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Anti-symmetric mode excitation and seismic response of base-isolated bridges under asynchronous input motion

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ABSTRACT

This paper investigates the effect of asynchronous earthquake ground motion on the transverse response of base-isolated bridges. In this context, the excitation of anti-symmetric modes of vibration under asynchronous input is examined and is statistically correlated with characteristic engineering demand parameters. Different ground motion scenarios are considered for various combinations of soil class, wave propagation velocity and loss of correlation patterns among different support motions, using a spectral representation method to generate m-variate, fully non-stationary, EC8 spectrum-compatible ground motion vector processes. It is shown that in the idealised case of the wave passage effect only, the detrimental effects of asynchronous excitation are concentrated on the very last piers along the direction of the seismic waves. However, when loss of coherency is also taken into account in a more realistic scenario, the impact of spatial variability is significantly more uniformly distributed. Most importantly, the conditional probability of a detrimental increase in an EDP of interest (i.e., pier base bending moments and deck drift) under multi-support excitation given that an anti-symmetric mode is excited is not only uniform but also considerably high. This is a clear evidence that the local increase of seismic demand in the bridge studied is associated with the excitation of the first anti-symmetric mode of vibration.

1. Introduction

During the last decades, the asynchronous excitation of long structures, such as bridges and pipelines, has attracted scientific attention. Past experience from catastrophic earthquakes, available data from dense accelerometric arrays all over the world and the evolution of computational power gave impetus to the systematic study of the spatial variability of earthquake ground motion (SVEGM) and its impact on extended structures. Bridges in particular, have been thoroughly studied both because of their wider socioeconomic importance and the fact that they commonly extend over distances equivalent to the seismic wavelengths or even cross irregular topographies. The result of the latter is that ground motions arriving at bridge supports may vary significantly in terms of arrival time, frequency content and amplitude, thus affecting significantly their seismic performance.

The causes of the SVEGM can generally be summarized in [1]: (a) the wave passage effect, (b) the loss of coherency of the seismic waves as a result of multiple reflections, refractions and superposition within the soil media, (c) the local site effects, and (d) the attenuation of the seismic waves, which, for the dimensions of the bridges usually examined, is not significant. Soil-structure interaction (SSI) has also been identified as an additional source of spatial variation [2] but is mainly accounted for in cases of spatially varying soil profiles or soft soil formations. The above sources of spatial variation of earthquake ground motion are expressed in terms of the signal correlation, which tends to decay with distance and frequency. Based on the records of dense seismograph arrays mainly in Taiwan, Japan and the U.S., the literature has proposed numerous coherency models (e.g. empirical [3–5], semi-empirical [6,7], analytical [8,9] etc.) that can be then used for generating suites of spatially variable motions.

Over the years, different methods have been developed for the computation of structural response under multi-support excitation, each one exhibiting different shortcomings [10]. For example, random vibration techniques and response spectrum oriented methods are not commonly used in practice since they are restricted to linear/linearized problems. On the other hand, simulation of non-synchronous ground motions in time history analysis is a more straightforward option for the calculation of the structural (linear or not) response in a Monte Carlo framework. In this context, numerous simulation techniques have been developed for the generation of spatially variable ground motions; these either describe the random field through the combination of a power spectral density (PSD) model with a coherency one, or they simulate

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them conditioned to “known” accelerograms [11,12]. Spectral representation is one of the most popular methods for the simulation of random fields [13,14]. Shinozuka [15] used spectral representation to simulate uni- and multi-variate, multi-dimensional, homogeneous or heterogeneous stationary processes. The computational efficiency of the method was improved with the use of the FFT technique in the case of stationary processes [16]. This method has also been further extended to simulate ergodic, multivariate, stochastic processes [17,18] so that different local soil conditions between the generation points [19,20] and multi-dimensional Gaussian stochastic fields' simulation could be considered [21]. Hao et al. [22] presented a method based on covariance decomposition for uniform soil conditions, while Gao et al. [23] extended this method in order to simulate ground motions at sites with different power spectral densities (PSD). Recently, Lavorato et al. [24,25] introduced an approach for the generation of arrays of asynchronous signals at different points in space, starting from natural accelerograms related to a given seismic event in order to increase the number of the available data including soil amplification treatment.

In accordance with modern seismic code provisions, different approaches have been proposed to meet the requirements for response spectrum compatibility of simulated ground motions. Hao et al. [22] presented an iterative process that modifies the Fourier coefficients of the simulated motions until the convergence between the target and the generated response spectra becomes sufficient, while Deodatis [19] introduced an iterative scheme that updates the PSD of the process. Bi and Hao [20] extended this approach by estimating the initial PSD with respect to the target response spectrum instead of considering an arbitrary one, thus leading to fewer iterations. However, the simulated ground motions produced from the aforementioned processes deviate from the Gaussian distribution and the mean computed coherence differs from the targeted one [26]. To overcome these weaknesses, Shields [26] recently presented a method that updates the evolutionary PSD through random functional perturbations. In addition, the method of Cacciola [27] for the simulation of fully non-stationary, spectrum-compatible earthquake motions at a single point, was extended for the purposes of multi-variate simulation by Cacciola and Deodatis [28]. In this method, spectrum compatibility is satisfied through the superposition of an appropriate corrective quasi-stationary process to a “known” fully non-stationary process that represents the seismological properties of the region. Cacciola and Zentner [29] further extended this method to include the natural variability of relevant ground motion parameters. The advantage of the last two methods lies in the fact that the generated ground motions do not need any iteration in order to match the targeted response spectra which is a major step forward compared to previous time consuming methods.

Given the breadth of available methods for the analysis of structural response under multiple support excitation, several analytical studies have been presented in the literature with the aim to investigate and quantify the sensitivity of different types and configurations of bridges to non-synchronous seismic input. For instance, random vibration analysis has been used to estimate the response of highway [30,31], suspension [32,33] and cable-stayed bridges [34–36]. The impact of multi-support excitation on the seismic behavior of bridges has also been investigated in the frequency (using response spectrum-based methods [1,37–43]) and the time domain. In the second case, numerous studies investigated both the linear and/or the non-linear response of different types of bridges, namely: (a) straight bridges on uniform [44–47] or varying soil profiles, ignoring [45,47,48] or accounting for the soil-structure interaction (SSI) effects [49,50], (b) curved bridges [47,51,52], (c) skewed bridges [45,53], and (d) isolated bridges [54–57]. An extensive comparative study of 27 different structural bridge systems was presented by Sextos and Kappos [58]. Sensitivity of cable-stayed bridges in terms of SVEGM has been studied analytically [34,59] and based on existing measurements. Sextos et al. [60] presented a study on the Evripos cable-stayed bridge using real, free-field records, as well as respective superstructure recordings obtained during the (M_s = 5.9, 1999) Athens earthquake. Soil-structure interaction has been further accounted for a 59-span bridge with several bearing types and irregularity features by Mwafy et al. [61] and Yang et al. [62].

Common theme across the aforementioned studies is the significantly different response of bridges under multi-support excitation. This may vary among different studies, however, in the vast majority of cases researchers agree that it is hard to be captured using uniform input ground motion assumptions. The influence of the SVEGM on the response of different bridge components is of course related to the engineering demand parameters examined and case sensitive to the ground motion scenario considered, a fact that hinders a realistic estimate of the SVEGM impact in advance and limits the application of deterministic schemes. As a result, naturally, the problem has gradually started being studied in a probabilistic manner.

A second general observation that the researchers tend to agree, in principle, is that when the loss of coherency to the spatially variable motions is minor or not considered in the formulation, the asynchronous excitation tends to have a favorable effect on the overall dynamic response of bridges. This is a convenient outcome, though only applicable in the rare case of uniform soil profiles along the bridge length, where the rate of coherency decay with distance is very mild due to limited reflections and refractions of seismic waves. In this case, the wave passage effect is dominant and effects of spatial variability can be neglected. In the majority of cases, however, the problem remains multi-parametric and quite unpredictable.

Nevertheless, there is one important observation that has not been thoroughly and systematically studied even though it has been made in several cases [33,42,44,46,47,50,59,60]. This is related to the excitation of higher anti-symmetric modes due to SVEGM. Currently, it is not clear how systematic this excitation is and its degree of correlation with potential detrimental effects of asynchronous motion.

Given the above lack of clarity, it is not surprising that most seismic codes worldwide do not address the above issue. In fact, with very few exceptions, they do not even recommend a solid approach to generate spatially variable ground motion suites. The way in which they try to approach the problem is mainly through indirect measures, such as larger seating deck lengths and simplified methods. It is only Eurocode 8 – Part 2 for bridges [63] and the New Italian Seismic Code [64] that explicitly deal with the SVEGM. However, the provisions of these codes aim at capturing solely bridges’ distress due to the pseudo-static response component ignoring the potential impact of higher anti-symmetric modes' excitation. What's worse, these simplified methods have a minor effect on the predicted design quantities when compared to more sophisticated ones and, quite naturally, they are not applicable to bridges which are insensitive to statically imposed displacements, such as for instance seismically isolated ones [58]. Overall, in all cases, modern seismic codes in the U.S., Europe and Asia are very reluctant to provide a detailed framework for considering the SVEGM effect in the design and assessment of bridges. This may be attributed to the widely prevailing perception that considering asynchronous earthquake input motion has a higher level of uncertainty compared to not addressing the problem at all.

In this context, the objective of this paper is to study the effects of spatial variability of earthquake ground motion on the dynamic response of base-isolated R/C bridges, with the specific aim to quantify the excitation of anti-symmetric modes of vibration and investigate its correlation with bridge response quantities. Different scenarios of input motion are considered involving soil classes, wave propagation velocities and loss of correlation patterns among the various supports. Lumped springs and dashpots are distinctly calculated for every different foundation and excitation case to model the interacting soil-bridge system, while excitation input motions are generated using an evolutionary PSD and are EC8 spectrum-compatible. The results of this analysis are presented in the following sections.