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Rotational components in structural loading

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ABSTRACT

In this paper, the rotational loading pattern of multi-storey buildings supported on the spread and continuous interconnected single foundations is discussed. To achieve this, simplified relations for the estimation of (1) point rotations; (2) spatial variation of strong ground motions, and (3) foundation input motions are derived. The height-wise variation of the earthquake rotational loading of multi-storey buildings is parametrically evaluated by considering the location of the first rigid floor diaphragm and foundation type. In addition, the effect of the kinematic soil–structure interaction on the response spectrum of the rotational and translational components is studied. The numerical results provide a deeper insight into the rotational loading of structures in the middle-field zone, and show how the rotational components may detrimentally affect the structural response of multi-storey buildings depending on their kinematic characteristics.

1. Introduction

As seismic waves propagate from the source to the ground surface along a certain wave passage, their characteristics, such as their amplitude and frequency content, change as they pass through the soil layers. Propagation of the seismic waves along different wave paths in the earth crust causes Spatial Variation of Strong Ground Motion (SVSGM). The propagation character of the seismic waves also induces the rotational components at any points on the ground surface, which may be estimated in terms of spatial derivatives of the corresponding translational motions [1–5].

A uniform loading pattern including six earthquake components corresponding to a point on the ground surface may be considered as the simplest form of the seismic excitation for the ordinary multi-storey buildings. However, such a loading pattern may result in the underestimation of the structural response considering the kinematic characteristics of the multi-storey buildings such as the geometrical configuration of their structural components and foundation properties [6,7,8,47]. Therefore, it is necessary that the seismic loading of the multi-storey buildings is determined considering their kinematic characteristics.

From the engineering aspect, three approaches have been used for the evaluation of the rotational motions and consequently, the rotational loading of structures subjected to the seismic waves, namely: point, surface, and foundation rotations [1–15]. When the earthquake shaking can be assigned to a single point, the rotational loading of structures may be performed by the point rotation [1–5], which corresponds to the gradient of the translational displacements at that point on the ground surface. The rotational excitation of the structures supported on large mat foundations is usually applied using surface rotation [9,10] or foundation rotation [6,7]. The surface rotation is defined as a mean slope of the area of the ground surface where the foundation is supported on. Approximate value of the input rotational motions at foundation level may be evaluated based on the surface rotation method while the seismic ground motions of at least two points under foundation surface are known [9,10]. However, when the ground motion pattern at all points under the foundation surface is mathematically determined; a better approximation of the input rotational motions at the foundation level can be obtained using the foundation rotation method [6,7].

The rotational loading of structures may be notably intensified due to the foundation effects on the input excitations [16]. For the structures supported on rigid mat foundations, considering the effects of the kinematic soil–structure interaction leads to filtering high-frequency components of the translational response and to the amplification of the rotational motions. Therefore, the rotational contribution to the seismic response of structures may be amplified if the effect of the soil–structure interaction is considered in the structural loading and modeling [13,17]. Asymmetric permanent strains at the foundation-soil level due to the soil nonlinearity [18] and foundation damage [19] during Strong Ground Motions (SGMs) can also cause the rotational excitation of structures.

Recent seismological data indicated that the ratio of the amplitude of the rotational components to the translational components

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in the near field can be significantly larger than that was expected in this zone [20,21]. In the past decade, this observation leaded to the attraction of the theoretical studies toward the near-field effects of the rotational excitations on the seismic behavior of structures [22–25], which showed that the rotational components may result in significant damages in multi-storey buildings and bridges. Despite these research, the influence of the rotational components on the structural response is still neglected by most of the seismic design codes probably due to: (1) lack of knowledge on the characteristics of the rotational motions because of insufficient amount of the recorded data and difficulty in presenting a quantitative assessment of the rotational components for given translational components, and (2) complexity in the derivation of simple loading patterns for structures subjected to the rotational excitations. The only exception is a very simplified approach to rotational effects presented in Eurocode 8 part 6 [26]. To overcome these difficulties, extensive investigations on the rotational components for generating synthetic rotational accelerograms, which have most compatibility with the existing recorded data as well as the cognition of the types of the rotational motions and their influences on the behavior of structures, are necessary.

Considering the wave passage effect, simplified approaches have been proposed for the application of the rotational loading in the seismic analysis of multi-storey buildings, such as (1) generating rotational accelerograms [3,5,13,32,33]; (2) introducing rotational response spectrum [8,14,15,26]; (3) deriving accidental eccentricities due to the torsional earthquake component [1,14,15,27–29], and (4) modifying base shear due to the combined action of the rocking and horizontal earthquake components [14,15]. The main objective of the present research is to provide more accurate relations for the rotational excitation of structures in comparison to the previous studies. In this case, after a brief review of the characteristics of the rotational components due to the wave passage effects, the combined action of the coherency and wave passage effects in deriving the rotational components in the middle-field zone is discussed. The rotational input motions corresponding to the spread and continuous interconnected single foundations are estimated and the foundation effect on the rotational response spectrum is studied. Finally, the height-wise variation of the earthquake rotational loading of multi-storey buildings is addressed by considering the location of the first rigid floor diaphragm and foundation type. The generated input motions in this study are derived in the linear frequency domain using random vibration approach and assuming ground motions as stationary Gaussian processes.

2. Mathematical representation of rotational excitation

Herein, three different approaches for the estimation of the rotational components are discussed in Sections 2.1 and 2.2, and the rotational loading of the multi-storey buildings is parametrically studied in Section 2.3.

2.1. Point rotation

The displacement components of the SGMs always accompany the rotational components induced by the spatial variation of seismic waves. The rotation may be considered as the gradient of the translational displacement at a point on the ground surface. In this subsection, two approaches for deriving point rotations are discussed by considering (1) wave passage effect, and (2) combined action of wave passage and coherency effects.

2.1.1. Wave passage effects

The rotational components are commonly estimated by considering the wave passage effects [1–3,13–15]. Herein, such an approach is briefly examined by comparing actual and synthesized Spectral Density Function (SDF) of rotational components. The rotational acceleration components of ground motions, $\left\{\ddot{\theta}^{g}(t)\right\}$, induced by the spatial variation of the seismic waves, in terms of the translational components, $\{\ddot{u}_x^g(t), \ddot{u}_y^g(t), \ddot{u}_z^g(t)\}$, along the Cartesian coordinate axes (Fig. 1(a)), for small deformations, may be expressed as:

$$\left\{\ddot{\theta}^{g}(t)\right\} = \frac{\partial \ddot{u}_z^g(t)}{\partial y}\vec{i} - \frac{\partial \ddot{u}_z^g(t)}{\partial x}\vec{j} + \frac{1}{2}\left[\frac{\partial \ddot{u}_y^g(t)}{\partial x} - \frac{\partial \ddot{u}_x^g(t)}{\partial y}\right]\vec{k} \tag{1}$$

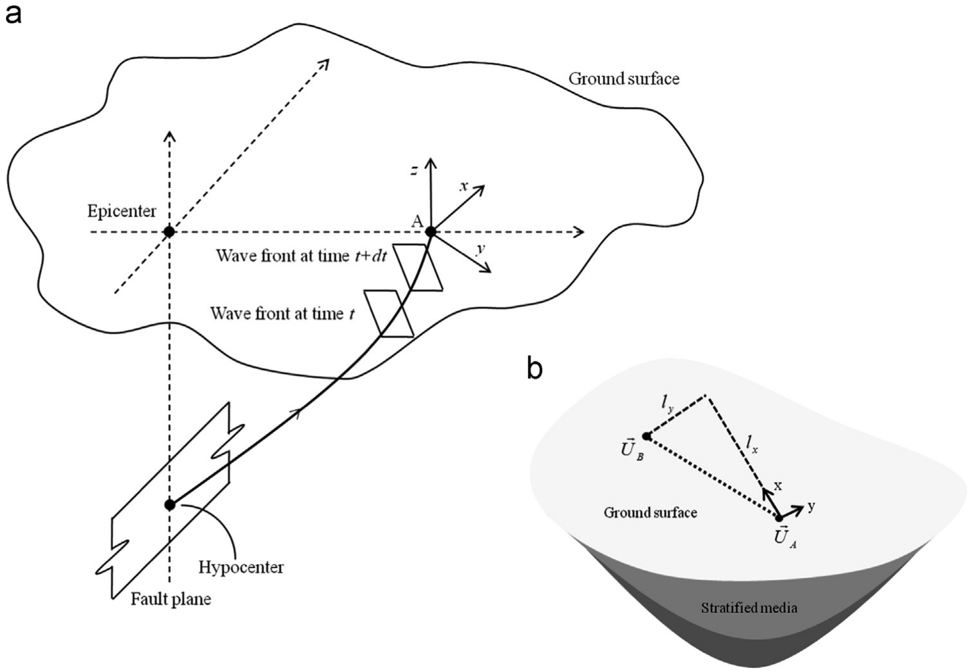

Fig. 1. Schematic diagram of the considered wave propagation system: (a) seismic wave propagation from the hypocenter to the site; (b) geometric interpretation of the system considered for SVSGM.