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The Effect of Torsional Ground Motion on Structural Response: Code Recommendation for Accidental Eccentricity

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Abstract In this article, data were collected from the Chiba dense array, which consists of 44 accelerometers with interstation spacing in the range of 5–300 m that are employed to estimate the torsional ground motion. The geodetic method was used to estimate torsional motions from the translational records in the Chiba dense array. The translational and computed torsional motions were then applied to the building models with different structural characteristics to evaluate the effectiveness of the accidental eccentricity levels proposed in various design codes. The results of analysis suggest that the 5% accidental eccentricity is on the safe side for most periods of interest in engineering practice. However, in the case of stiff structures (with periods shorter than 0.3 sec), an increase of up to four times in building displacement is observed by including the torsional excitation. Furthermore, we found that the accidental eccentricity coefficient increased up to 0.6 at periods shorter than 0.3 sec, which is 12 times larger than what is proposed by the codes.

Introduction

Rotational excitations (torsional and rocking) induced by seismic waves have been ignored in engineering practice, first because inexpensive measuring devices were not available until quite recently and second because rotational motion effects were erroneously believed to be small for typical man-made structures (Bouchon and Aki, 1982). Consequently, the dynamic analyses of structures have been carried out by neglecting the excitation by the rotational ground motions. Meanwhile, many structural failures and damage caused by earthquakes could be linked to differential and rotational ground motions. The torsional response of tall buildings in Los Angeles was ascribed to torsional excitation during the San Fernando earthquake of 1971 (Trifunac, 2006), and the rotational and longitudinal differential motions appear to have caused the collapse of bridges during the 1971 San Fernando, 1978 Miyagi-ken-Oki (Bycroft, 1980), and 1994 Northridge earthquakes (Trifunac *et al.*, 1996).

Newmark (1969) was first to propose a simple relationship to approximately account for the torsional excitation components of the ground motion. He devised a deterministic procedure for estimating an increase in displacement of symmetric-plan buildings caused by plane waves. This was further explored in several other studies (Nathan and MacKenzie, 1975; Morgan *et al.*, 1983; Rutenberg and Heidebrecht, 1985). Other studies have emphasized the importance of torsional and rocking components for seismic analysis and design of structures (Lee and Trifunac, 1985; Ghafory-Ashtiany and Singh, 1986; Lee and Trifunac, 1987; Gupta and Trifunac, 1989; Todorovska and Trifunac, 1990a, b, 1992; Trifunac, 1997) and of the torsional and rocking excitation resulting from the wave passage effects (Todorovska and Trifunac 1993; Trifunac *et al.*, 1999; Trifunac and Gičev, 2006). De La Llera and Chopra (1994) used translational ground motions recorded by accelerometers installed on the foundations of buildings. They neglected inplane bending and shear deformation of the foundation and computed the torsional acceleration of the building base from $a_{g\theta}(t) = [a_{g1}(t) - a_{g2}(t)]/d$, where $a_{g1}(t)$ and $a_{g2}(t)$ are the translational accelerations (in both x or y) recorded at locations 1 and 2 at the base of the building, and d is the distance between the two locations, which varies within the range from 5–110 m. These torsional accelerograms were used to estimate the effect of torsional motion on structural response and to define accidental torsion in buildings resulting from torsional excitation.

Building codes require that the effect of torsion be considered by applying the equivalent lateral forces at a distance e_d from the center of stiffness (CS) resulting in story torques in addition to shear and overturning moments (Fig. 1). Current design recommendations specify that the lateral force be applied at the center of mass (CM)—that is, at the distance equal to the static stiffness (e) from the CS—and that this force be shifted through e_a to obtain increased force in each structural element. Thus, the design eccentricity is $e_d = e + e_a$. This first term is intended to account for the coupled lateral torsional response of the building arising from the lack

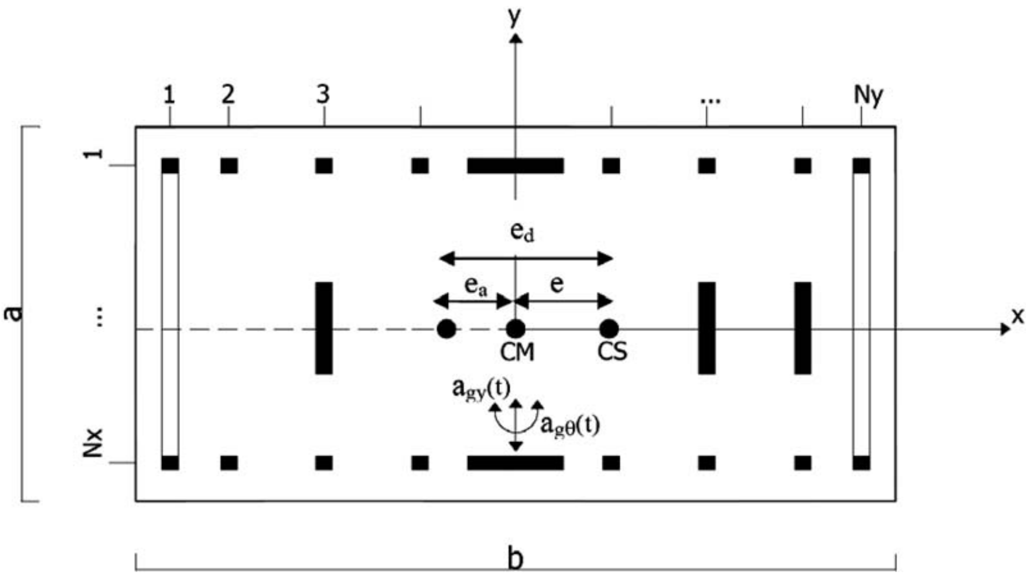

Figure 1. Plan of the assumed single-story system.

of symmetry in the plan. The additional term, known as accidental eccentricity, is introduced to account for eccentricities due to discrepancies between the mass, stiffness, and strength distributions used in analysis and true distribution at the time of an earthquake together with torsional vibrations induced by base torsional motions.

This accidental eccentricity is assumed to be a fraction of the plan dimension, βb, where b is the dimension of the building's plan perpendicular to the direction of ground motion. The coefficient β in different seismic codes is proposed to be in the range of 0.05–0.10. These values are based on the findings of elastic analyses of rigidly supported structures and on engineering judgment (Newmark, 1969).

Because there are no direct recordings of torsional ground motion (Suryanto *et al.*, 2006), the data from seismic dense arrays provide a unique opportunity to estimate torsional ground motion approximately, which could be evaluated with different orders of accuracy (Langston, 2007a,b). Ghayamghamian and Nouri (2007, 2008) studied the rotational ground motions and their dependence on seismic parameters, using Chiba dense-array data, and a possibility of estimating torsional ground motion from translational records was investigated. They computed torsional motion from the difference of two translational records on the ground.

In this study, the geodetic method will be used. It includes multiple stations in estimation of torsional motion (Spudich *et al.*, 1995). Because of the closely spaced instruments in the Chiba array and the regular arrangement of instruments at the two inner rings (Fig. 2), a better estimation of torsional motion can be achieved using multiple stations up to high frequencies (<11 Hz) (Langston, 2007b). The estimated torsional motions from different earthquakes were then applied to the buildings with different specifications to study the structural responses to the torsional excitation component and to evaluate the effects of torsional motion on the typical values of accidental eccentricity (e_a, a part of the design eccentricity) as used by different design codes.

Chiba Dense Array and Ground-Motion Data

Measurement of the spatial variation of the seismic wave field for engineering applications requires dense-array recordings. Depending upon the aim of observation, there are several manners in which seismometers and accelerometers can be arranged. A 3D-array system was installed at Chiba, an experiment station of the Institute of Industrial Science, University of Tokyo, in 1982 (Fig. 2). The Chiba station is located about 30 km east of Tokyo (Katayama *et al.*, 1990). The topographical and geological conditions of the site are generally simple, with the ground surface being almost flat, and the signals from all of the seismometers and strain gauges are recorded at every 0.005 sec. In this array, seismometers and accelerometers are placed, with a minimum separation distance of 5 m, both on the ground surface and in boreholes. The array system is composed of 15 boreholes with 44 three-component accelerometers, nine are densely arranged. Stations C1–C4 and P1–P4 are, respectively, placed on circles with radii of 5 and 15 m with respect to station C0, which is placed at the center of these two rings.

Nine events that were recorded with high signal-to-noise ratios (SNRs) and a wide range of magnitudes and peak ground accelerations (PGAs) were selected (Ghayamghamian and Nouri, 2007). Specifications of these events, together with their SNRs for station C0, are given in Table 1. The noise level for these events was estimated by taking motions prior to the first arriving energy of the event. SNRs for different events and station pairs were calculated by taking the root mean square of the signal-to-noise Fourier spectral ratio. In addition, variations of the noise levels against frequency for each station and event were also studied.

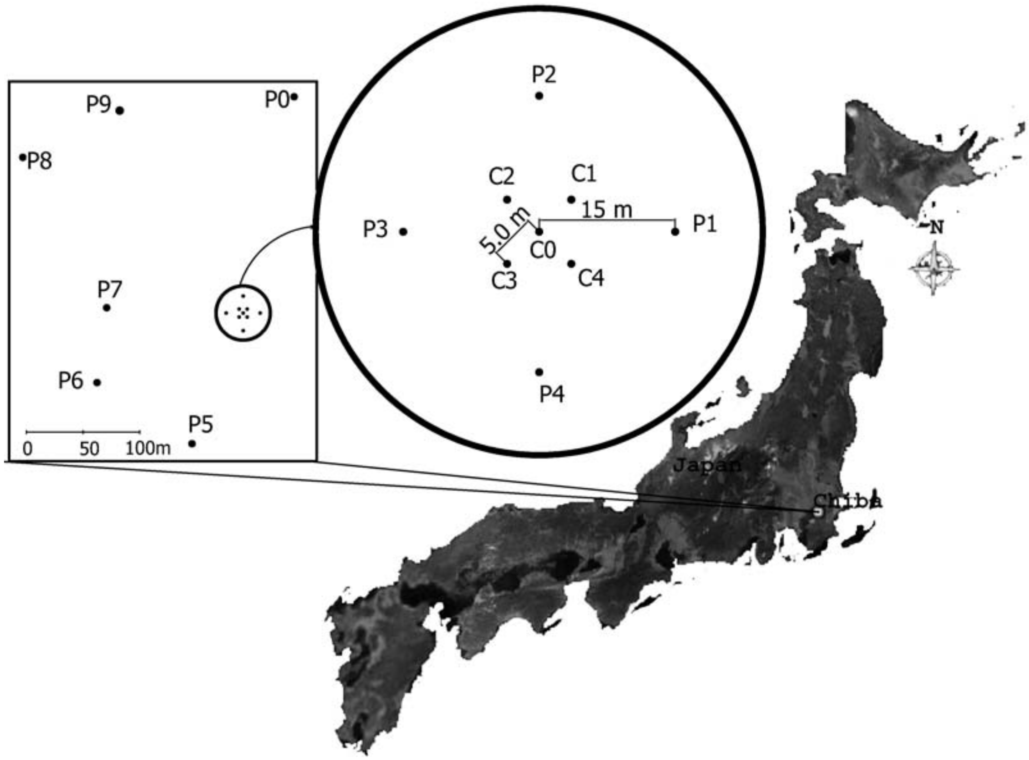

Figure 2. Chiba array configuration and reference system.

Estimation of Torsional Motion

The average torsional motions can be approximated from the difference of two translational records in an array of stations (Hao, 1996; Ghayamghamian and Motosaka, 2003; Huang, 2003; Ghayamghamian and Nouri, 2007). Spudich *et al.* (1995) introduced a geodetic method that can estimate torsional motion using multiple stations. At least three stations must be used to determine the horizontal-displacement gradient with this method. They showed that the time-dependent displacement-gradient matrix **G** can be estimated from the ground-displacement components u^i ($i = 1 \ldots N$) recorded at N stations by solving the following set of equations:

$$d_i = \mathbf{G}R_i = \begin{pmatrix} \partial_x u_x & \partial_y u_x & \partial_z u_x \\ \partial_x u_y & \partial_y u_y & \partial_z u_y \\ \partial_x u_z & -\partial_z u_y & -\eta(\partial_x u_x + \partial_y u_y) \end{pmatrix} R_i, \quad (1)$$

where, x, y, and z are the coordinates of orthogonal axes, $\eta = \lambda(\lambda + 2\mu)$, λ, and μ are the Lamé parameters, $d_i = u_i - u_0$, and $R_i = r_i - r_0$. u_i, r_i and u_0, r_0 are the displacements at the coordinates of the ith station and the reference station (with subscript 0), respectively. This method was applied to studying the dynamic deformations induced by the 1992 Landers earthquake (M 7.4) and recorded by the U.S. Geological Survey Parkfield seismic array (UPSAR) in California (Spudich *et al.*, 1995). In addition, Suryanto *et al.* (2006) used the same method to compare array-derived tor-

Table 1
Specification of Selected Events

Number	Event Number	Focal Depth (km)	Distance (km)	PGA (cm/sec^2) NS	PGA (cm/sec^2) EW	M_{JMA}	SNR Percent at Station C0	Reliable Frequency Range
1	33	73.3	104.5	52	60	6.5	98.6	>0.20
2	37	57.9	44.7	400	293	6.7	99.8	>0.20
3	42	47.6	37.9	117	79	5.2	98.7	>0.30
4	46	55.3	47.7	57	71	5.6	98.5	>0.30
5	47	55.7	55.2	32	34	6.0	98.1	>0.30
6	81	96.0	42.2	71	86	6.0	98.7	>0.30
7	82	69.0	62.4	38	51	5.3	97.2	>0.30
8	84	50.0	40.2	91	121	5.4	98.8	>0.30
9	87	92.0	52.4	91	94	5.9	99.0	>0.20

sional ground motion with direct-ring laser measurements and found the two to be in good agreement.

Bodin *et al.* (1997) showed that to obtain array-gradient estimates accurate to within ~90% of the true gradients, the array dimensions must be less than one quarter wavelength of the dominant energy in the wave train. Later, Langston (2007a,b) indicated that the accuracy order of finite difference approximation depends also on the geometry of the array. He found that the station spacing must be ~10% of a horizontal wavelength to obtain 90% accuracy, and these finite difference estimates are in first and second order of accuracy for irregular and regular arrays, respectively. Regarding estimated large-wave velocity (Yamazaki and Turker, 1992) and the very closely spaced instruments in the Chiba array, the torsional motions can be accurately evaluated for the two closely spaced rings, stations C0 and C1–C4 and C0 and P1–P4, up to the high-frequency range (< 11 Hz). Figure 3 shows an example of typical recorded translational accelerations (east–west [EW] and north–south [NS] directions) at stations C0 and C1–C4 and calculated torsional accelerations for event 84.

The Structural Model System and Analysis Procedure

A single-story building consisting of a rigid roof diaphragm supported on massless columns and walls is assumed as shown in Figure 1. The ith resisting plane in the x direction has stiffness k_{xi} and is located at a distance y_i from the CM of the building; analogously, the stiffness and location of plane i in the y direction are defined by k_{yi} and x_i, respectively. These resisting plans may have different stiffness in the y direction and may be asymmetrically located about the y axis, creating an eccentricity e between the CM and the CS of the building. The system is symmetric about the x axis and therefore is a one-way eccentric system. The number of resisting planes in the x and y directions is N_x and N_y, respectively.

The dynamic response of the system to the base translational acceleration in the y direction, $a_{gy}(t)$, and base torsional acceleration, $a_{g\theta}(t)$, is described by two degrees of freedom—the translational displacement u_y of the CM along the y direction and the displacement ru_θ of the rigid diagram at distance r from the CM due to only the rotation u_θ of the rigid diagram—with r being the radius of gyration of the system about a vertical axis passing through the CM. The equations of motion of the system can be written as:

$$\begin{bmatrix} m & 0 \\ 0 & m \end{bmatrix} \begin{Bmatrix} \ddot{u}_y \\ r\ddot{u}_\theta \end{Bmatrix} + \begin{bmatrix} K_y & K_y e/r \\ K_y e/r & K_\theta/r^2 \end{bmatrix} \begin{Bmatrix} u_y \\ ru_\theta \end{Bmatrix} = -m \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{Bmatrix} a_{gy}(t) \\ ra_{g\theta}(t) \end{Bmatrix}, \quad (2)$$

where m is the lumped mass at the roof diaphragm, $K_y = \sum_i^{N_y} k_{yi}$ is the lateral stiffness of the system, $K_\theta = \sum_{i=1}^{N_y} k_{yi} x_i^2 + \sum_{i=1}^{N_x} k_{xi} y_i^2$ is the torsional stiffness of the building with respect to the CM, and $e = \sum_{i=1}^{N_y} k_{yi} x_i / \sum_{i=1}^{N_y} k_{yi}$ is the static eccentricity of the building.

By dividing equation (2) by m, the equation of motion can be written as follows:

$$\begin{Bmatrix} \ddot{u}_y \\ r\ddot{u}_\theta \end{Bmatrix} + \omega_y^2 \begin{bmatrix} 1 & e/r \\ e/r & \Omega^2 + (e/r)^2 \end{bmatrix} \begin{Bmatrix} u_y \\ ru_\theta \end{Bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{Bmatrix} a_{gy}(t) \\ ra_{g\theta}(t) \end{Bmatrix}, \quad (3)$$

where $\Omega = \omega_\theta/\omega_y$, $\omega_y = \sqrt{K_y/m}$ is the uncoupled lateral, and $\omega_\theta = \sqrt{K_{\theta R}/(mr^2)}$ is the uncoupled torsional frequency of the building. $K_{\theta R} = K_\theta - K_y e^2$ is the torsional stiffness of the building with respect to center of resident. Thus, the assumed single-story system is characterized by four parameters: ω_y, Ω, e/r, and r.

Equation (3) is solved to determine the response of systems for two excitation cases: (1) $a_{gy}(t)$ and $a_{g\theta}(t)$ acting simultaneously, and (2) $a_{gy}(t)$ alone. The ratio between the building's responses computed for these two excitation cases, which is denoted here as the normalized building response, provides a measure of the changes in the response due to torsional excitation. Normalized response larger than unity implies that accidental torsion resulting from rotational excitation has the effect of increasing the building's response. To solve the coupled differential equations of motion, a modal time-history analysis is applied. The response of the system to earthquake motions (horizontal and torsional) is expressed by the combination of two of the modal responses. The response quantities of interest are the peak values over time of the lateral displacements at distance $-r$ from the CM (left side of CM, i.e., the flexible side of the building). These are denoted as $(U^*_{-r})_0$ and $(U_{-r})_0$ when computed for the excitation cases (1) and (2), respectively. The normalized displacement $(\hat{U}_{-r})_0 = (U^*_{-r})_0/(U_{-r})_0$ is computed for each system defined by parameters ω_y, Ω, e/r, and r and for each of the nine events listed in Table 1.

Eccentricity e_a relative to the CM specifies the location at which the equivalent static lateral force or base shear, V, should be applied to a one-story system to account for the accidental torsion of the system arising from rotational excitation. For the derivation that follows, V is chosen as the static force applied at the CM that produces a displacement $(U_{-r})_0$ at $x = -r$, the peak dynamic displacement due only to the translational component of ground motion:

$$(U_{-r})_o = \frac{V}{K_y} + \frac{Ve}{K_\theta}(e + r). \quad (4)$$

Next, the same static force V is applied eccentrically relative to the CM at distance e_a, yet to be determined. This accidental eccentricity is determined so that it satisfies the requirement that the displacement at $x = -r$ is the same as $(U^*_{-r})_0$

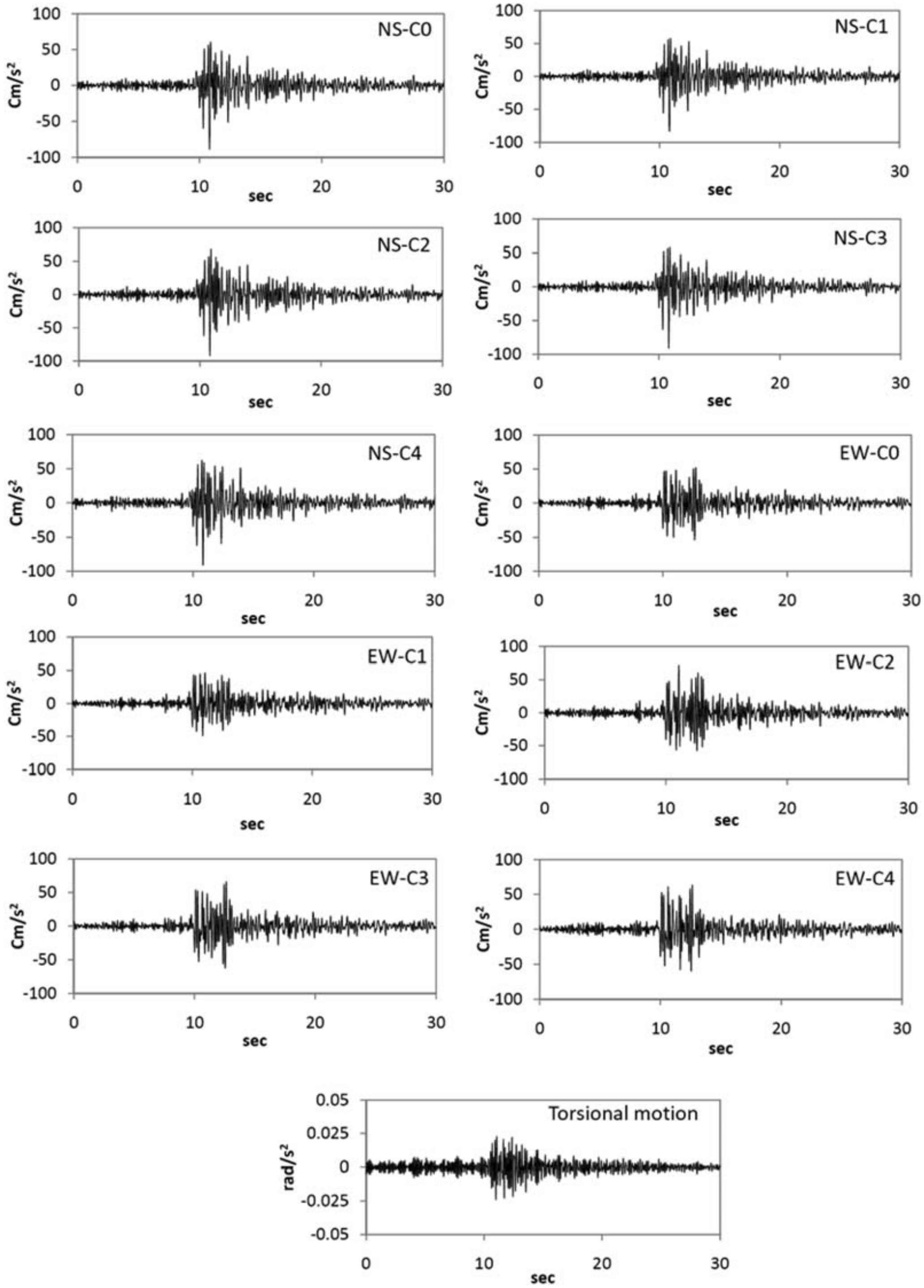

Figure 3. Typical recorded translational accelerations (EW and NS) at stations C0 and C1–C4 and calculated torsional accelerations for event 84.

(the peak dynamic displacement due to the simultaneous action of the translational and rotational components of ground motion):

$$(U^*_{-r})_o = \frac{V}{K_y} + \frac{V(e+e_a)}{K_\theta}(e+r). \tag{5}$$

Dividing equation (4) by (5) and solving for e_a, we obtain

$$\frac{e_a}{b} = [(\hat{U}_{-r})_o - 1]\left(\frac{\Omega^2}{1+e/r} + e/r\right)(r/b). \tag{6}$$

Note that V does not appear in the equations for e_a/b (De La Llera and Chopra, 1994). This accidental eccentricity can therefore be used in conjunction with any reasonable value of V, including the code values. Equation (6) relates the accidental eccentricity e_a to the normalized displacement $(\hat{U}_{-r})_o$ at a distance r to the left of the CM. Normalized displacements at other locations, such as the left edge of the building plan, could also be used in determining e_a. The resulting accidental eccentricities e_a are, however, quite insensitive to the location selected, provided the two points are on the same side with respect to the CS. It is noteworthy that the values of accidental eccentricity computed from equation (6) are still valid for a special class of multistory buildings that satisfy the following properties: (1) the CM of all floors lies on a vertical line, (2) the resisting planes are arranged such that their principal axes form an orthogonal grid in the plan and are connected at each floor by a rigid diaphragm, and (3) the lateral stiffness matrices of all resisting planes along one direction are proportional to each other (Hejal and Chopra, 1987).

Numerical Analysis of Building Response

Some parameters that will be examined are as follows: building systems with an uncoupled vibration period (T_y) in the range of 0.01–3 sec; a torsional-to-lateral frequency ratio (Ω) of 2/3, 1, and 3/2; plan dimensions of 50 and 100 m; and three plan aspect ratios $a/b = 0.25$, 0.5, 1. The mean values of the normalized displacement $(\hat{U}_{-r})_0$ for the buildings with different combinations of the previous parameters are computed and are shown in Figures 4 and 5. It is seen that the normalized displacement decreases as the Ω value increases, which means that the system becomes torsionally stiffer. It reaches a value of over more than 4.3 when T_y is around 0.10 sec for $b = 100$ m, $e/r = 0.0$, and $\Omega = 2/3$. This describes an increase in the response of the building due to torsional excitation by, about, 300% in the mean. The normalized displacement rapidly decreases as T_y increases. At

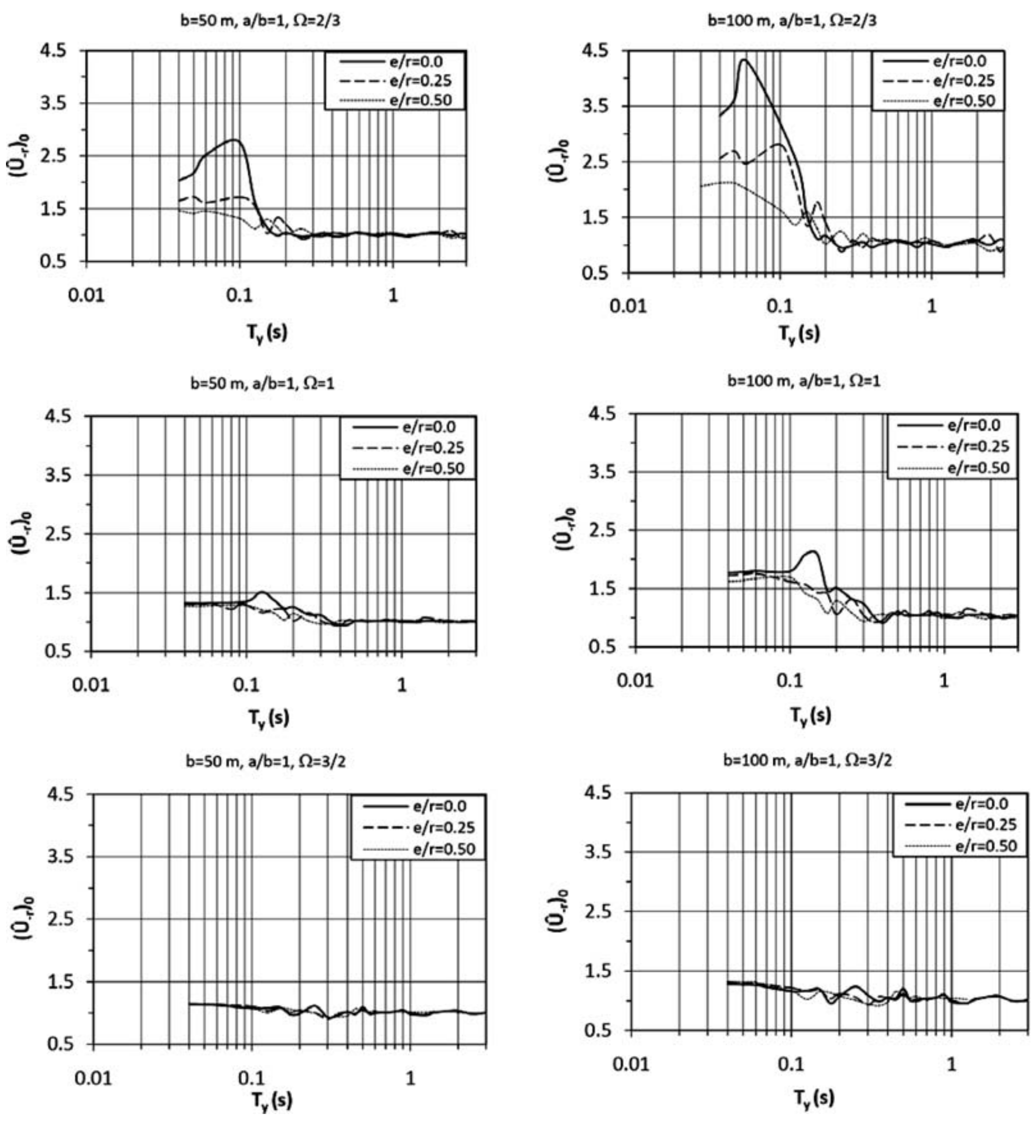

Figure 4. Normalized response $(\hat{U}_{-r})_0$ as a function of T_y for $\Omega = 2/3$, 1, and 3/2; $e/r = 0$, 0.25, and 0.50; $a/b = 1$; and $b = 50$ and 100 m.

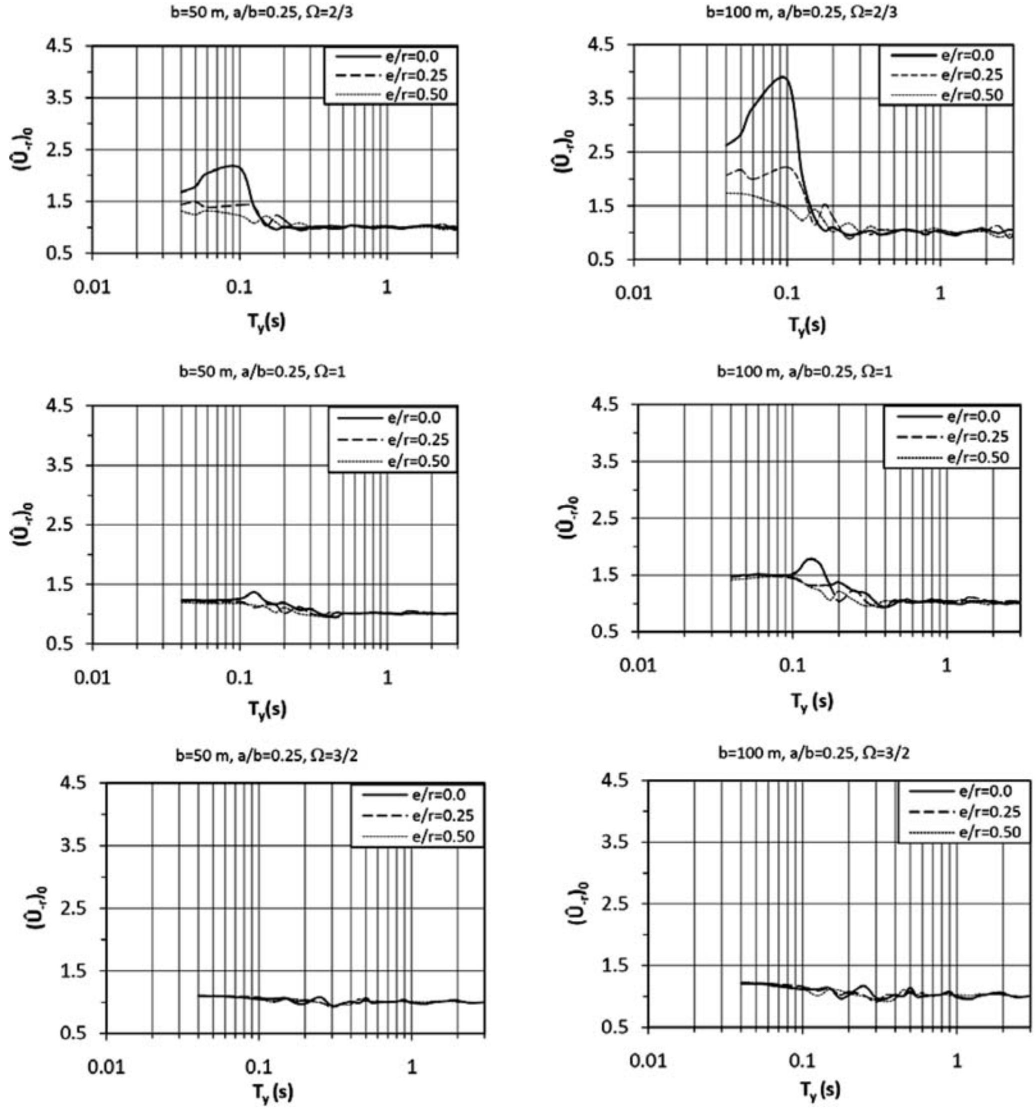

Figure 5. Normalized response $(\hat{U}_{-r})_0$ as a function of T_y for $\Omega = 2/3$, 1, and $3/2$; $e/r = 0$, 0.25, and 0.50; $a/b = 0.25$; and $b = 50$ and 100 m.

long periods, the mean increase in displacement is less than 5% for the structures with plan dimensions of 50 m. However, in the case of buildings with larger dimensions, the mean increase is near 5% for the same periods. The increase in building displacement resulting from torsional excitation is insensitive to change in the static eccentricity (e/r) unless the structures are very stiff (i.e., T_y is small) and the frequency ratios are small. In the cases we studied, the increase in displacements due to torsional ground motion is larger for a symmetric building ($e/r = 0$) compared to with the unsymmetrical ones, especially at short periods and for small frequency ratios. As illustrated in Figure 6, the increase in the building response due to torsional excitation is insensitive to the plan dimensions at long periods and large values of the frequency ratio (buildings are torsionally stiff). We found similar trends for other aspect ratios. The increase in the displacement of buildings shows larger values for the large aspect ratios. This becomes clear from comparison of Figures 4 and 5.

The accidental eccentricity is a part of design eccentricity, which is specified by different design codes. In this article, we studied the accidental eccentricity in simple building models resulting from torsional excitation. The accidental eccentricity in terms of normalized displacement and other parameters is explained by equation (6). As shown in Figure 7, the accidental eccentricity (e_a/b) tends to be large at very short periods ($T_y < 0.3$ sec) and with small values of Ω (torsionally flexible structures), and it decreases rapidly at long periods, finally reaching a maximum of 60% for a system with $\Omega = 2/3$ and $T_y = 0.06$ sec. The negative accidental eccentricity can be observed in some cases, showing the decrease in structural response due to the torsional motion. In Figure 8, the estimated normalized displacement and accidental eccentricity are also compared with the result

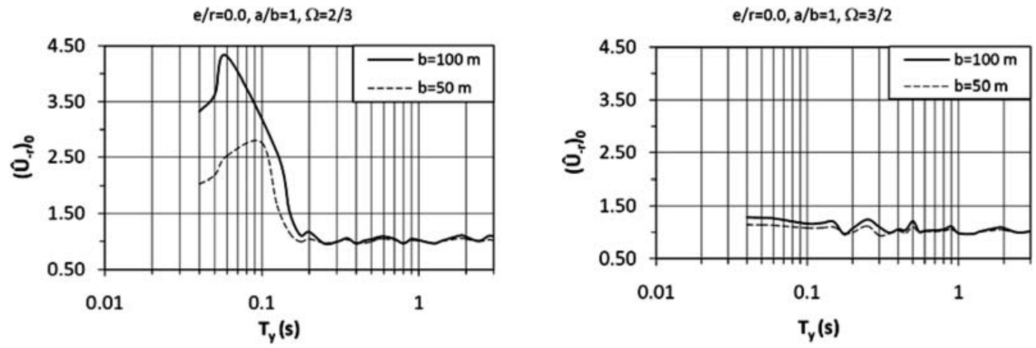

Figure 6. Normalized response $(\hat{U}_{-r})_0$ as a function of T_y for $\Omega = 2/3$ and $3/2$; $e/r = 0$; $a/b = 1$; and $b = 50$ and 100 m.

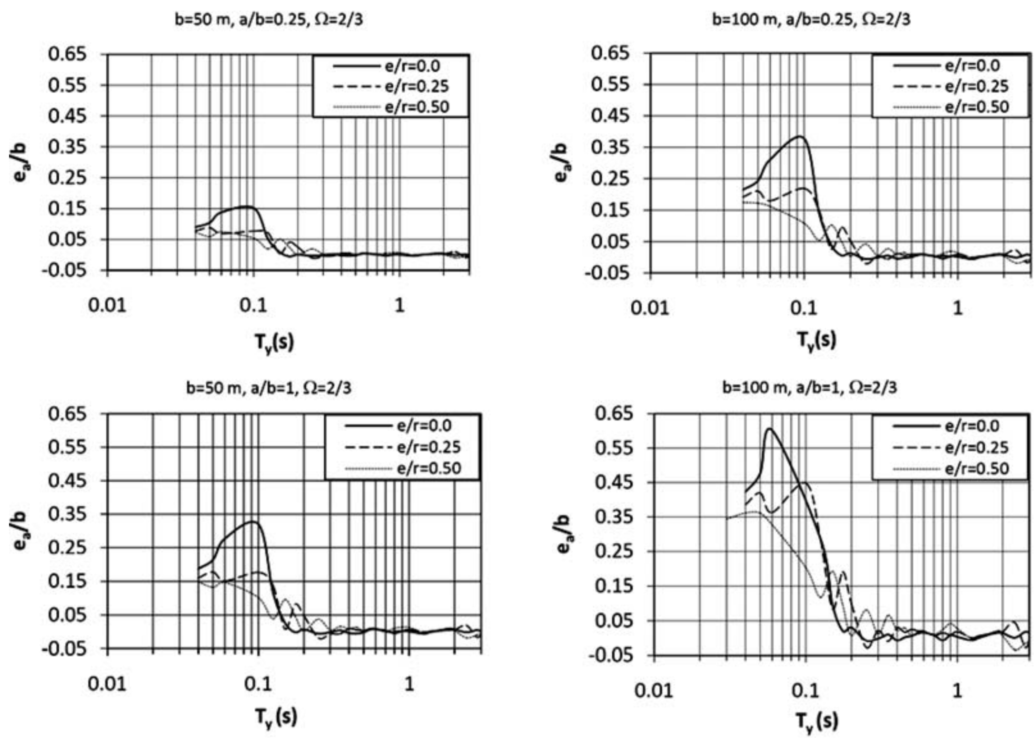

Figure 7. Normalized accidental eccentricity as a function of T_y for $\Omega = 2/3$; $e/r = 0$, 0.25, and 0.50; $a/b = 0.25$ and 1; and $b = 50$ and 100 m.

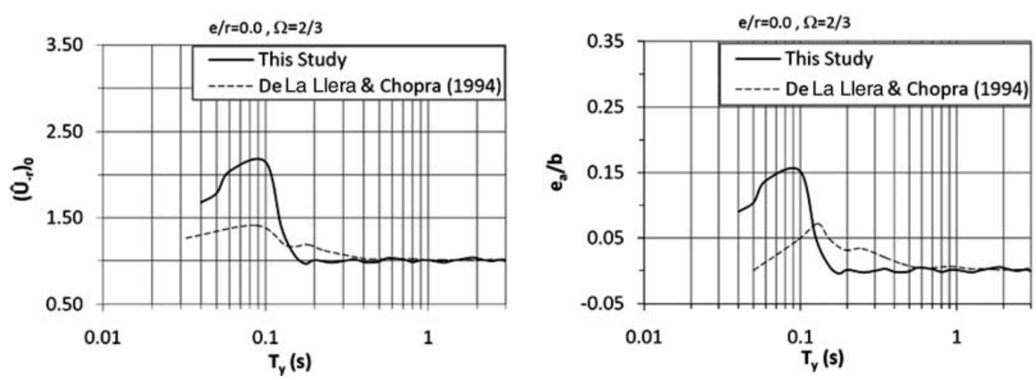

Figure 8. Normalized response $(\hat{U}_{-r})_0$ and normalized accidental eccentricity as a function of T_y for $\Omega = 2/3$, $e/r = 0$, $a/b = 1$, and $b = 50$ m. Comparison of this study and a study by De La Llera and Chopra (1994).

obtained by De La Llera and Chopra (1994). Our results reveal larger values for normalized displacement and accidental eccentricity at short periods, and the results are consistent at long periods where the effect of torsional excitation fades away.

The building codes specify an accidental eccentricity of $0.05b$ or $0.10b$, independent of the period (T_y) and frequency ratio (Ω). The computed values of e_a due to torsional excitation are in the range of $0.6b$ to $0.08b$ at short periods ($T_y < 0.3$ sec) and low-frequency ratios ($\Omega < 1$), which is much larger than the codes' values for accidental eccentricity. The average value of e_a/b resulting from torsional excitation for periods within the range of engineering interest shows values less than 0.01 (1%). Therefore, assuming a constant value for accidental eccentricity, at different periods it may result in over- or underestimation of the torsional response of structures.

Discussion and Conclusion

Dynamic response estimates of structures subjected to earthquake-induced base excitations are often simplified by ignoring the rotational (rocking and torsional) components of ground motion. This has been a widely accepted practice in the engineering community, largely caused by the lack of recorded torsional ground motions. Furthermore, most studies have been based on assumed models for torsional ground motion, and none had the benefit of being tested against field measurements. In this article, the torsional motion is estimated by a geodetic method using data of the Chiba dense array. The estimated torsional motions were utilized to investigate the structural response and to evaluate the accidental eccentricity induced by the torsional excitation. The building model with different structural specifications was analyzed after being subjected to both translational and torsional ground motions. The results can be summarized as follows:

1. The increase in the displacements of symmetric or asymmetric buildings due to torsional excitation of the ground is largest for structures with very short translational periods (less than about 0.3 sec) and small frequency ratios ($\Omega < 1$). For such structures, the accidental eccentricities e_a resulting from torsional ground motions are found to be larger than those proposed by the design codes.
2. The increase in the displacements due to torsional excitation is sensitive to the frequency ration (Ω) and static eccentricity (e/r) only at the short periods (stiff structures).
3. The structural response of stiff structures increases significantly when subjected to torsional excitation for both large and small plan dimensions.
4. For laterally stiff and torsionally flexible structures ($T_y < 0.3$ and small values of Ω), the proposed coefficients in most building codes underestimate the accidental torsion.
5. From the results in this study, it is found that the accidental eccentricity should depend on the structural characteristics and needs to be increased to 0.6 for periods shorter than 0.3 sec.

Data and Resources

Data from the Chiba array were obtained from the Earthquake Disaster Mitigation Engineering Institute of Industrial Science, University of Tokyo, based on the reports of development of a strong-motion database for the Chiba seismometer array (Katayma *et al.*, 1990).

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