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Effect of vertical component of earthquake on the response of pure-friction base-isolated asymmetric buildings

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Abstract

This study has been conducted to evaluate the effects of the vertical component of earthquake on the response of pure-friction base-isolated asymmetric buildings. The pure-friction base-isolated asymmetric building is idealized as a three-dimensional single-storey building resting on sliding supports. The sliding surface is modeled by interface rigid contact elements. The response of this idealized system subjected to three-component (including vertical component) and two-component (excluding vertical component) of earthquake excitations is investigated. As an example, the Northridge 1994 earthquake record is used on the structural model. The performance of asymmetric pure-friction base-isolated system is investigated with the help of peak response ratio of sliding to fixed base systems. It is observed that the vertical component of the strong earthquake excitation, significantly affects the response of pure-friction base-isolated torsionally coupled system.

Keywords: Pure friction; Asymmetric buildings; Vertical component of earthquake

1. Introduction

In the recent years, the concept of base isolation has attracted considerable attention in the seismic design of buildings. The main idea is to isolate the structure from the ground, instead of the conventional techniques of strengthening the structural members. This procedure appears to have considerable potential in preventing earthquake damage to structures and their internal sensitive equipment. The devices, which isolate the structure at its base, have two important characteristics: horizontal flexibility and energy absorbing capacity. The flexibility of the isolation system increases the fundamental period of the structure, shifting it out of the region of dominant earthquake energy. The energy absorbing capacity increases damping, and therefore, reduces excessive displacements due to the lateral flexibility of the isolation system. Several base isolation systems have been developed. Wide range frequency input and insurance of maximum acceleration transmissibility equal to maximum limiting frictional force have made the frictional type systems advantageous to conventional rubber bearing systems. The pure-friction type is the simplest one among a variety of frictional type base isolation systems that have been proposed. On the other hand, if the center of mass and the center of stiffness of the superstructure of pure-friction base-isolated building do not coincide, the structure will have both lateral and torsional motions when subjected to lateral earthquake motion. Furthermore, during an earthquake the system will experience the vertical component of the earthquake as well, which could influence the lateral as well as the torsional response of the pure-friction base-isolated system.

The response of sliding buildings has been widely studied under unidirectional support motions [1–4]. Few studies, however, have been carried out on these systems subjected to bi-directional lateral ground motion [5–7]. Jangid [5] studied the response of a symmetric structure with sliding support to bi-directional (i.e. two horizontal components) earthquake ground motion. He incorporates the coupling effects due to circular interaction between the frictional forces and states that the design sliding displacement may be underestimated if the bi-directional

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interaction of frictional forces is neglected. The lateral–torsional response of base-isolated structures, with sliding isolation system due to bi-directional lateral ground motion, is studied by Nagarajaiah et al. [6], and Jangid and Datta [7]. The objective of their studies is to identify the key system parameters that lead to significant torsional coupling in the sliding base-isolated structures. However, very little attention has been given to the effects of vertical component of earthquake excitation on buildings with sliding isolation system [8–10]. Lin and Tadjbakhsh [8] evaluated the effect of vertical ground motion on the horizontal response of the pure-friction system. The necessity of considering the vertical component of earthquake in the design of buildings with sliding support is pronounced by Liaw et al. [9]. They stated that the frictional stress is a function of vertical reaction, which is produced by the supporting element on the foundation mat. Hence, both these vertical and frictional forces vary when there is vertical motion on the sliding system. As an example, they use the El-Centro earthquake records on two-dimensional structural model, to verify the effect of vertical component on the lateral response of the system. Shakib and Fuladgar [10] evaluated the effects of three components of earthquake excitations on the response of pure-friction base-isolated structures. The symmetric structure is idealized as a three-dimensional single-storey building resting on the sliding support. They observed that the sliding support is quite effective in reducing the seismic lateral response of the structure subjected to three components of the earthquake excitations. This effect is strongly dependent on the system period as well as the input motion. So far, the performance of torsionally coupled system with sliding support under vertical component of earthquake has not yet been studied.

In the present study, the lateral–torsional response of base-isolated buildings, with pure-friction isolation system subjected to three-component (including vertical component) and two-component (excluding vertical component) of the earthquake excitations is investigated. The effect of vertical component of the Northridge 1994 earthquake record (Rinaldi station) on the lateral and torsional response of the system is illustrated for a wide range of parametric studies.

2. Structural system and modeling

Fig. 1 represents the assumed structural system, which is an idealized three-dimensional single-storey building model, mounted on a sliding support. The top mass m_s that supported on mass-less columns and the base mass m_b are rigid decks. The structure is assumed to be linear elastic. This is a reasonable assumption, since the purpose of the base isolation is to reduce the earthquake forces on the structure. The center of mass (CM) of the top mass and the base mass are assumed to be vertically aligned. The planwise distributions of structural stiffness are asymmetric relative to the x- and y-axes. Thus, the center of rigidity (CR) of the structure is eccentric relative to CM (i.e. e_x and e_y). The system is subjected to three- and two-component earthquake excitations.

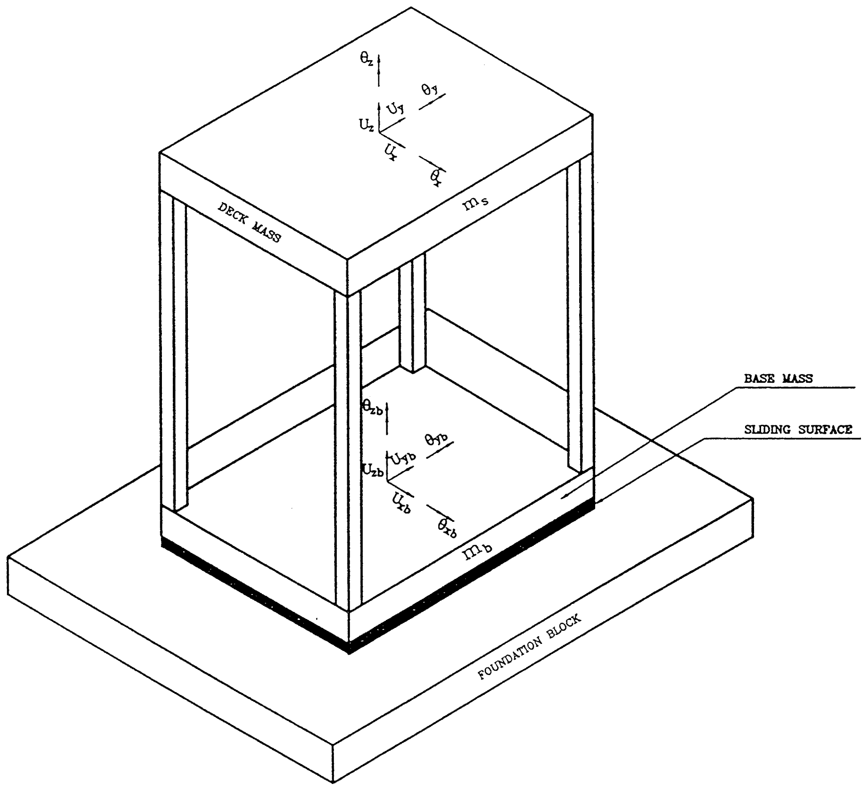
The frictional stresses mobilized at the sliding support have ideal coulomb-friction characteristics, which is implemented in the analysis by assuming elasto-plastic behavior with very high initial stiffness. The coefficient of friction of the sliding supports remains constant and independent of pressure and velocity. However, this assumption limits the applicability of the results in general cases since it is known that: (i) as the pressure at the sliding interface reduces, the coefficient of friction increases and vice-versa, and (ii) friction is velocity dependent in sliding isolators [11]. The sliding support is isotropic, i.e. there is the same coefficient of friction in the orthogonal directions of motion in the horizontal plan. The sliding support is modeled by the interface rigid-contact elements that are shown in Fig. 2. The base mass is idealized as a rigid plane resting on interface rigid-contact elements. Under static conditions the sliding support is subjected to initial vertical reactive forces resulting from the gravity force of the building.

Twelve degrees of freedom is considered at the center of the floor and the center of the sliding base. These degrees of freedom are the displacements in x, y, and z directions, rocking in two orthogonal directions, and torsion about z-axis as shown in Fig. 1. u_x, u_y, u_z, θ_x, θ_y, θ_z (in center of floor mass level) and u_{xb}, u_{yb}, u_{zb}, θ_{xb}, θ_{yb}, θ_{zb} (in center of sliding base mass) denote the above degrees of freedom. Therefore, the assembled stiffness matrix of the structure will be of the form:

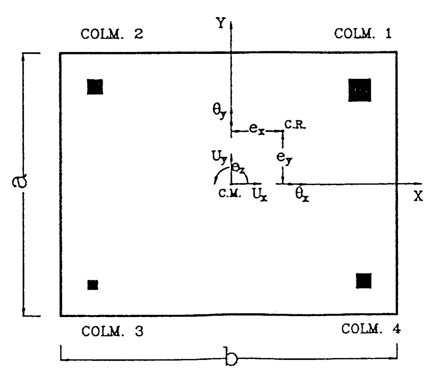
$$[K_{sup}] = \begin{bmatrix} [K_{bb}] & [K_{bs}] \\ [K_{sb}] & [K_{ss}] \end{bmatrix}; \qquad [K_{bb}] = [K_{ss}] = -[K_{bs}] = -[K_{sb}] \tag{1}$$

where the sub-matrices of the above stiffness matrix and their elements are as follows:

$$[K_{bb}] = \begin{bmatrix} K_{xx} & 0 & 0 & 0 & 0 & K_{x\theta_z} \\ 0 & K_{yy} & 0 & 0 & 0 & K_{y\theta_z} \\ 0 & 0 & K_{zz} & K_{z\theta_x} & K_{z\theta_y} & 0 \\ 0 & 0 & K_{\theta_x z} & K_{\theta_x\theta_x} & K_{\theta_x\theta_y} & 0 \\ 0 & 0 & K_{\theta_y z} & K_{\theta_y\theta_x} & K_{\theta_y\theta_y} & 0 \\ K_{\theta_z x} & K_{\theta_z y} & 0 & 0 & 0 & K_{\theta_z\theta_z} \end{bmatrix} \tag{2a}$$



(a) - 3-D Model



(b) - Plan

Fig. 1. Idealized single-storey asymmetric building supported on the sliding pure-friction: (a) 3-D Model; (b) plan of the system.

$$K_{xx} = \sum_i^n k_{ix}\; K_{yy} = \sum_i^n k_{iy}\; K_{zz} = \sum_i^n k_{iz} \tag{2b}$$

$$K_{\theta_x\theta_x} = \sum_i^n k_{iz}y_i^2\; K_{\theta_y\theta_y} = \sum_i^n k_{iz}x_i^2$$

$$K_{\theta_z\theta_z} = \sum_i^n k_{ix}y_i^2 + \sum_i^n k_{iy}x_i^2\; K_{x\theta_z} = K_{\theta_z x} = -\sum_i^n k_{ix}y_i$$

$$K_{z\theta_x} = K_{\theta_x z} = \sum_i^n k_{iz}y_i\; K_{y\theta_z} = K_{\theta_z y} = \sum_i^n k_{iy}x_i$$

$$K_{z\theta_y} = K_{\theta_y z} = -\sum_i^n k_{iz}x_i\; K_{\theta_x\theta_y} = K_{\theta_y\theta_z} = \sum_i^n k_{iz}x_iy_i$$

In which k_{ix}, k_{iy} and k_{iz} are the stiffness of the ith column in the x, y, and z directions, respectively. x_i and y_i denote the x and y coordinates of the column with respect to the center of deck mass. n denotes the number of columns in the storey. The location of the center of resistance with respect to center of geometry or center of mass in the x- and y-directions is defined by e_x and e_y:

$$e_x = \frac{K_{y\theta_z}}{K_{yy}} \quad e_y = -\frac{K_{x\theta_z}}{K_{xx}} \tag{3}$$

e_x and e_y are referred to as static eccentricities between the center of resistance and center of mass. With the help

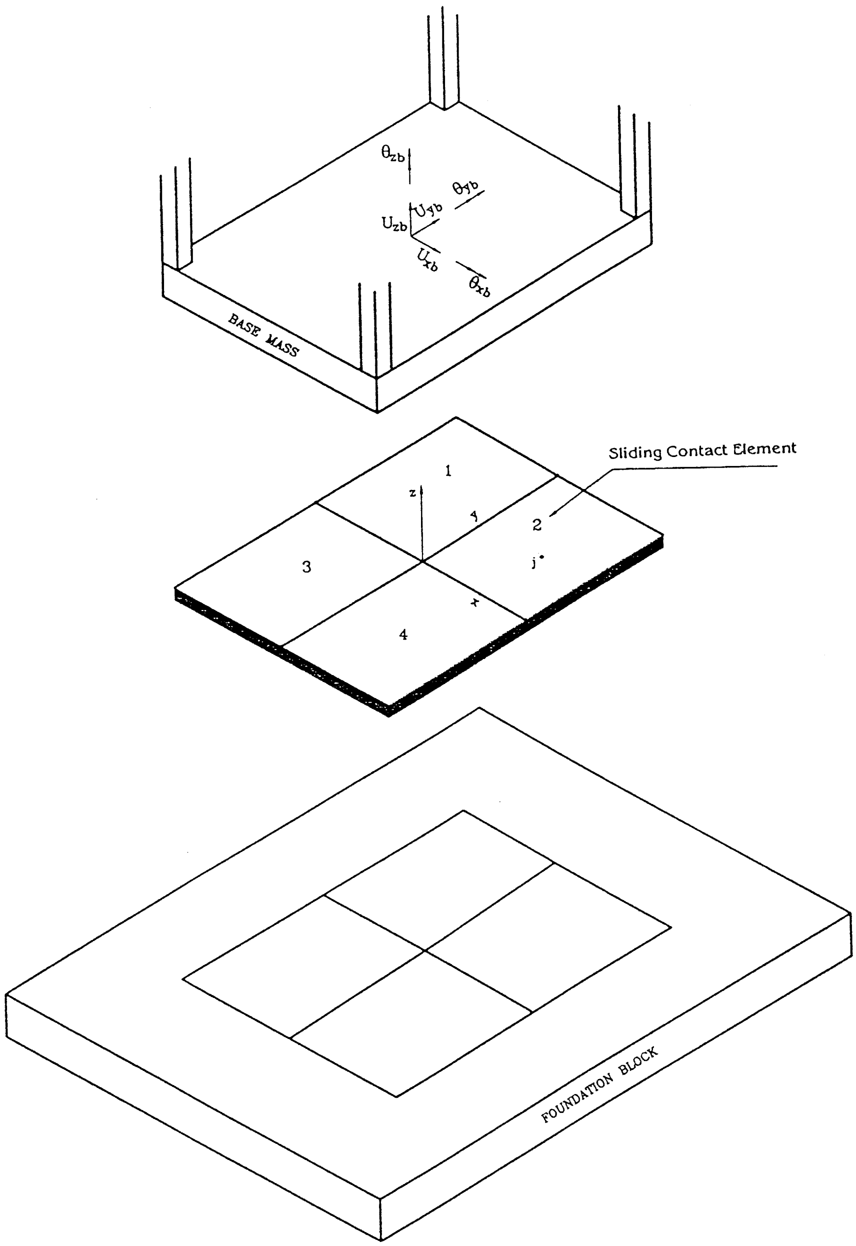


Fig. 2. Sliding element model.

of the quantities defined above, the uncoupled frequencies is as following:

$$\omega_x = \left(\frac{K_{xx}}{m_s}\right)^{1/2} \omega_y = \left(\frac{K_{yy}}{m_s}\right)^{1/2}$$
$$\omega_z = \left(\frac{K_{zz}}{m_s}\right)^{1/2} \omega_\theta = \left(\frac{K_{\theta_z\theta_z}}{m_s r^2}\right)^{1/2} \tag{4}$$

In which m_s is the mass of the structure and r is the radius of gyration of deck about the vertical axis through CM. ω_x, ω_y, ω_z, and ω_θ is interpreted as the uncoupled natural frequencies of the fixed base structure. The torsional mass (mr^2) is varied to provide various uncoupled torsional to lateral frequency ratios ω_θ/ω_x for fixed base condition. The diagonal mass matrix of the structure will be of the form:

$$[M_{\mathrm{sup}}] = \begin{bmatrix} [M_b] & 0 \\ 0 & [M_s] \end{bmatrix} \tag{5a}$$

where $[M_b]$ and $[M_s]$ are as following:

$$[M_b] = \begin{bmatrix} m_b & 0 & 0 & 0 & 0 & 0 \\ & m_b & 0 & 0 & 0 & 0 \\ & & m_b & 0 & 0 & 0 \\ & & & I_{xx_b} & 0 & 0 \\ & \mathrm{sym} & & & I_{yy_b} & 0 \\ & & & & & I_{zz_b} \end{bmatrix} \tag{5b}$$

$$[M_s] = \begin{bmatrix} m_s & 0 & 0 & 0 & 0 & 0 \\ & m_s & 0 & 0 & 0 & 0 \\ & & m_s & 0 & 0 & 0 \\ & & & I_{xx_s} & 0 & 0 \\ & \text{sym} & & & I_{yy_s} & 0 \\ & & & & & I_{zz_s} \end{bmatrix} \tag{5c}$$

In which m_b is the mass of base raft and I_{xx_b},I_{yy_b},I_{zz_b} are the mass moment of inertia of base in x, y, and z direction, respectively. Parameters in $[M_s]$ matrix have similar definition for the structure.

The sliding support is modeled by an interface rigid-contact element. This interface rigid-contact element is developed based on the joint element proposed by Beer [12] and Buczkowski and Kleiber [13]. This element has zero thickness and it is shown in Fig. 2. The displacement at any point on the rigid-contact element of the sliding base, such as j can be written in the form of:

$$\{\delta\}_j = \begin{Bmatrix} u \\ v \\ w \end{Bmatrix}_j = \begin{Bmatrix} u_{xb} \\ u_{yb} \\ u_{zb} \end{Bmatrix} + \begin{bmatrix} 0 & 0 & -y \\ 0 & 0 & x \\ y & -x & 0 \end{bmatrix} \begin{Bmatrix} \theta_{xb} \\ \theta_{yb} \\ \theta_{zb} \end{Bmatrix} \tag{6}$$

where x and y are the coordinates of the point j in rigid-contact element with respect to CM of base deck. Eq. (7) can be re-written as:

$$\{\delta\}_j = \begin{Bmatrix} u \\ v \\ w \end{Bmatrix}_j = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & -y \\ 0 & 1 & 0 & 0 & 0 & x \\ 0 & 0 & 1 & y & -x & 0 \end{bmatrix} \begin{Bmatrix} u_{xb} \\ u_{yb} \\ u_{zb} \\ \theta_{xb} \\ \theta_{yb} \\ \theta_{zb} \end{Bmatrix} \tag{7}$$

$$= [N]\{U\}$$

In which $\{\delta\}_j$ is the vector of relative displacement of the rigid-contact element, $\{U\}$ is the vector of displacement at CM of base deck, and $[N]$ is the transformation matrix. In the rigid-contact element, the following relationship between traction acting on the sliding support and relative displacements can be written:

$$\{t\} = [D^{ep}]\{\delta\} \tag{8}$$

Vector $\{t\}$ is equal to $\{t_{s_1}\ t_{s_2}\ t_n\}^T$; the vector elements t_{s_1} and t_{s_2} are the shear tractions in the x- and y-directions, respectively, and t_n is the contact pressure. The matrix $[D^{ep}]$ could be written as:

$$[D^{ep}] = [D^e] - [D^p] \tag{9}$$

$[D^e]$ is the diagonal elasticity matrix; the diagonal elements are k_{s_1}, k_{s_2}, and k_n. k_{s_1} and k_{s_2} are the shear stiffness on the x- and y-directions, and k_n is the vertical stiffness at any point on the interface element. $[D^p]$ is the modification matrix and can be derived in the following form:

$$[D^p] = \frac{1}{H} \begin{bmatrix} H_{11} & H_{12} & H_{13} \\ & H_{22} & H_{23} \\ \text{sym} & & H_{33} \end{bmatrix} \tag{10a}$$

in which

$$\begin{aligned} H &= t_{s_1}^2 k_{s_1} + t_{s_2}^2 k_{s_2} + \mu^4 t_n^2 k_n \\ H_{11} &= t_{s_1}^2 k_{s_1}^2;\ H_{12} = t_{s_1} t_{s_2} k_{s_1} k_{s_2};\ H_{13} = t_{s_1} t_n \mu^2 k_{s_1} k_n \\ H_{22} &= t_{s_2}^2 k_{s_2}^2;\ H_{23} = t_{s_2} t_n \mu^2 k_{s_2} k_n;\ H_{33} = \mu^2 t_n^2 k_n^2 \end{aligned} \tag{10b}$$

Therefore, the stiffness matrix for the contact element is:

$$[k^e] = \int_A [N]^T [D^{ep}][N] \mathrm{d}A \tag{11}$$

The integration is carried out within the mapped unit square using 3×3 Gauss quadrature.

In this study, the non-linear behavior of rigid-contact element is characterized by slip taking place at the sliding surface. If the shear strength of the sliding surface is exceeded, irreversible slip occurs. Therefore, the yield function is:

$$F_s = t_s + \kappa \tag{12a}$$

in which

$$t_s = \sqrt{(t_{s_1}^2 + t_{s_2}^2)} \text{ and } \kappa = \mu t_n \tag{12b}$$

In which μ is the coefficient of friction. In this study, the yield function has been assumed as a circular interaction curve between the two orthogonal directions and vertical stress (t_n) is affected by the vertical component of the earthquake. When the stresses are on the yield function, k_{s_1} and k_{s_2} are assumed to be zero. For computation of stress increments because of ideal plasticity, where the yield surface form a meaningful limit, a proportional scaling of stresses (or radial return procedure) have been used to obtain stresses [12].

3. System dynamic equilibrium

The governing differential equations of motion for the whole system (structure and sliding support) can be stated in the matrix form as:

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + \{p(u)\} = -[M]\{\ddot{u}_g\} \tag{13}$$

In which $\{u\}$ is the vector of displacement for global system and it has 12 components (Fig. 1); $[M]$ is the lumped mass matrix of the global system; $[C]$ is the viscous damping matrix; $\{p(u)\}$ is the non-linear internal force vector, which is indicated as a function of the nodal parameters $\{u\}$. If the yield function in rigid-contact element is not violated, $\{p(u)\}$ will be equal to $[K]\{u\}$ in which $[K]$ is the whole stiffness matrix of the system (i.e. the stiffness matrix of the structure and rigid-contact elements). If the yield function in rigid contact element is violated, $\{p(u)\}$ is obtained by assembling the linear internal forces of structure elements and the non-linear internal forces of rigid-contact elements. The vector $\{\ddot{u}_g\}$ includes two horizontal components and the vertical component, i.e. $\{\ddot{u}_{gx} \;\; \ddot{u}_{gy} \;\; \ddot{u}_{gz}\}^T$.

The differential equation of motion (Eq. (13)) is solved in incremental form by employing the Newmark-β method assuming constant-average acceleration over a short time interval. In convergent process, the Newton–Raphson is used for solution of the non-linear problem. Also, an energy tolerance is used to terminate iteration if the convergence is achieved.

4. Numerical study and discussion

The performance of the pure-friction base-isolated asymmetric building subjected to three-component earthquake (vertical component included) and two-component earthquake (vertical component excluded) is investigated for a wide range of parametric studies (e_y/a, e_x/e_y, ω_θ/ω_x, T_x, T_y/T_x, T_z/T_x). T_x, T_y, and T_z are the uncoupled natural periods of the fixed base structure and are equal to $2\pi/\omega_x$, $2\pi/\omega_y$, and $2\pi/\omega_z$, respectively. The above parameters may be varied, by changing the stiffness properties of the structure and the torsional mass. The damping ratio of the system is assumed to be 5% of critical damping. The friction coefficient of the sliding support, $\mu = 0.1$ and the mass ratio m_b/m_s are taken as unity. In the sliding surface, shear and normal stiffness are assumed to have very high values during the non-sliding state. The parametric studies are carried out, by applying the 1994 Northridge earthquake records (Rinaldi receiving station). A small time interval, $\Delta t = 0.0002$ s, is employed for the computations. The convergence tolerance, $|E(i)|/|E(1)| = 1.0 \times 10^{-20}$, is taken for iteration. The maximum numbers of iteration in each time step are taken as 15. Responses are obtained for both sliding and fixed base asymmetric systems. The response quantities of interest are the response ratio R ($u_{rx} = u_x - u_{xb}$, $u_{ry} = u_y - u_{yb}$, $\theta_{rz} = \theta_z - \theta_{zb}$); the peak base displacements (u_{xb}, u_{yb}); and the torsion (θ_{zb}). The response ratio R is defined as the ratio of the peak response of the symmetric and asymmetric pure-friction base-isolated system relative to base mass to the peak response of the corresponding fixed base system. This ratio is an index of the performance of the asymmetric building with the sliding support.

The effect of vertical component of the earthquake excitation on the response of eccentrically pure-friction base-isolated system is presented in Fig. 3. In Fig. 3a the response ratio (R) for u_{rx}, u_{ry} and θ_{rz} versus e_y/a are shown for $T_x = 0.4$, $\omega_\theta/\omega_x = 1.0$, $e_x/e_y = 0$, $T_y/T_x = 1.0$ and $T_z/T_x = 0.5$. The variation of the response ratio R for u_{rx} of three-component earthquake in small eccentricity ratio is significantly higher than that of two-component earthquake. The same pattern of variation is observed for the response ratio R of u_{ry} in all the eccentricity ranges. The response ratio R for θ_{rz} of three-component earthquake is also considerably increased compared to the response ratio of the system subjected

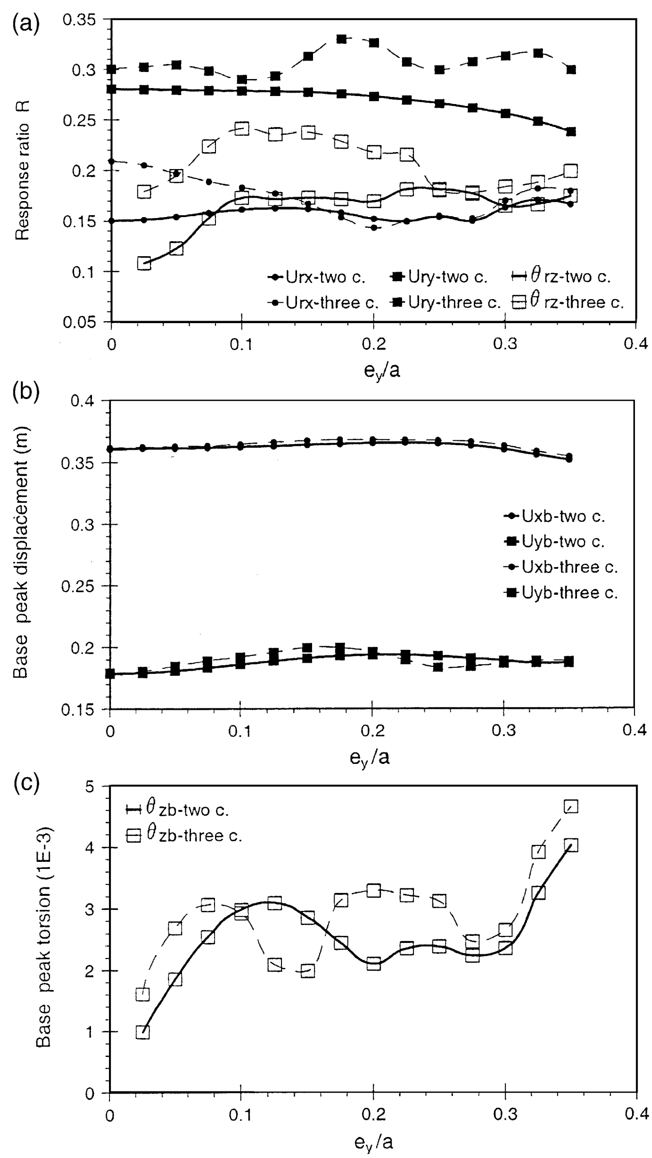


Fig. 3. Variations of response ratio R and peak base response versus e_y/a for system with $T_x = 0.4$, $\omega_\theta/\omega_x = 1.0$, $e_x/e_y = 0$, $T_y/T_x = 1.0$ and $T_z/T_x = 0.5$.

to two-component earthquake for $e_y/a < 0.20$. As the eccentricity ratio increases from this value, the response ratio R for θ_{rz} of three-component earthquake gets closer to the response ratio of two-component earthquake. This variation of the response indicates that the vertical component of earthquake considerably affects the torsional response ratio in moderate eccentricity (i.e. $e_y/a < 0.2$) and increases the torsional response ratio. This effect is reduced for high eccentricity values (i.e. $e_y/a > 0.2$). Fig. 3b and c show the variations of base peak displacement (u_{xb}, u_{yb}) and torsion (θ_{zb}) versus e_y/a with the same constant system parameters mentioned above. The variation of the response ratio of the system subjected to three- and two-component earthquake is almost the same on the entire range of eccentricity. It is interesting to note that the base peak torsion (θ_{zb}) is highly influenced by e_y/a ratio.

The ratio of uncoupled torsional frequency to uncoupled lateral frequency is an important parameter in the behavior of the asymmetric buildings; that is, highly influences the response of such systems [14]. In Fig. 4, variation of the response ratio (R) versus uncoupled torsional frequency to uncoupled lateral frequency ratio (ω_θ/ω_x) for $T_x = 0.4$, $e_y/a = 0.1$, $e_x/e_y = 0$, $T_y/T_x = 1.0$ and $T_z/T_x = 0.5$ is presented. When the system is subjected to two-component earthquake, the response ratio R for u_{rx} and u_{ry} increases mildly with the increase of the ratio of uncoupled torsional frequency to uncoupled lateral frequency. The response reaches its maximum for ω_θ/ω_x equal to unity and after that it shows reduction. For $\omega_\theta/\omega_x > 1.2$, the response ratio almost remain constant. The response ratio of the torsional displacement θ_{rz} increases mildly and then this ratio remains constant for $\omega_\theta/\omega_x > 1$. When the system is affected by three-component earthquake the pattern of variation of the response ratio R is completely different from the response ratio R of the system subjected to two-component earthquake. In other words, the response ratio for the above case is considerably increased and therefore, the effectiveness of sliding support base-isolated system is less pronounced. The maximum response ratio of u_{rx} and u_{ry} in this case are shifted to $\omega_\theta/\omega_x = 1.3$. The response ratio R for θ_{rz} of the system subjected to three-component earthquake increases sharply in the range of $0.4 < \omega_\theta/\omega_x < 0.8$ and reaches its maximum value in $\omega_\theta/\omega_x = 0.8$. The effect of vertical component on the response of base peak displacements remains insensitive for the ω_θ/ω_x ratios. In Fig. 4c, the variation of the base peak torsion, θ_{zb} is plotted versus the ω_θ/ω_x ratio leading to the maximum amplification at $\omega_\theta/\omega_x = 1$.

Fig. 5 presents the effect of fundamental period, T_x on the response of pure-friction base- isolated asymmetric buildings subjected to three- and two-component earthquake. The variation of response ratios, R versus T_x for $e_y/a = 0.1$, $\omega_\theta/\omega_x = 1.0$, $e_x/e_y = 0$, $T_y/T_x = 1.0$ and $T_z/T_x = 0.5$ is shown in Fig. 5a. The response ratio R for u_{rx}, u_{ry} and θ_{rz} for three- and two-component earthquake are nearly the same for all the values of T_x except in the range of $T_x < 0.5$. The pattern of variation of the response ratio decreases mildly up to T_x equal to 0.7, and then increases sharply with the increase of T_x. Fig. 5b and c show the variation of base peak displacement and torsion versus T_x, respectively. The base peak displacements, u_{xb} and u_{yb} for three- and two-component earthquake are nearly the same. The variations of base peak torsion, θ_{zb} for all the selected values of T_x for three- and two-component earthquake is also almost the same. It is worth noting that the base peak torsion for both cases increase mildly up to T_x equal to 1.0 and then it increases sharply, especially in the range of $1.0 < T_x < 1.5$.

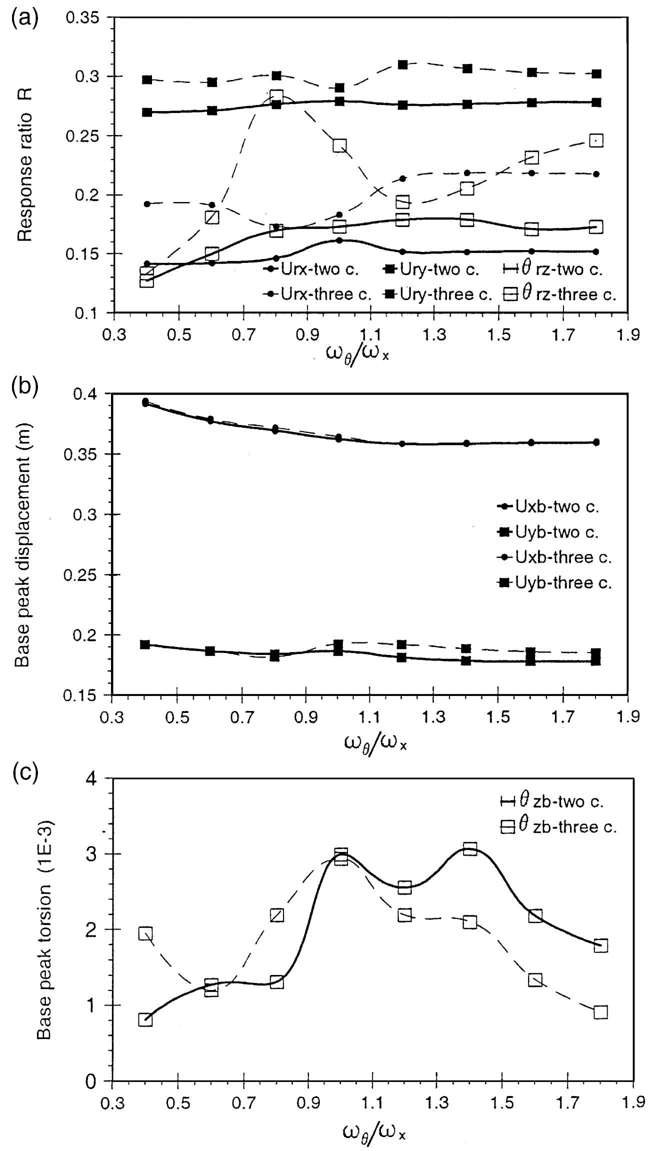


Fig. 4. Variations of response ratio R and peak base response versus ω_θ/ω_x for system with $T_x = 0.4$, $e_y/a = 0.1$, $e_x/e_y = 0$, $T_y/T_x = 1.0$ and $T_z/T_x = 0.5$.

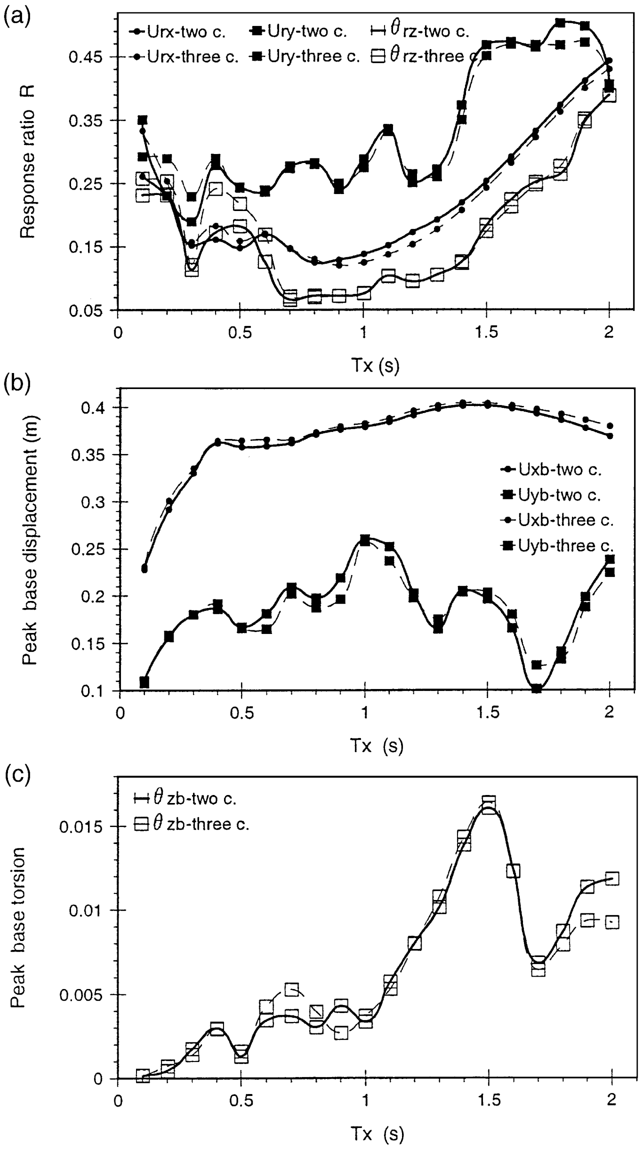


Fig. 5. Variations of response ratio R and peak base response versus T_x for system with $e_y/a = 0.1$, $\omega_\theta/\omega_x = 1.0$, $e_x/e_y = 0$, $T_y/T_x = 1.0$ and $T_z/T_x = 0.5$.

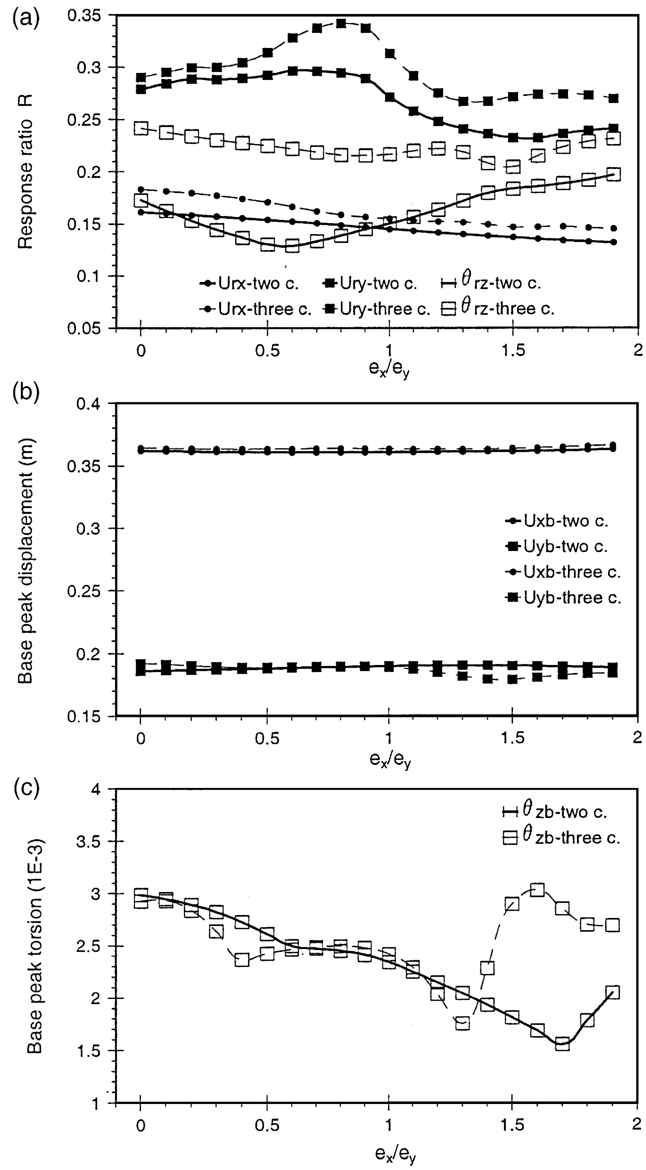


Fig. 6. Variations of response ratio R and peak base response versus e_x/e_y for system with $T_x = 0.4$, $e_y/a = 0.1$, $\omega_\theta/\omega_x = 1.0$, $T_y/T_x = 1.0$ and $T_z/T_x = 0.5$.

In order to evaluate the effect of two-way eccentricity ratio (e_x/e_y) on the response of pure-friction base-isolated asymmetric system subjected to three- and two-component earthquake Fig. 6 is presented. The variation of response ratio R for u_{rx}, u_{ry} and θ_{rz} versus e_x/e_y for $T_x = 0.4$, $e_y/a = 0.1$, $\omega_\theta/\omega_x = 1.0$, $T_y/T_x = 1.0$ and $T_z/T_x = 0.5$ is shown in Fig. 6a. As this figure shows, the variation of response ratio R for u_{rx}, u_{ry} and θ_{rz} in all ranges of e_x/e_y is not considerably influenced. However, the vertical component of earthquake highly influences the response ratio R for u_{rx}, u_{ry} and θ_{rz}. The influence is more significant for $e_x/e_y < 1$. The variation of the base peak displacement, u_{rx}, u_{ry} and θ_{rz} of the two-way eccentric pure-friction base-isolated system for two- and three-component earthquake are shown in Fig. 6b. The figure indicates that the base peak displacement for three- and two-component earthquake in the entire values of e_x/e_y is nearly the same. The variation of the base peak torsion, θ_{zb} versus e_x/e_y for three- and two-component earthquake is presented in the Fig. 6c. The vertical component of earthquake significantly affects the response ratio, especially for $e_x/e_y > 1.4$.

Fig. 7 presents the effect of lateral periods ratio (T_y/T_x) on the response of pure-friction base-isolated asymmetric system subjected to three- and two-component earthquake. Fig. 7a shows the variation of response ratio R for u_{rx}, u_{ry} and θ_{rz} versus T_y/T_x for $T_x = 0.4$, $e_y/a = 0.1$, $e_x/e_y = 0$, $\omega_\theta/\omega_x = 1.0$, and $T_z/T_x = 0.5$. For two-component earthquake, the response ratio R for u_{rx} increases fluctuationally with increases in T_y/T_x ratio.

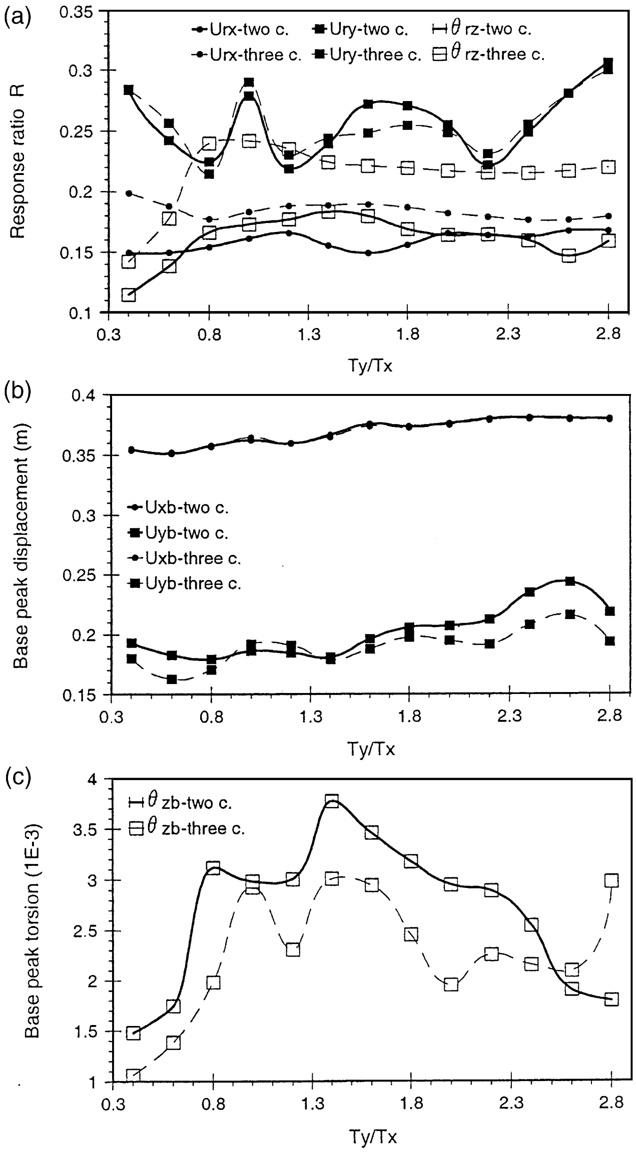


Fig. 7. Variations of response ratio R and peak base response versus T_y/T_x for system with $T_x = 0.4$, $e_y/a = 0.1$, $\omega_\theta/\omega_x = 1.0$, $e_x/e_y = 0$ and $T_z/T_x = 0.5$.

The response ratio R for u_{ry} does not show the consistent pattern of variation over the T_y/T_x. The response ratio for θ_{rz} highly increases for $T_y/T_x < 0.8$ and then it almost remains constant throughout the T_y/T_x ratio. For three-component earthquake, the response ratio R for u_{rx} and θ_{rz} is considerably increased and the response ratio R of u_{ry} is increased in the majority of lateral period ratio. Therefore, this influence must be taken into account in designing such system. Otherwise, the effectiveness of the pure-friction systems will be underestimated. In Fig. 7b, variation of the base peak displacements u_{xb} and u_{yb} versus T_y/T_x for the same constant parameters are plotted. Here, the base peak displacements are almost the same in both cases and they increase mildly with variation of T_y/T_x ratio. But the base peak torsion θ_{zb} increases with the increase of T_y/T_x ratio and reaches its maximum in $T_y/T_x = 1.4$, after that it decrease. By considering the vertical component response ratio R of θ_{zb} decreases for $T_y/T_x < 2.5$ and it increases for the other values of T_y/T_x as considered in this study.

Fig. 8 is plotted to show the effect of vertical to lateral period ratio (T_z/T_x) on the response of pure-friction base-isolated asymmetric building subjected to three- and two-component earthquake. Fig. 8a shows the variation of responses ratio, R for u_{rx}, u_{ry} and θ_{rz} versus T_z/T_x for $T_x = 0.4$, $e_y/a = 0.1$, $e_x/e_y = 0$, $\omega_\theta/\omega_x = 1.0$, and $T_y/T_x = 1.0$. Without considering the vertical component of earthquake the ratio of response for all the values of T_z/T_x are almost constant. But, while considering the

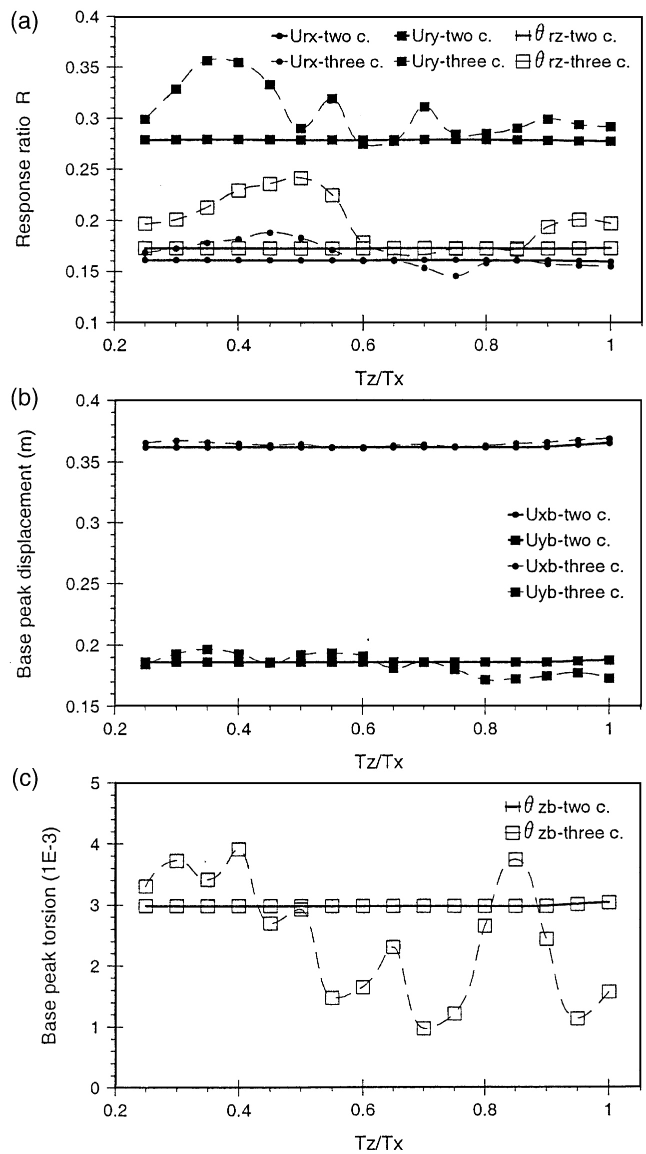


Fig. 8. Variations of response ratio R and peak base response versus T_z/T_x for system with $T_x = 0.4$, $e_y/a = 0.1$, $\omega_\theta/\omega_x = 1.0$, $e_x/e_y = 0$ and $T_y/T_x = 1.0$.

vertical components the response ratio for all the values of T_z/T_x are considerably varied. The response ratio R for u_{rx} increases for $0.25 < T_z/T_x < 0.6$ and decreases $T_z/T_x > 0.6$. The response ratio R for u_{ry} for all the values of T_z/T_x are almost greater in case of three-component earthquake, compared to two-component earthquake. The response ratio R for θ_{rz} are greater in case of three-component, compared to two-component earthquake for all other the values of T_z/T_x ratios, except in the range of $0.6 < T_z/T_x < 0.85$. In Fig. 8b, the base peak displacements, u_{xb} and u_{yb} versus T_z/T_x ratios are plotted. The variation of the response ratio for u_{xb} and u_{yb} are not considerable on T_z/T_x ratio. In Fig. 8c, the base peak torsion, θ_{zb} versus T_z/T_x is plotted. As it can be seen from the figure, the variations of base peak torsion are highly influenced with the variation of the T_z/T_x ratios.

5. Conclusion

The effect of the vertical component of the earthquake on an idealized three-dimensional single-storey asymmetric building supported on the pure-friction base-isolated system subjected to three-component (including vertical component) and two-component (excluding vertical component) Northridge 1994 earthquake record is presented. The performance of this system is compared with the fixed base asymmetric building for a set of important structural parameters. From the trend of the results, the following conclusions may be drawn.

The effectiveness of asymmetric building resting on pure-friction base-isolated system subjected to three-component earthquake may be less than that of the corresponding system subjected to two-component earthquake. This is due to the fact that the vertical component of the earthquake highly influences the lateral response of the pure-friction base-isolated asymmetric system.

The torsional response of the structure in the moderate range of eccentricities (i.e. $e_y/a < 0.2$) increases considerably when the system subjected to the three-component earthquake compared to the system subjected to two-component earthquake. This illustrates the effect of the vertical component of earthquake on the torsional response of the asymmetric building with low and moderate range of eccentricities.

The base displacements of the system subjected to two- and three-component earthquake are less sensitive to the parametric variations. However, the base torsion of the system is highly influenced by the vertical component of earthquake as well as the system parameters.

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