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# Evaluation of soil-structure intreraction effects on the non-stationary random seismic response of vertically mass irregular steel buildings

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*Abstract*—**In this paper, the effects of soil-structure interaction is evaluated in seismic response of non-geometric vertically irregular steel buildings. Non-uniform distribution of mass along the height of a 10 story steel frame building with fully restrained moment connections is investigated in the framework of random analysis. Frequency-independent spring and dashpot set in parallel was used to involve soil-structure interaction effects in the analysis procedure. The results are compared in form of the maximum mean square value of story drift response. It is observed that foundation flexibility varies demand distribution through structure height. Depend on the position of heavier stories, the maximum mean square value of story drifts change, as well. Compare to the regular structure, mass irregularity through the bottom half stories of structure has the maximum demand difference in case of fixed base model. Among the flexible base structures, mass irregularity of the 5th floor has the maximum increase of drift demands up to 23%.**

*Keywords*—**Mass irregularity,Non-stationary random ground motion, Soil-structure interaction, Seismic response, Steel shear buildings**

## I. Introduction

Soil–structure interaction (SSI) is one of the major subjects in earthquake engineering domain that has been paid comprehensive attention in recent years [1-6]. It concerns the coupled system of structure and soil. The predominant effects of SSI are period modification, hysteretic energy dissipation and input motion variations. The SSI model is more flexible than the commonly assumed fixed-base systems that have a longer natural period than the fixed-base structure. Due to the radiation damping in the soil, the SSI model usually has a higher damping ratio, which can drastically influence the response of the structure [7].

After1985 Mexico earthquake, researchers focus on the effects of SSI on seismic behavior of irregular systems [8, 9] . Perfect regularity is an idealization that rarely occurs in constructions and irregular configurations are almost happened in real structures.

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Generally, vertically irregular buildings are more vulnerable to earthquake hazards compare to the buildings with regular configuration [10-13]. Variation of mass, stiffness and strength through the structure height makes non-geometric vertical irregularity in structures. Usually, construction of buildings with different story usage, impose mass irregularity to the system. Through recent researches, it was observed that the amount and position of heavier stories play an important role in seismic performance of mass irregular buildings [10, 11, 14]. Meanwhile, low attention has been attributed to the effects of SSI on seismic response of these types of irregular structures.

In this paper, the seismic performance of vertically mass irregular steel buildings is evaluated through non-stationary random vibration analysis. The SSI effects are also considered by using frequency independent spring-dashpot set in parallel. The position of irregular stories was varied through the bottom half floors. Four different irregular models was evaluated with both the fixed and flexible bases.The results are given in form of the maximum mean square value of story drift at each story level.

## II. Numerical model and equations of motion

In this paper, the superstructure was considered as a 3D steel shear building with 10 stories, resting on an elastic homogeneous half-space. The floor to floor story height was considered 3m. The floor systems were assumed to be rigid in their own planes and inextensible columns are supporting the 5x5m rigid floor decks. Similar to the common residential building of Iran, gravity loads were supposed 7.0kN/m$^2$ and 2.0kN/m$^2$ for dead and live loads, respectively[15]. The efficiency of frame elements was controlled by the earliest seismic design code of Iran [16, 17]. The mass irregularity through structure height was limited to the level of 200%, compare to the regular structure.

The equation of motion for the whole system is given as:

$$[M]\{\ddot{v}(t)\}+[C]\{\dot{v}(t)\}+[K]\{v(t)\}=\{P(t)\} \tag{1}$$

where, $M, C, K$ are mass, damping and stiffness matrix, respectively. For interaction forces, frequency independent spring-dashpot set in parallel was considered at foundation level [18]. Considering a circular footing with radius of $r_0$, resting on a linear half-space with shear wave velocity of $V_s$, Poisson's ration of $\upsilon$ and mass density of $\rho$ ,the frequency independent spring coefficients for transitional (T), vertical (V) and rotational (R) vibration of the system are expressed as[19]:

$$k_T = \frac{32(1-\upsilon)}{7-8\upsilon} G r_0 \; ; \; k_Z = \frac{16}{3} G r_0^3 \; ; \; k_R = \frac{8}{3(1-\upsilon)} G r_0^3 \qquad (2)$$

where, $G$ is the shear the modulus of soil:

$$G = V_s^2 \rho \qquad (3)$$

In this paper, the shear wave velocity and the mass density of soil were considered 200m/s and 1900Kg/m$^3$, respectively. The radius of circular footing considered 4m, as well.For frequency independent damping coefficients, the following relations are given:

$$C_T = 2D_T \sqrt{K_T M_T} \; ; \; C_Z = 2D_Z \sqrt{K_Z I_Z} \; ; C_R = 2D_R \sqrt{K_R I_R} \qquad (4)$$

where $M_T$ is transitional mass and $I_Z$ is polar moment of inertia and $I_R$ is moment of inertia for rocking of the rigid body and

$$D_T = \frac{0.288}{\sqrt{\frac{(7-8\upsilon)M_T}{32(1-\upsilon)\rho r_0^3}}} \; ; \; D_Z = \frac{0.5}{1+2\frac{I_Z}{\rho r_0^5}}$$
$$D_R = \frac{0.15}{\left(1+\frac{3(1-\upsilon)I_R}{8\rho r_0^5}\right)\sqrt{\frac{3(1-\upsilon)I_R}{8\rho r_0^5}}} \qquad (5)$$

Note that for the superstructure, 3 DOF namely, two lateral translations and a rotation about the vertical axis, were considered per floor. Also, 5 degrees of freedom due to interaction forces at foundation level is added to the equations of motion. The fundamental period of the fixed and flexible base structures are 1.07sec and 1.28sec, respectively. Fig. 1 represents the idealized SSI model of structure.

In Eq.1, $\{P(t)\}$ is the external dynamic load. For earthquake ground motion:

$$\{P(t)\} = -[M]\{R\}\ddot{x}_g(t) \qquad (6)$$

where $\{R\}$ is the index vector of the inertial forces. Through random analysis procedure, the ground motion acceleration $\ddot{x}_g(t)$ is assumed to be the uniformly modulated non-stationary random process:

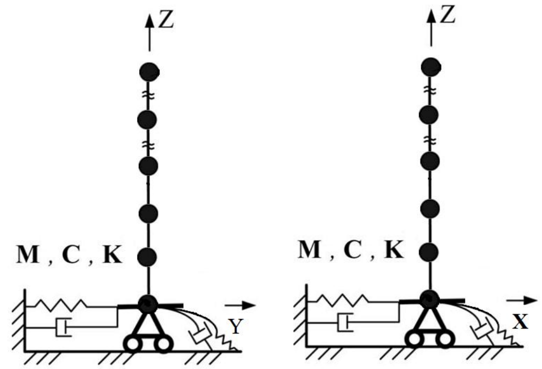


Figure 1. Structural model

$$\ddot{x}_g(t) = A(t) f(t) \qquad (7)$$

where $A(t)$ is a given deterministic modulation function of the input acceleration, and $f(t)$ is a zero-mean-valued stationary random Gaussian process. In this paper, the envelop function is considered as [20, 21]:

$$A(t) = \exp(-0.13t) - \exp(-0.45t) \qquad (8)$$

The time-dependent power spectral density (PSD) matrix of the displacement response can be obtained by performing a Fourier transformation of the correlation function matrix $[R_v(t,\tau)]$:

$$\begin{aligned}[S_v(t,\omega)] &= \frac{1}{2\pi}\int_{-\infty}^{\infty}[R_v(t,\tau)]e^{-i\omega\tau}d\tau \\ &= [\Phi][H(\omega)][\Phi]^T[M]\{R\}A(t_1)[S_f(\omega)]\times \\ &\quad A(t_2)\{R\}^T[M]^T[\Phi][H^*(\omega)][\Phi]^T\end{aligned} \qquad (9)$$

where, $[H(\omega)]$ and $[H^*(\omega)]$ are diagonal frequency response and the complex conjugate function matrix of the structure :

$$H_{n,n}(\omega) = \frac{1}{\omega_n^2 - \omega^2 + i2\zeta_n\omega_n\omega} \qquad (10)$$

$[S_f(\omega)]$ is the power spectral density matrix of stationary random Gaussian process. In this paper, the modified version of Kanai-Tajimi model was adopted for describing ground motion acceleration [22, 23]. The mean square matrix of displacement could be obtained by integrating the PSD matrix of the displacement response within the frequency domain:

$$
\begin{aligned}
E\left[v^2\right] &= E\left[\{v(t)\}\{v(t)\}^T\right] \\
&= \int_0^\infty \left[S_v(t,\omega)\right] d\omega \\
&= [\Phi]\left[\int_0^\infty \left[H(\omega)\right][\Phi]^T [M]\{R\} A(t_1)\left[S_f(\omega)\right] \times \right. \\
&\qquad \left. A(t_2)\{R\}^T [M]^T [\Phi]\left[H^*(\omega)\right] d\omega \right][\Phi]^T
\end{aligned}
\tag{11}
$$

So, the mean square value of story drifts is given as:

$$E\left[\Delta_i^2\right] = E\left[\left(v_i(t) - v_{i-1}(t)\right)^2\right] \tag{12}$$

## III. Results and dissection

The maximum mean square value of story drift response at each story level was plotted for both flexible and fixed base structures (Fig.2 to 6). In case of regular structure (Fig.2), it is observed that the maximum drift demand is concentrated at the upper half of the fixed base structure (actually at the 7th story). Meanwhile, for the flexible base model of regular structure, maximum demand is potentially concentrated at the 4th story. So, in contrast to the fixed base structure, SSI varied demand distribution through the structure height as well as it increases the maximum drift demands up to 60%.

Compare to the regular structure, increase of story mass at the 1st floor has no significant effect on the drift demand variations (Fig.3). For both the fixed and flexible base models, the variation of maximum mean square value of story drifts is limited to 2%. In comparison to the same fixed base irregular model, the SSI increases the maximum drift demands up to 55%.

Compare to the fixed base model with the same irregularity, the mass irregularity of the 3rd floor increases the maximum drift demand of the SSI model up to 100%. The position of critical drift demand is the same as the regular structure for both the fixed and flexible base models. Variation of the maximum mean square value of story drifts is low for fixed base model (up to 2%), however, irregularity caused an increase of 23% in drift demands of the SSI model, compare to the regular structure.

Concentration of the drift demands is high through the middle part of the fixed base model of mass irregularity at the 5th floor. Compare to the regular structure, mass irregularity increases the maximum mean square value of drift demands up to 70% as well. The maximum difference between the drift demands of the SSI and fixed base models is up to 11%. However, 6% demand reduction is observed for the SSI model, compare to the SSI model of the regular structure.

Mass irregularity through the bottom half stories (stories 1 through 5) increases drift demands of the fixed base model. Compare to the regular structure, the maximum mean square value of drift demand at the 7th floor has been increased up to 85%. In comparison to the same regular structure, the maximum demand variation of the SSI model limited to 6%. The maximum drift demand of the fixed and flexible base structures shows that the SSI varies the maximum demands up to 10% in this case of irregularity.

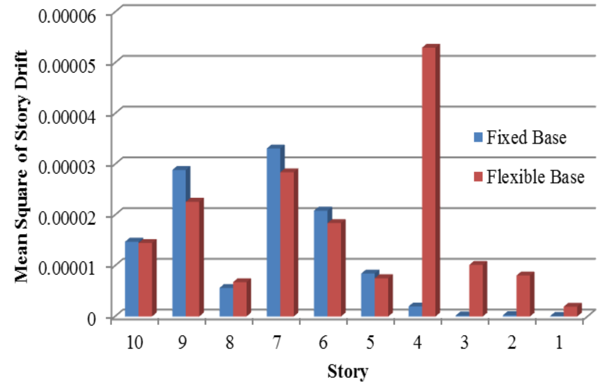


Figure 2. The maximum mean square value of story drift for regular structure

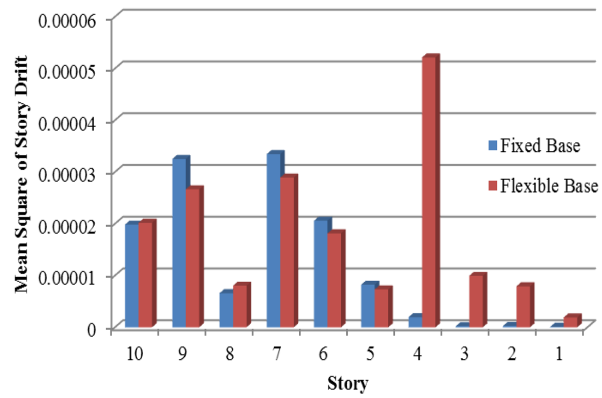


Figure 3. The maximum mean square value of story drift for mass irregularity at the 1st floor

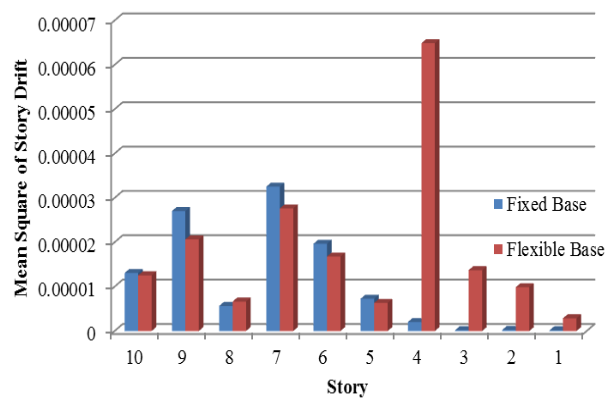


Figure 4. The maximum mean square value of story drift for mass irregularity at the 3rd floor

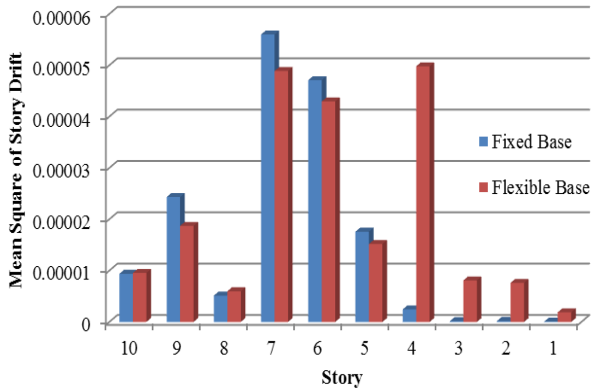


Figure 5. The maximum mean square value of story drift for mass irregularity at the 5th floor

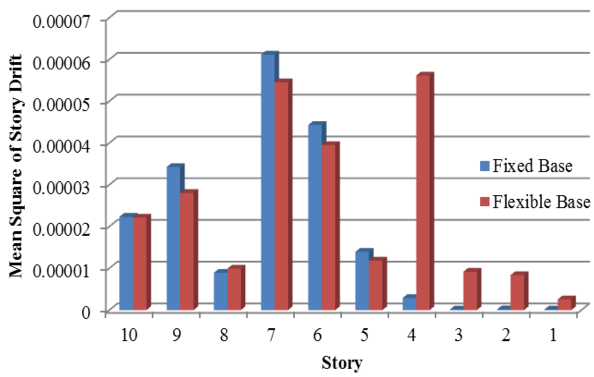


Figure 6. The maximum mean square value of story drift for mass irregularity through 1st to the 5th floors

## IV. Conclusion

In this paper, the effect of soil-structure interaction was evaluated in seismic response of vertically mass irregular buildings. The non-stationary random seismic response of a 10 story steel structure was evaluated for both the flexible and fixed base models. Comparison of the results was performed by evaluating the mean square value of drift demands through the structure height.

It is observed that for the fixed base structures, drift demands are more concentrated through the upper half of structure and foundation flexibility increases the demands through the middle and lower floors. The maximum demand difference between the same irregular fixed and flexible base structures is observed in case of mass irregularity at the 3rd floor. In this case, 23% increase of the mean square value of story drifts represents the highest demand variation among the SSI models. Demand variations are high for the irregular fixed base structures that, 85% increase of the maximum mean square value of story drifts is reported in case of mass irregularity though the 1st and 5th stories. Compare to the regular structure, the lowest demand variation is observed in case of mass irregularity at the 1st floor for both the fixed and flexible base models.

Generally, foundation flexibility varies the amount and distribution of demands through structure height. Depend on the position of the heavier stories, the mean square value of the drift demands varied but, in comparison to the regular structure, as the irregularity location is altered through the structure height, the position of the maximum demand does not significantly change.

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