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NEW SEISMIC INTENSITY PARAMETERS FOR ROTATIONAL COMPONENTS

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Abstract

Seismic intensity parameters reflect the destructive potential of the strong ground motions and are commonly considered as the primary tools in seismic risk assessment and earthquake-resistant design of structures. During sixty years ago, a large number of intensity parameters have been proposed in order to characterize the inherent features of the earthquake translational components. The numerical results of recent research studies have illustrated that the rocking and torsional components may also have detrimental effect on the seismic behavior of structures and their influence should be included in seismic design codes. However, no intensity parameter has been currently introduced to measure the destructive effect of earthquake rotational components on the structures. The rotational components can be evaluated in terms of spatial derivatives of their corresponding translational ground motions and, hence, are highly correlated to the translational components. In the present study, the earthquake rotational motions are simulated considering the effects of both time delay and loss of coherency. Using the mathematical relationship between the translational and rotational components, new seismic intensity parameters for application to the rotational ground motions are derived. These intensity parameters are corresponding to the widely used intensity parameters for characterizing the earthquake translational components, i.e. peak ground acceleration, Nau and Hall indices, first-mode pseudo-spectral acceleration and Housner spectrum intensity.

Keywords: Strong ground motion; Rotational components; Coherency; Response Spectrum; Seismic intensity parameter.

1. Introduction

In spite of the fact that all six components, three translational and three rotational, are needed to describe the strong ground motions (SGMs), very few research studies have investigated the effects of the rotational (rocking or torsional) components on the seismic behavior of structures as compared to those of the translational ones. This may be justified because of the lack of earthquake records of rotational SGMs. In engineering practice, the rotational components are usually simulated, using the classical elasticity theory, in terms of spatial derivatives of their corresponding translational ones [1-4]. In this approach, only the effect of time delay in wave propagation of spatially variable ground motions is usually taken into account to simulate the rotational components, even though the loss of coherency can also contribute significantly to the rotational SGMs [5-7]. Soil-structure interaction (SSI) may also generate rotational components in addition to filtering the high-frequency content of input ground motions [6].

Seismic intensity parameters (SIPs) reflect the destructive potential of the SGMs, and are commonly considered as the primary tools for the seismic risk assessment and earthquake-resistant design of structures. During the last sixty years, a large number of SIPs have been proposed in order to characterize the inherent features of the earthquake translational components [8-11]. The numerical results of recent research studies have illustrated that the rotational (rocking or torsional) components may also have a significant effect on the seismic behavior of structures, and their influence should be incorporated in seismic design codes [1-6]. In spite of the fact that the effect of the rotational components is partially considered in modern seismic design codes [4, 12], no SIP has yet been introduced to measure the destructive effect of the rotational components on structures.

Herein, the effect of both time delay and loss of coherency is considered to develop simple formulae for generating the rocking and torsional acceleration components. Using the proposed approach, four well-known SIPs, i.e. peak ground acceleration, Nau and Hall indices, first-mode pseudo-spectral acceleration and Housner spectrum intensity, which are currently utilized to measure the structural damage due only to translational excitations, are revised to assess the destructive action of rotational SGMs on structures. Finally, the application of the first-mode pseudo-spectral acceleration for the estimation of the contribution of the torsional and rocking components to the seismic excitation of a typical five-story building is discussed.

2. Rotational Components

The vector of the rotational acceleration components of SGMs, $\left\{\ddot{\vec{\theta}}^{g}(t)\right\}$, induced by the spatial variation of the seismic waves, may be expressed, for small deformations, in terms of the translational components, $\left\{\ddot{u}_{x}^{g}(t), \ddot{u}_{y}^{g}(t), \ddot{u}_{z}^{g}(t)\right\}$, as [4]:

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

where superscript *g* refers to the ground motion, and subscripts *x*, *y* and *z* refer to the directions of the Cartesian coordinate axes. The first two terms on the right-hand side of Eq. 1 are the rocking components, which are correlated to the vertical ground motion (component along the *z*-axis), and the third term in Eq. 1 is the torsional component, which is correlated to the horizontal ground motions (components along the *x*- and *y*-axes). In the far field, if the *x*-axis is defined along the radial direction of the seismic wave propagation, Eq. 1 may be simplified as [1]:

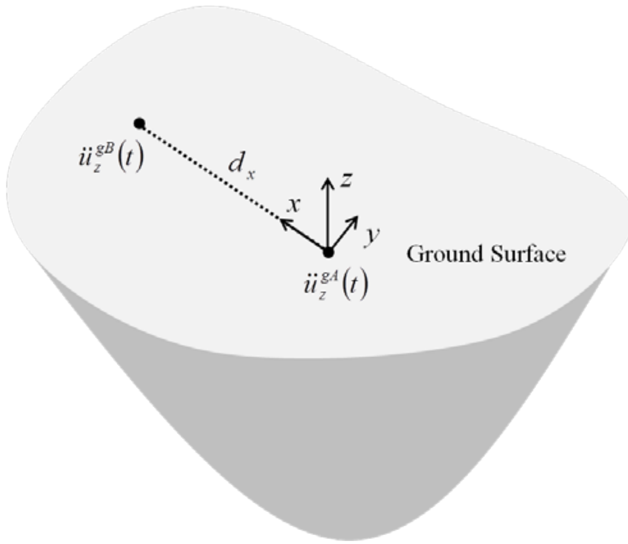

Fig. 1. Geometric layout for the estimation of the rocking component of seismic ground motions.

$$\left\{\vec{\ddot{\theta}}^{g}(t)\right\} = 0\vec{i} - \frac{\partial \ddot{u}_z^{g}(t)}{\partial x}\vec{j} + \frac{1}{2}\frac{\partial \ddot{u}_y^{g}(t)}{\partial x}\vec{k} \tag{2}$$

Eq. 2 indicates that the spatial variation of ground motions along the transverse direction of wave propagation (*y*-axis) can be ignored in the far field.

Considering the rocking component about the *y*-axis on the right-hand side of Eq. 2 (or Eq. 1), the average ground rotation about the *y*-axis can be obtained from the vertical acceleration components at points *A* and *B* on the ground surface (Fig. 1) as:

$$\ddot{\theta}_y^{gAB}(t) = \frac{\ddot{u}_z^{gB}(t) - \ddot{u}_z^{gA}(t)}{d_x} \tag{3}$$

where d_x is the separation distance between points *A* and *B* along the *x*-axis (Fig. 1). When seismic waves propagate along the *x*-direction with a constant apparent velocity, V_x, in a homogeneous random field, the motions at points *A* and *B* may be defined using the following coherency function model, $\gamma_{AB}(d_x,\omega)$, [13]:

$$\gamma_{AB}(d_x,\omega) = |\gamma_{AB}(d_x,\omega)| \exp\left[-i\omega\frac{d_x}{V_x}\right] = \exp\left[-\left(\frac{\lambda_x \omega d_x}{V_S}\right)^2\right]\exp\left[-i\omega\frac{d_x}{V_x}\right] \tag{4}$$

in which $|\gamma_{AB}(d_x,\omega)|$ is the coherency loss function; $i = \sqrt{-1}$; ω is the circular frequency; λ_x is a dimensionless factor with values typically in the range between 0 and 0.5, and V_S is the shear wave velocity in the random medium. Utilizing Eq. 4, the spectral density function (SDF) of the rocking component of Eq. 3 can be evaluated as:

$$S_{\ddot{\theta}y\ddot{\theta}y}^{gAB}=\frac{2S_{\ddot{z}\ddot{z}}^{g}(\omega)}{d_x^2}\left[1-\left|\gamma_{AB}(d_x,\omega)\right|\cos\left(\omega\frac{d_x}{V_x}\right)\right] \tag{5}$$

where $S_{\ddot{z}\ddot{z}}^{g}(\omega)$ is the SDF of the vertical acceleration component in the random medium. The rocking component at a point on the ground surface can be considered equivalent to the slope of the line that connects two points when their separation distance approaches zero. In this case, if d_x in Eq. 5 tends to zero, the SDF of the rocking acceleration component at a point on the ground surface can be obtained as:

$$S_{\ddot{\theta}y\ddot{\theta}y}^{g}(\omega)=\omega^2R_\theta^2S_{\ddot{z}\ddot{z}}^{g}(\omega) \tag{6}$$

where:

$$R_\theta=\sqrt{\frac{2\lambda_x^2}{V_S^2}+\frac{1}{V_x^2}} \tag{7}$$

The frequency amplitude of the rocking acceleration component can be expressed using Eq. 6 as:

$$\left|\ddot{\Theta}_y^g(\omega)\right|=\omega R_\theta\left|\ddot{U}_z^g(\omega)\right| \tag{8}$$

where $\left|\ddot{U}_z^g(\omega)\right|$ is the amplitude of the Fourier transform of $\ddot{u}_z^g(t)$. On the other hand, the rocking acceleration component about the y-axis at x can be derived, in the frequency domain, using Eq. 2 as:

$$\ddot{\Theta}_y^g(x,\omega)=-\frac{\partial\ddot{U}_z^g(x,\omega)}{\partial x}=-\frac{\partial}{\partial x}\left[\left|\ddot{U}_z^g(\omega)\right|\exp\left[-i\varphi_z^g(x,\omega)\right]\right]=i\left|\ddot{U}_z^g(\omega)\right|\exp\left[-i\varphi_z^g(x,\omega)\right]\frac{\partial\varphi_z^g(x,\omega)}{\partial x} \tag{9}$$

in which it is implicitly assumed that the SDF of the vertical translational component is space-invariant. Considering that x approaches zero, and substituting Eq. 9 into Eq. 8 leads to:

$$\frac{\partial\varphi_z^g(x,\omega)}{\partial x}=\omega R_\theta \tag{10}$$

Hence, Eq. 9 can be simplified at $x = 0$ to:

$$\ddot{\Theta}_y^g(\omega)=i\omega R_\theta\left|\ddot{U}_z^g(\omega)\right|\exp\left[-i\varphi_z^g(\omega)\right] \tag{11}$$

and from Eq. 11, the rocking acceleration component, in the time domain, can be presented as:

$$\ddot{\theta}_y^g(t)=-\frac{\partial\ddot{u}_z^g(t)}{\partial x}=-R_\theta\frac{\partial\ddot{u}_z^g(t)}{\partial t}=-R_\theta\dddot{u}_z^g(t) \tag{12}$$

Eq. 12 indicates that, if constant values for both the apparent velocity and the loss of coherency are considered for describing the coherency effect, a constant phase difference, equal to $\pi/2$, exists between the vertical and the rocking acceleration components. Similarly, the earthquake torsional component (the third term on the right-hand side of Eq. 2) can be obtained, and, consequently, Eq. 2 can be expressed as:

$$\left\{\ddot{\vec{\theta}}^{g}(t)\right\} = 0\vec{i} - R_\theta \ddot{u}_z^{g}(t)\vec{j} + \frac{R_\theta \ddot{u}_y^{g}(t)}{2}\vec{k} \tag{13}$$

Eq. 13 can be adopted to simulate the rotational components along the principal axes [14] of strong ground motions in the far field. In the following section, Eq. 13 is utilized to derive new seismic intensity parameters for the rotational components.

3. Seismic Intensity Parameters for Rotational Components

In Sections 3.1 to 3.4, the characteristics and application of four existing SIPs for the translational components is briefly reviewed, and their revised forms are presented for considering effects of the rocking and torsional components. In Section 3.5, using kinematic characteristics of structures, an approach for relating the SIPs of translational and rotational components is proposed, and application of the first-mode pseudo-spectral acceleration to a typical five-story buildings is examined.

3.1. Peak Ground Acceleration

Peak ground acceleration (PGA) is the simplest, widely used SIP that has been also utilized in many seismic design codes. The SGMs with high PGAs are usually, but not always, more destructive than motions with lower ones. It is often assumed that the ratio of the PGA of the vertical component to the PGA of the horizontal ones is 2/3 for engineering purposes. However, this ratio is generally greater than 2/3 in the near filed and less than 2/3 in the far field. From Eq. 13, the PGA of the rotational components can be approximated as:

$$Rocking: PGA_{\theta y} = \max\left|\ddot{\theta}_y^{g}(t)\right| \cong R_\theta \max\left|\ddot{u}_z^{g}(t)\right| \cong \frac{2\pi R_\theta PGA_{uz}}{T_z} \tag{14.a}$$

$$Torsion: PGA_{\theta z} = \max\left|\ddot{\theta}_z^{g}(t)\right| \cong \frac{R_\theta}{2} \max\left|\ddot{u}_y^{g}(t)\right| \cong \frac{\pi R_\theta PGA_{uy}}{T_y} \tag{14.b}$$

where [11]:

$$T_z = 2\pi \frac{PGV_{uz}}{PGA_{uz}} \quad , \quad T_y = 2\pi \frac{PGV_{uy}}{PGA_{uy}} \tag{15}$$

are the predominant periods of seismic waves of vertical (*z*-axis) and horizontal (*y*-axis) components, respectively, and PGV is the peak ground velocity.

3.2. Nau and Hall indices

Nau and Hall (1982) [10] proposed the time integrals of the squared translational ground motions as the intensity indices, E^a, E^v, and E^d, without including the damping ratio and gravity acceleration as used in Arias intensity [9]. Their proposed relations can be revised for the rotational components, using Eq. 13, as follows:

$$Rocking:\begin{cases} E_{\theta y}^{a}=\int_{0}^{t_d}\left(\ddot{\theta}_y^g(t)\right)^2dt=R_\theta^2\int_{0}^{t_d}\left(\ddot{u}_z^g(t)\right)^2dt \\ E_{\theta y}^{v}=\int_{0}^{t_d}\left(\dot{\theta}_y^g(t)\right)^2dt=R_\theta^2\int_{0}^{t_d}\left(\dot{u}_z^g(t)\right)^2dt=R_\theta^2E_{uz}^{a} \\ E_{\theta y}^{d}=\int_{0}^{t_d}\left(\theta_y^g(t)\right)^2dt=R_\theta^2\int_{0}^{t_d}\left(u_z^g(t)\right)^2dt=R_\theta^2E_{uz}^{v} \end{cases} \tag{16.a}$$

$$Torsion:\begin{cases} E_{\theta z}^{a}=\int_{0}^{t_d}\left(\ddot{\theta}_z^g(t)\right)^2dt=\frac{R_\theta^2}{4}\int_{0}^{t_d}\left(\ddot{u}_y^g(t)\right)^2dt \\ E_{\theta z}^{v}=\int_{0}^{t_d}\left(\dot{\theta}_z^g(t)\right)^2dt=\frac{R_\theta^2}{4}\int_{0}^{t_d}\left(\dot{u}_y^g(t)\right)^2dt=\frac{R_\theta^2}{4}E_{uy}^{a} \\ E_{\theta z}^{d}=\int_{0}^{t_d}\left(\theta_z^g(t)\right)^2dt=\frac{R_\theta^2}{4}\int_{0}^{t_d}\left(u_y^g(t)\right)^2dt=\frac{R_\theta^2}{4}E_{uy}^{v} \end{cases} \tag{16.b}$$

where t_d is the total duration of the SGM, and superscripts a, v and d refer to the acceleration, velocity and displacement, respectively.

3.3. First-Mode Pseudo-Spectral Acceleration

The first-model pseudo-spectral acceleration represents the seismic force applied to the structure in quasi-static analyses, and is usually used for scaling SGMs in response history analyses. The mathematical representation of the displacement (SD), velocity (SV) and acceleration (SA) response spectrum is:

$$SD^2=C_d^2\int_{-\infty}^{+\infty}S^g(\omega)\left|H_D(\omega)\right|^2d\omega \quad , \quad SV^2=C_v^2\int_{-\infty}^{+\infty}\omega^2S^g(\omega)\left|H_D(\omega)\right|^2d\omega \quad , \quad SA^2=C_a^2\int_{-\infty}^{+\infty}\omega^4S^g(\omega)\left|H_D(\omega)\right|^2d\omega \tag{17}$$

where C_d, C_v and C_a are the corresponding peak factors of each response spectrum, and $H_D(\omega)$ is the displacement transfer function:

$$H_D(\omega)=\frac{1}{m\left[\left(\omega_1^2-\omega^2\right)+2i\xi_1\omega_1\omega\right]} \tag{18}$$

with ω_1 and ξ_1 indicating the fundamental natural frequency and damping ratio of a single-degree-of-freedom oscillator, respectively. Substituting rotational components from Eq. 13 into Eq. 17 results in:

$$Rocking:\begin{cases} SD_{\theta y}^2=C_d^2\int_{-\infty}^{+\infty}R_\theta^2\omega^2S_{\ddot{z}\ddot{z}}^g(\omega)\left|H_D(\omega)\right|^2d\omega \\ SV_{\theta y}^2=C_v^2\int_{-\infty}^{+\infty}R_\theta^2\omega^4S_{\ddot{z}\ddot{z}}^g(\omega)\left|H_D(\omega)\right|^2d\omega \end{cases} \rightarrow \begin{cases} SD_{\theta y}\cong R_\theta SV_{uz} \\ SV_{\theta y}\cong R_\theta SA_{uz} \end{cases} \rightarrow \begin{cases} PSV_{\theta y}\cong\frac{2\pi}{T_1}R_\theta SV_{uz} \\ PSA_{\theta y}\cong\left(\frac{2\pi}{T_1}\right)^2R_\theta SV_{uz} \end{cases} \tag{19.a}$$

$$Torsion:\begin{cases} SD_{\theta z}^2 = \dfrac{C_d^2}{4}\displaystyle\int_{-\infty}^{+\infty} R_\theta^2 \omega^2 S_{\ddot{y}\ddot{y}}^g(\omega)\left|H_D(\omega)\right|^2 d\omega \\ SV_{\theta z}^2 = \dfrac{C_v^2}{4}\displaystyle\int_{-\infty}^{+\infty} R_\theta^2 \omega^4 S_{\ddot{y}\ddot{y}}^g(\omega)\left|H_D(\omega)\right|^2 d\omega \end{cases} \rightarrow \begin{cases} SD_{\theta z} \cong \dfrac{R_\theta SV_{uy}}{2} \\ SV_{\theta z} \cong \dfrac{R_\theta SA_{uy}}{2} \end{cases} \rightarrow \begin{cases} PSV_{\theta z} \cong \dfrac{\pi}{T_1} R_\theta SV_{uy} \\ PSA_{\theta z} \cong 2\left(\dfrac{\pi}{T_1}\right)^2 R_\theta SV_{uy} \end{cases} \tag{19.b}$$

where PSV and PSA are the pseudo-spectral velocity and acceleration, and T_1 is the fundamental period of the single-degree-of-freedom oscillator.

3.4. Housner Spectrum Intensity

The Housner spectrum intensity (HSI) is defined as the area underneath the pseudo-velocity response spectrum (PSV) between the period (T) of 0.1 *sec* and 2.5 *sec*. It can be used to evaluate the earthquake input energy and damage capacity to ordinary structures, such as multi-story buildings. For the rotational components, the equivalent HSI can be evaluated, using Eqs. 19.a and b, in terms of the translational components as:

$$Rocking: HSI_{\theta y} = \int_{0.1\sec}^{2.5\sec} PSV_{\theta y}(\xi, T)dT = 2\pi R_\theta \int_{0.1\sec}^{2.5\sec} \frac{SV_{uz}(\xi, T)}{T} dT \tag{20.a}$$

$$Torsiuon: HSI_{\theta z} = \int_{0.1\sec}^{2.5\sec} PSV_{\theta z}(\xi, T)dT = \pi R_\theta \int_{0.1\sec}^{2.5\sec} \frac{SV_{uy}(\xi, T)}{T} dT \tag{20.b}$$

where ξ is the damping ratio ($\xi = 0.05$).

3.5. Application to Multi-Story Buildings

Two quantities H^{eff} (effective height of the structure) [3], and r (the radius of gyration about center of the rigidity of the structure) [3] can be used to related the translational and rotational SIPs in their application to multi-story buildings. In fact, the multiplication of the rotational components by these two quantities, i.e. rocking component by H^{eff} and torsional component by r, can provide us a roughly estimate of their effect on the structural loading compared to the translational components. This point is further illustrated in the following. Based on the seismic design code recommendations, first-mode pseudo-spectral acceleration is the best SIP for the estimation of the destructive effect of seismic excitations on multi-story buildings [15, 16]. Thus, herein, the application of Eqs. 19.a and b to a typical five-story building is discussed. In this case, the quantity ρ is defined as the indicator of the contribution of the rotational components to the seismic excitation compared to their corresponding horizontal one as:

$$Rocking: \rho_{\theta y/uy} = \frac{H^{eff} PSV_{\theta y}(\xi, T_1)}{PSV_{uy}(\xi, T_1)} = \frac{2\pi R_\theta H^{eff}}{T_1} \frac{SV_{uz}(\xi, T_1)}{PSV_{uy}(\xi, T_1)} \cong \frac{2\pi R_\theta H^{eff}}{T_1} \frac{PSV_{uz}(\xi, T_1)}{PSV_{uy}(\xi, T_1)} \tag{21.a}$$

$$Torsion: \rho_{\theta z/uy} = \frac{rPSV_{\theta z}(\xi, T_1^\theta)}{PSV_{uy}(\xi, T_1)} = \frac{\pi R_\theta r}{T_1^\theta} \frac{SV_{uy}(\xi, T_1^\theta)}{PSV_{uy}(\xi, T_1)} \cong \frac{\pi R_\theta r \Omega}{T_1} \frac{PSV_{uy}(\xi, T_1^\theta)}{PSV_{uy}(\xi, T_1)} \tag{21.b}$$

where $\Omega = T_1 / T_1^\theta$,and T_1 and T_1^θ are the fundamental lateral and torsional periods of the structure, respectively. Consider a typical five-story building with total height 20 *m*, and plan dimensions 10 *m* × 10 *m* located on a site with stiff soil conditions (V_{S30} = 300 *m/sec*). For this evaluation, assuming T_1 = 0.5 *sec*, H^{eff} = 14 *m*, r = 4.1 *m*, $\Omega = 1$, R_θ = 0.003 *rad.sec/m* [4, 5], $PSV_{uz}(\xi, T_1)/PSV_{uy}(\xi, T_1)$ = 2/3 [15], and using Eqs. 21.a and b result in: $\rho_{\theta y/uy}$ = 0.52 and $\rho_{\theta z/uy}$ = 0.08. This simple calculation indicates significant contribution of the rocking component to the structural loading, which is approximately 30% in total seismic excitation and approximately 50% of the translational excitation for the considered structure. This estimate is in agreement with the numerical results of the previous studies [4, 5] that used the same R_θ in the rotational excitation of multi-story buildings [4] and tall structures [5]. Herein, the contribution of the torsional component to the seismic loading is not comparable to the rocking component, but its effect can be increased with the increase of the dimension of the structure (*r*) and torsional stiffness (Ω) as previously discussed in Ref. [3] in detail. The importance of the rocking component in the seismic behavior of modern multi-story buildings, and tall and stiff structures that adopt new mechanisms for energy dissipation, such as the one discussed in Refs. [17, 18], and torsional component in the seismic response of extensive and long structures with rigid in-plane diaphragms, such as short-span continues skewed bridges [19, 20], may need special attention, and further study is required to appropriately address the problem. The present study provides simple quantitative criteria for the estimation of the effect of the rotational components on the seismic excitation of structure, which follows the original research by Falamarz-Shiekhabadi et al. 2016 on the revised seismic intensity parameters for the horizontal and rocking components [21].

4. Conclusions

In this study, a new method was developed for the evaluation of the rotational components with the consideration of the effects of both time delay and loss of coherency. In addition, new seismic intensity parameters corresponding to peak ground acceleration, Nau and Hall indices, first-mode pseudo-spectral acceleration and Housner spectrum intensity were derived to measure the destructive effects of the rotational (torsional and rocking) components on structures. The application of the first-mode pseudo-spectral acceleration to a typical five-story building was examined for both torsional and rocking components. The main advantages of the methodology proposed herein are (1) its clear physical interpretation, and (2) its simplicity in estimation of the contribution of the rotational components to the seismic excitation of structures. Certainly, further study is still necessary to examine the applicability of the proposed seismic intensity parameters in practice.

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