDIM

HPDIM Seismic pounding frequently caused serious damage on the superstructures of bridges and even the collapse of bridges during past earthquakes (Bi et al., 2011).

In the absolute-response-oriented direct approach presented in Section 4.4.2, structural absolute responses can be derived in equations (4.4.20), (4.4.21), and (4.4.22) for par-tially coherent, fully coherent, and completely incoherent tridirectional nonstationary SVGM, respectively, based on the obtained pseudo-response of absolute displacement given in equation (4.4.19).

In obtaining structural absolute responses in Section 4.4.2, the conventional method (CM) is used (Jia et al., 2013). Besides, this section presents three other methods in obtaining structural absolute responses, including improved conventional method (I-CM) in Section 6.2.2, HPDIM in Section 6.2.3, I-HPDIM in Section 6.2.4, discussions on these four methods in Section 6.2.5, and implementation and verification of the proposed SVA methodology in general finite element analysis (FEA) platform ANSYS in Section 6.2.6.

6.2.1 Conventional Method (CM)

In the direct scheme of equations of motion presented in Section 4.4.2, power spectral den-sity (PSD) of absolute displacement Xs under partially coherent tridirectional nonstationary ground motions is derived in equation (4.4.20), where the conventional method



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(CM) is used in obtaining structural stochastic response (Jia et al., 2013)

As seen from equation (4.4.20), a total of 2r transient analyses are required to be con-ducted for both the real and imaginary parts of the input pseudo-excitation Pjeiot, by means of direct dynamic integration methods, such as the Duhamel integration, Newmark method, or Wilson- θ method, to derive response PSD function at each discrete frequency step by superposition of response results from all r modes, i.e., the total number of transient analyses spatial seismic motions. Moreover, I-HPDIM can also enhance computational efficiency by choosing only the output responses of interest, rather than the entire structural responses required to be calculated in the scheme of I-HPDIM and the absolute-response-oriented scheme of PEM. Because structural responses at certain locations of structures are of interest as response output, these outputs of interest, e.g., Xi and Xj in Figure 6.1(a), can be selected in I-HPDIM, thereby reducing time of computation (Zhang et al., 2013a).

Because the proposed I-HPDIM can achieve significant computational efficiencies and good accuracy, it is implemented in a general FEA platform (with powerful and versatile modelling and analysis capabilities) for stochastic seismic analysis of structures. Details on the improved computational efficiency of I-HPDIM are given in Section 6.2.5, and details of its FE implementation are presented in Section 6.2.6.

6.3 Practical Application: Seismic Pounding Analysis of Bridges

To demonstrate the ANSYS implementation of the proposed I-HPDIM combined with the absoluteresponse-oriented scheme of PEM, seismic pounding analysis of a high-pier railway bridge under tridirectional nonuniformly modulated nonstationary SVGM is con-ducted.

6.3.1 Bridge Seismic Pounding

Seismic pounding of bridge is attributed to the large

out-of-phase movement between adjacent segments owning to different dynamic characteristics, spatial variabilities of ground motions, and soil-structure interaction (SSI). To preclude pounding effect, the most straightforward approach is to provide sufficient separation distances between adjacent

6.3 PRACTICAL APPLICATION: SEISMIC POUNDING ANALYSIS OF BRIDGES



Conclusions

Recorded seismic ground motions exhibit spatial variations in their amplitude and phases, and spatial variations of ground motions have an important effect on the response of long structures, e.g., long span bridges. However, there is gap between the code-specified provisions and the realistic representation of spatially varying groundmotions (SVGM)and the corresponding stochastic vibration analysis (SVA) approaches. This study is devoted to bridge this gap. The main contributions and findings are summarized below.



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