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Effects of wave passage on torsional response of symmetric buildings subjected to near-fault pulse-like ground motions

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A B S T R A C T

This article investigates the effects of wave passage on the torsional response of elastic buildings in the near-fault region. The model of the soil-foundation-structure system is a symmetric cylinder placed on a rigid circular foundation supported on an elastic halfspace. The idealized model is subjected to obliquely incident plane SH waves simulating the action of near-fault pulse-like motions. The response of the structure is assessed in terms of the relative twist between the top and the base of the superstructure. A parametric analysis of the maximum relative twist as a function of the input parameters of the seismic excitation and soil-foundation-structure system is performed to identify the parameters that control the torsional response of buildings due to wave passage in the near-fault region. It is shown that the torsional response is most sensitive to a key parameter of the near-fault ground motion referred to as "pulse period". Specifically, large rotations are observed when the pulse period is close to the torsional period of the structure. It is also demonstrated that the wave passage effects are controlled by the wave apparent velocity, rather than the local site conditions. Furthermore, broadband near-fault ground motions from three hypothetical earthquakes of different magnitude are generated, and the torsional responses due to the simplified pulse-like and broadband ground motions are compared against each other. The results show that the simplified pulse model that describes the coherent seismic radiation is able to represent the main features of the near-fault ground motions that cause large torsional response. The maximum relative twist at resonance is found to be $\sim 10^{-3}$ rad, a value that is consistent with the upper bound of rotations in structures reported in the literature.

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1. Introduction

During an earthquake, buildings may undergo torsional response in addition to translational response. For buildings with inherent eccentricity (i.e. non-symmetric distribution of masses or load-resisting elements), torsion is induced by the geometrical separation of the centers of mass and stiffness, resulting in coupled lateral-torsional response. On the other hand, spatially varying seismic excitations due to ground motion incoherence and wave passage effects contribute to the torsional response of both symmetric and asymmetric buildings. The ground motion incoherence, which arises from the scattering effect of seismic waves traveling through an inhomogeneous medium, is typically investigated using random-vibration-based procedures, whereas the wave passage effect considers deterministically ground motions that differ in phase from point to point due to the seismic wave front impinging the foundation-soil interface obliquely. Several studies have investigated the effects of wave passage and ground motion incoherence on the torsional response of buildings, but only a few are summarized in this section. The interested reader is referred to Anagnostopoulos et al. [1] for a comprehensive literature review of earthquake-induced torsion in structures.

Newmark [32] made the first rational attempt to investigate the torsional response of symmetric buildings due to base rotation arising from earthquake wave motions. Luco [20,21] presented the mathematical formulation of the torsional steady-state response of a symmetric, elastic structure placed on a surface-supported or embedded foundation under the action of obliquely incident plane SH waves accounting for soil-structure interaction effects. It was demonstrated that large displacements associated with torsional response may be generated even for symmetric structures. Luco and Wong [24] presented the earthquake response of symmetric, elastic structures subjected to SH wave excitations with different angles of incidence and to Rayleigh waves. The results revealed that the response to non-vertically incident waves is significantly different from that obtained on the basis of the usual assumption

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of vertically incident SH waves.

Luco and Wong [25] and Luco and Mita [22] investigated the dynamic response of rigid foundations supported on an elastic halfspace under the effect of a spatially varying ground motion. The results indicated that the spatial randomness of ground motion produces effects similar to the deterministic effects of wave passage, including reduction of the translational components of the response at high frequencies and generation of rocking and torsional response. Veletsos and Prasad [46] arrived at a similar conclusion, and further indicated that the kinematic interaction effects due to ground motion incoherence and wave passage may be interrelated. It should be noted that although the studies by Luco and Wong [25] and Luco and Mita [22] focused exclusively on the dynamic response of the foundation and did not examine the response of the superstructure, the calculation of the torsional response at the foundation level is an essential step for further investigating the dynamic structural response.

Heredia-Zavoni and Barranco [13] examined the torsional response of symmetric structural systems subjected to spatially varying ground motions due to loss of coherence, wave passage, and local soil conditions. Torsional effects were found to be significant depending on the aspect ratio of the system, the soil conditions, and the times for the seismic waves to travel across the base of the system, especially for structural systems with fundamental periods close to the predominant period of the ground. De la Llera and Chopra [9] extracted base torsional excitations, associated with spatially varying ground motions, from translational ground motions recorded at the foundation level of actual buildings. It was shown that accidental torsion increases the building displacements by less than 5% for systems that are torsionally stiff or have lateral vibration periods longer than 0.5 s, whereas short-period (less than 0.5 s) and torsionally flexible systems may experience a significant increase in response.

Juarez and Aviles [17] examined the combined torsional effects of structural asymmetry and foundation rotation induced by wave passage in flexibly supported structures. The foundation was considered to be embedded into an elastic halfspace and the earthquake excitation was assumed to be composed of obliquely incident SH waves. An effective eccentricity was defined by matching the equivalent static displacement at the flexible edge of the structure with the peak dynamic displacement. For a low-rise structure, the effects of foundation rotation were found to be detrimental and even more important than those of structural asymmetry, whereas the reverse was observed for a mid-rise structure. The effects of rocking excitation were found to be insignificant compared to those of the torsional excitation.

Near-fault ground motions are frequently characterized by intense velocity and displacement pulses of relatively long duration, which clearly distinguish them from typical far-field ground motions. Even though intermediate- and long-period structures are particular susceptible to near-fault pulse-like seismic excitations, the attention regarding the effects of such motions on structures has almost exclusively focused on translational vibrations. Only a few studies have touched upon the effects of impulsive motions on the torsional response of buildings due to wave passage or ground motion incoherence. For instance, Heredia-Zavoni and Barranco [13], although not focusing explicitly on pulse-like seismic excitations, modeled the ground motion input as a narrowband process with a dominant frequency, and concluded that torsional response due to spatially varying ground motions could be significant when the torsional period of the structure is close to the predominant period of the ground motion. In a recent study, Gicev et al. [10] examined the translation, torsion and wave excitation of a two-dimensional building model supported by a nonlinear rectangular, flexible foundation embedded in nonlinear soil. The building model was excited by an earthquake half-sine pulse of a plane SH wave that was intended to model pulse-like motions observed in the near-fault region. Their results showed that the part of energy due to non-translational motion increases rapidly as the angle of incidence (relative to vertical) increases. Gicev et al. [10] also concluded that the building response becomes spatially more complex as the ratio of building width and wavelength of incident waves increases.

Building upon the methodology and results presented by Meza-Fajardo [30] (see also [31]), this article aims to identify the key parameters of the soil-foundation-structure system and ground motion input that control the effects of wave passage on the torsional response of symmetric, elastic buildings under the action of near-fault pulse-like motions. The soil-foundation-structure model proposed by Luco [20] is adopted to calculate the torsional response of the buildings, whereas the mathematical model proposed by Mavroeidis and Papageorgiou [27] is used to describe the coherent component of the near-fault ground motions. The building torsional response is assessed in terms of the relative twist between the top and the base of the superstructure. The characteristics of the transfer function, ground excitation model, and torsional response are investigated through a detailed parametric analysis using realistic physical properties of the soil-foundation-structure system. Finally, broadband near-fault ground motions from hypothetical earthquakes are generated, and the torsional response due to simplified and broadband ground motions are compared to assess the effectiveness of idealized pulse models to estimate accurately the building torsional response due to wave passage in the near-fault region.

2. Soil-foundation-structure system

2.1. Model configuration

Fig. 1 illustrates the soil-foundation-structure model under the action of an obliquely incident plane SH wave proposed by Luco [20]. This model is adopted in the present study to investigate the effects of wave passage on the torsional response of symmetric, elastic buildings subjected to near-fault pulse-like ground motions. The superstructure is modeled by a uniform elastic bar of height H and radius a with mass moment of inertial about the z-axis I_b, hysteretic damping factor ξ, and fixed-base fundamental frequency in torsion ω_1. The foundation is represented by a rigid circular disc with the same radius as that of the superstructure and mass moment of inertia with respect to the z-axis I_0. The soil is assumed to be an elastic, homogeneous and isotropic halfspace with density ρ_s, shear modulus μ, and shear wave velocity β.

As discussed by Luco [20], the frequency response of the soil-foundation-structure system illustrated in Fig. 1 can analytically be calculated by considering the ground motion input as an obliquely incident plane SH wave of amplitude $u_{g0}/2$ and frequency of steady-state excitation ω, which would lead to a free-field motion of amplitude u_{g0} on the ground surface. The plane SH wave is assumed to propagate at an angle Θ with respect to the x axis (i.e. angle of incidence) and the particle movement is parallel to the y axis, as shown in Fig. 1.

It should be pointed out that the soil-foundation-structure model proposed by Luco [20] may oversimplify certain aspects of the problem under investigation. For instance, soils and structures subjected to strong ground shaking in the near-fault region may undergo nonlinear response, which cannot be captured by the adopted soil-foundation-structure model that assumes linear response. However, the soil-foundation-structure model proposed by Luco [20] is considered to be a suitable model for this study because it facilitates the extensive parametric analysis that is required to identify the input parameters of the seismic excitation

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