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Research Article

Shock Response Analysis of Soil-structure Systems under Seismic Environment

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Abstract: Shock response analysis of the soil-structure systems induced by near-fault pulses is investigated. Vibration transmissibility of the soil-structure systems is evaluated by Shock Response Spectra (SRS). Medium-to-high rise buildings with different aspect ratios located on different soil types as well as different foundations with respect to vertical load bearing safety factors are studied. Two types of mathematical near-fault pulses, i.e., forward directivity and fling step, with different pulse periods as well as pulse amplitudes are selected as incident ground shock. Linear versus nonlinear Soil-Structure Interaction (SSI) condition are considered alternatively and the corresponding results are compared. The results show that nonlinear SSI is likely to amplify the acceleration responses when subjected to long-period incident pulses with normalized period exceeding a threshold. It is also shown that this threshold correlates with soil type, so that increased shear-wave velocity of the underlying soil makes the threshold period decrease.

Keywords: Ground shock, rocking isolation, soil-structure interaction, shock response spectrum

INTRODUCTION

Shock and vibration isolation reduces the excitation transmitted to systems requiring protection. An example is the insertion of isolators between equipment and foundations supporting the equipment. The isolators act to reduce effects of support motion on the equipment and to reduce effects of force transmitted by the equipment to the supporting structure. Isolators act by deflecting and storing energy at resonant frequencies of the isolation system, thereby decreasing force levels transmitted at higher frequencies. The dampers act by dissipating energy to reduce the amplification of forces that occur at resonance (Piersol and Paez, 2010).

The principal idea in base isolation is to reduce the seismic responses by inserting low-stiffness, high-damping components between the foundation and the structure (Skinner *et al*., 1993). This way, the natural period and damping of the structure will be increased, which can reduce the responses of the superstructure, especially inter-story drifts and floor accelerations (Naeim and Kelly, 1999). Alternatively, base displacements in those systems, especially under near-fault ground motions, are increased (Hall *et al*., 1995). The first concerns about this issue were arisen after 1992 Landers and then 1994 Northridge earthquakes, where long-period pulse-type ground motions were observed in near-fault records. Evidence show that earthquake records in near-field regions may have large energy in low frequencies and can cause drastic responses in base isolated structures (Heaton *et al*., 1995).

Past studies in the literature reveal that nonlinear Soil-Structure Interaction (SSI) including foundation uplift and soil yield can exhibit base isolating effects due to hysteretic damping of the underlying soil. These effects can be significant during strong ground motions when the superstructure is mounted on a shallow foundation with sufficiently low static vertical load bearing safety factor (Anastasopoulos *et al*., 2010). On the other hand, geometry of the superstructure should also enable the rocking motions of the foundation to emerge as a remarkable mode of vibration in seismic performance of the soil-structure system. In such condition, the so-called inverted-pendulum structures (Housner, 1963) can benefit from energy absorbing capacity of the underlying soil namely rocking isolation. This context motivated Koh and Hsiung (1991a, b) to study base isolation benefits of 3D rocking and uplift. In their studies, three-dimensional cylindrical rigid block rested on a Winkler foundation of independent springs and dashpots were examined. They compared response of the model under earthquake-like excitations when the foundation was allowed to uplift versus no-uplift condition. It was concluded that restricting uplift can introduce higher stresses and accelerations inside the structure.

The aim of this study is shock response analysis of the soil-structure systems induced by near-fault pulses.

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Vibration transmissibility of the soil-structure systems is evaluated using Shock Response Spectra (SRS). An in-depth parametric study is conducted. Medium-to-high rise buildings with different aspect ratios as well as foundations with different safety factors located on different soil types are studied. Two types of near-fault ground shocks with different pulse periods as well as pulse amplitudes are selected as input excitation. Linear versus nonlinear SSI condition are considered alternatively and the corresponding results are compared.

NUMERICAL MODEL

The soil-structure system modeled in this study consists of multi-story building structures based on surface mat foundation located on soil medium. Numerical model subjected to near-fault ground shocks is schematically illustrated in Fig. 1.

Superstructure: Shear building models are most commonly used in research studies on seismically isolated buildings. To this aim, a generic simplified model is created to represent a class of structural systems with a given natural period and distribution of stiffness over the height (Alhan and Sürmeli, 2011). In this study, the superstructure is a shear building regular in plan and height. Dead and live loads according to ASCE/SEI 7-10 (2010) are assumed 600 and 200 kg/m^2, respectively. Medium-to-high-rise buildings with 10, 15 and 20 stories and story height of 3.0 m are modeled. First-mode natural periods of fixed-base structure are 1.0, 1.5 and 2.0 *s* for 10-, 15- and 20- story buildings, respectively which are consistent with approximate fundamental period formulas introduced in ASCE7-10. Open SEES software (Fenves *et al*., 2004) is used to perform the nonlinear dynamic analyses. Rayleigh damping of the superstructure is equal to 5% of critical damping. The superstructure elements are assumed with no ductility and P-Delta effect is included.

Interacting system: The interacting system called substructure consists of soil-foundation ensemble which induces base-isolating effects to the structure. The square mat foundation with thickness of 1.0, 1.5 and 2.0 m are considered for 10-, 15- and 20-story buildings, respectively. Brick elements are used to model the foundation. Dimensions of the foundation plan are designed according to vertical load bearing capacity of soil medium. Rigid foundation with no embedment is considered in this study.

Four types of soil media with a wide range of shear-wave velocity (V_s) are considered representing soft to very dense soil in accordance with site classification introduced in ASCE7-10. The soil is considered as a homogenous half–space medium and is not modeled directly in this study. Simplified models are used to include substructure effects such as soil flexibility, radiation damping, foundation uplift and soil yield.

The horizontal (sway) impedance of the foundation is based on Cone model formulas (Wolf and Deeks, 2004). However, in vertical and rocking directions, the foundation area is assumed to be rested on a set of distributed nonlinear vertical springs in accordance with so-called subdisk method recommended by Wolf (1994). To include the foundation uplift and soil yield phenomena, the vertical nonlinear elastic-perfectly plastic gap material is assigned to the vertical springs. The interacting systems corresponding to linear as well as nonlinear SSI condition are schematically illustrated in Fig. 2.

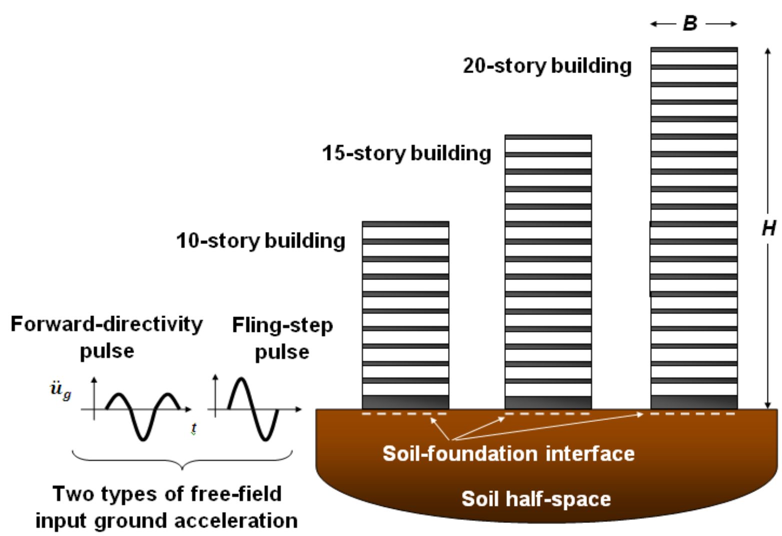

Fig. 1: Soil-structure systems subjected to near-fault ground shocks

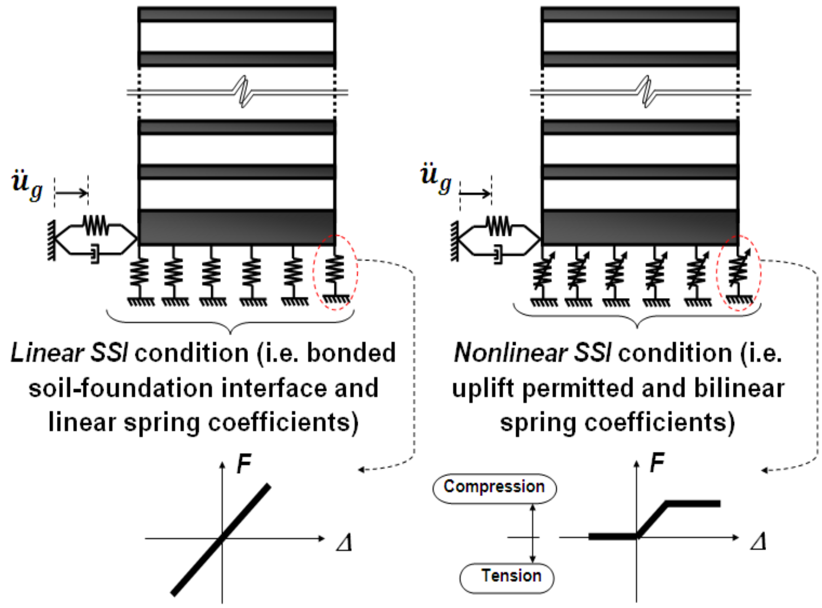

Fig. 2: Two alternative interacting systems including linear versus nonlinear SSI condition

MATHEMATICAL NEAR-FAULT PULSES

Sinusoidal functions of fling step and forward directivity type of near-fault ground motions are used in this study (Sasani and Bertero, 2000; Kalkan and Kunnath, 2006). The acceleration time history of fling-step and forward-directivity pulses is presented in the following.

Fling-step pulse:

$$a(t) = \frac{2\pi D}{\tau^2}\sin\left[\frac{2\pi}{\tau}(t - T_i)\right]; \quad t \in (T_i, T_i + \tau) \tag{1}$$

Forward-directivity pulse:

$$a(t) = \begin{cases} \dfrac{2\pi D}{\tau^2}\sin\left[\dfrac{2\pi}{\tau}(t - T_i)\right] \quad ; \\ \qquad t \in (T_i + 0.5\tau, T_i + \tau) \\ \dfrac{\pi D}{\tau^2}\sin\left[\dfrac{2\pi}{\tau}(t - T_i)\right] \quad ; \\ \qquad t \in [T_i, T_i + 0.5\tau] \cup [T_i + \tau, T_i + 1.5\tau] \end{cases} \tag{2}$$

where, D denotes the maximum amplitude of the ground displacement derived by double time integration of ground acceleration, $a(t)$ and then τ and T_i denote pulse period and pulse arrival time, respectively.

In this study, normalized period is defined as pulse-to-fixed-base structure period ratio (τ/T). This dimensionless parameter is assumed within 0.5 to 2.5. Recent studies postulate that within this range, salient properties of structural response subjected to real near-field ground motions can be predicted with reasonable approximation (Alavi and Krawinkler, 2004; Sehhati *et al*., 2011). Moreover, intensity of the idealized ground motions is assumed to vary from moderate to very strong. For this purpose, Peak Ground Velocity (PGV) varies from 20 to 220 cm/s. In this study, unidirectional excitation is exerted to the base when the simplified pulse models of fling step and forward directivity are used.

PARAMETRIC STUDY

The parametric study in this study involves different dimensionless quantities to represent various geometric and dynamic properties of the superstructure and the underlying soil, as well. These non-dimensional parameters are presented the following:

$$a_0 = \frac{\omega_{fix} H}{V_s} \tag{3}$$

$$SR = \frac{H}{B} \tag{4}$$

where, a_0, ω_{fix}, H, V_s, SR and B stand for non-dimensional frequency, circular frequency of the fixed-base structure, superstructure height, shear-wave velocity of soil, slenderness ratio and width of the superstructure, in the same order. Dimensionless frequency parameter, a_0, is introduced as an index for the structure-to-soil stiffness ratio (Veletsos, 1997; Wolf, 1985). In this study, this parameter is assumed 0.25, 0.5, 1 and 2 to cover different levels of soil flexibility. According to (3), the a_0 equal to 0.25, 0.5, 1.0 and 2.0 is corresponding to shear-wave velocity of soil 754, 377, 188 and 94 *m/s*, respectively.

Regarding to (4), SR parameter stands for slenderness of the superstructure. In this study, low-, as well as high-aspect ratio structures are represented by SR of 2 and 4, respectively. Besides, with regard to nonlinear SSI incorporated in this parametric study, the following non-dimensional parameter is also considered:

$$F_S = \frac{N_{uo}}{N_u} \tag{5}$$

where, N_{uo}, N_u and F_S denote the soil bearing capacity under purely vertical static loading, the vertical applied load and factor of safety against vertical load bearing of the foundation, respectively. F_S is set equal to 1.2, 1.85 and 2.5 to represent severely-loaded, rather heavily-loaded and rather lightly-loaded foundations, respectively (Gazetas *et al*., 2013).

For shock response analysis of the soil-structure system, maximum response acceleration at a given i^{th} story (MRA_i) is defined as time-domain extreme value of absolute response acceleration of the i^{th} floor. Peak value of MRA_i along height of the structure is defined as *PMRA*. This index is compared in two alternative linear as well as nonlinear SSI condition as introduced in Fig. 2. In second case, foundation uplift and soil yield is permitted during dynamic time-history analyses. Comparison of the two SSI condition reveals rocking isolation effects of foundation uplift and soil yield on controlling accelerations transmitted to the superstructure when subjected to near-fault ground shocks. To quantify the rocking isolations effects of nonlinear SSI on controlling transmitted accelerations, the following index is defined:

$$q_{accel} = \frac{PMRA^{(NLSSI)}}{PMRA^{(LSSI)}} \tag{6}$$

where, q_{accel} denotes maximum response acceleration ratio which is equal to *PMRA* at nonlinear SSI condition, $PMRA^{(NLSSI)}$ divided by the same value at linear SSI condition, $PMRA^{(LSSI)}$.

SHOCK RESPONSE SPECTRUM (SRS) OF THE SOIL–STRUCTURE SYSTEMS

Vibration transmissibility of the soil-structure systems is evaluated in this section using shock response spectrum. As illustrated in Fig. 3 and 4, the ordinate of each SRS curve represents the q_{accel} ratio as introduced in (6). The abscissa τ/T of the SRS represents the ratio of the excitation pulse duration τ to the natural period T of the rocking isolation (or natural period of rocking response of the foundation). Almost 16000 time history analyses are performed in this study. Accordingly, the SRS pairs with continuous and dash lines in Fig. 3 and 4 represent mean and standard deviation (σ) of the primary SRS curves ensemble, respectively. The SRS pairs are plotted with respect to different incident pulse periods τ to show the effect of shock intensity.

In Fig. 3 the effect of soil type on vibration transmissibility of the soil-structure systems is investigated through comparing SRSs for different values of a_0, (3). The results show that nonlinear SSI is likely to amplify the acceleration responses when subjected to long-period incident pulses with normalized period τ/T exceeding a threshold. It is shown that this threshold τ/T correlates with soil type. In more precise words, when a_0 decreases (i.e., at more dense sites) the threshold τ/T moves to left as displayed in Fig. 3. For instance, the incident pulse with normalized period greater than the threshold, $\tau/T \geq 1.25$, leads to response amplification in a 10-story building located on very dense site (a_0 = 0.25). On the other hand, comparing individual SRS curves on each graph of Fig. 3 reveals that increasing the ground shock intensity results in steeper slope of SRS. This fact shows that nonlinear SSI is more activated subject to incident pulses with greater amplitudes.

In Fig. 4 the effect of incident pulse type on vibration transmissibility of the soil-structure systems is examined through comparing SRSs of forward directivity versus fling step pulses. The results show that long-period forward directivity pulses can result in significant response amplification, especially when the pulse amplitude intensifies. In contrast, nonlinear SSI subject to short-period forward directivity pulses with high amplitudes can reduce the acceleration responses down to almost 50% for the 15-story building as presented in Fig. 4. In addition, the two graphs of Fig. 4 depict that vibration transmissibility of nonlinear SSI is more period-dependent subject to forward directivity pulses compared to fling step ground shock.

The effect of building height on vibration transmissibility of the soil-structure systems is investigated through comparing SRSs for different number of stories in Fig. 5. It is shown that this threshold τ/T beyond which the acceleration responses are amplified, correlates with building height. To restate, when number of stories of the building increases, the threshold τ/T moves to left as displayed in Fig. 5. This fact reveals that more high-rise buildings subjected to near-fault pulses are more prone to acceleration response amplification due to nonlinear rocking motions.

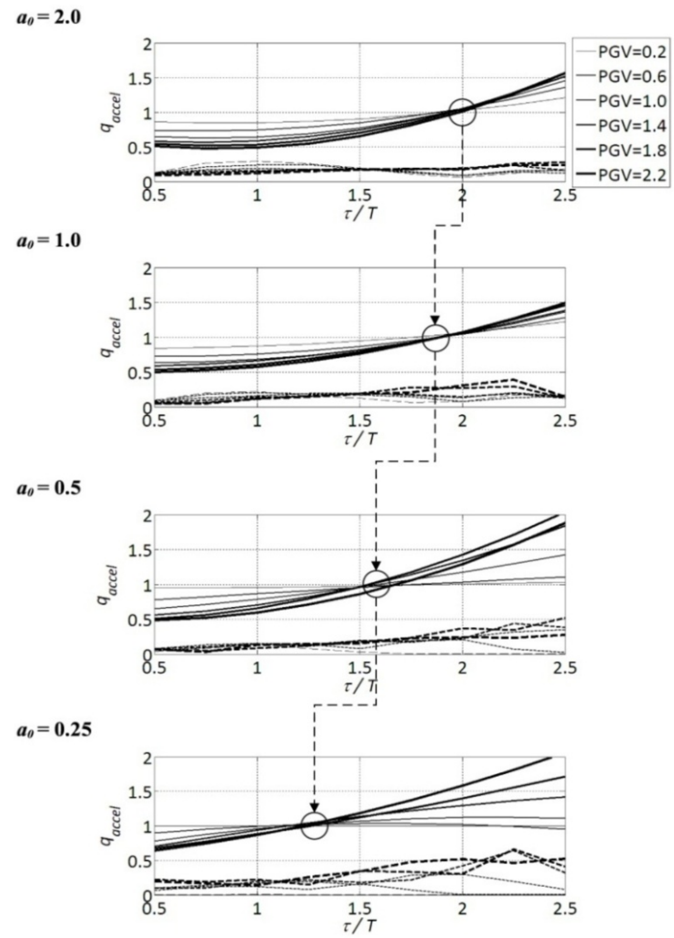

Fig. 3: Shock response spectra of the 10-story building located on different soil types. PGV varies from 0.2 to 2.2 *m/s*. Continuous and dash lines represent mean value and standard deviation (σ), respectively

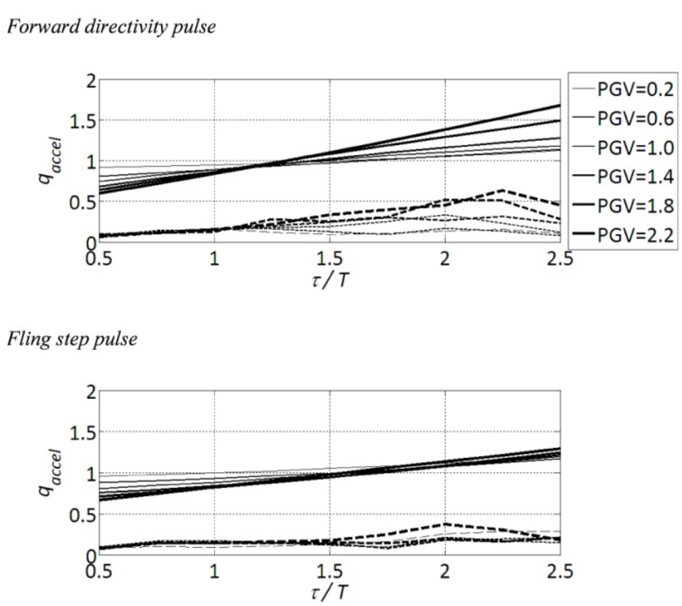

Fig. 4: Shock response spectra of 15-story building subjected to different incident pulse types. PGV varies from 0.2 to 2.2 *m/s*. Continuous and dash lines represent mean value and standard deviation (σ), respectively

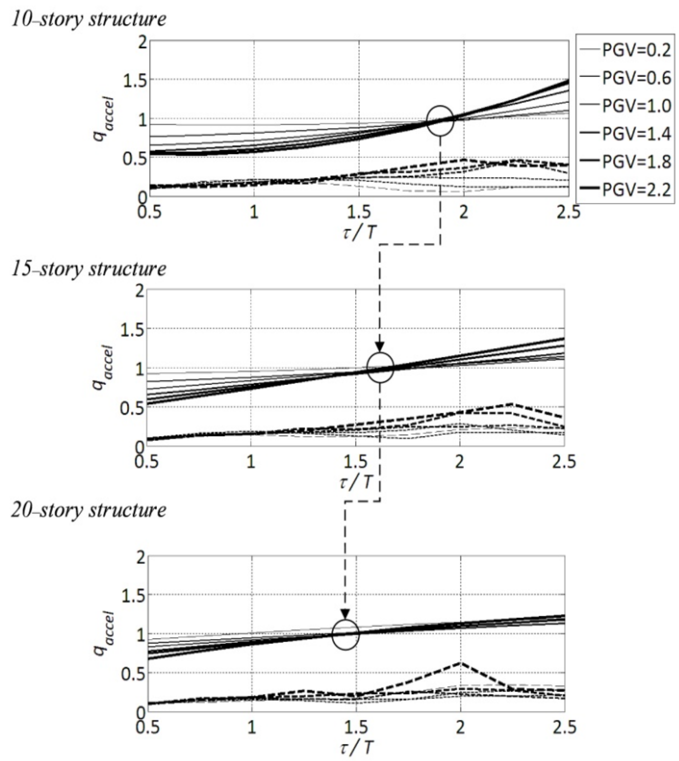

Fig. 5: Shock response spectra of structures with different numbers of stories. Continuous and dash lines represent mean value and standard deviation (σ), respectively

CONCLUSION

This study concerns shock response analysis of the soil-structure systems induced by near-fault pulses. To this end, vibration transmissibility of the soil-structure systems is evaluated using shock response spectra. An in-depth parametric study including almost 16000 time history analyses are performed. Medium-to-high rise buildings with different aspect ratios as well as foundations with different safety factors located on different soil types are studied. Two types of near-fault ground shocks, i.e., forward directivity and fling step pulses, with different pulse periods as well as pulse amplitudes are selected as input excitation. Linear versus nonlinear SSI condition are considered. Maximum response acceleration ratio q_{accel} is selected as vibration transmissibility index in linear compared to nonlinear SSI condition.

The results show that nonlinear SSI is likely to amplify the acceleration responses when subjected to long-period incident pulses with normalized period τ/T exceeding a threshold. This threshold τ/T correlates with soil type, so that increasing shear-wave velocity of the underlying soil, the threshold τ/T decreases. On the other hand, increase in ground shock intensity results in steeper slope of SRS, i.e., greater period dependency. Furthermore, comparing SRSs of forward directivity versus fling step pulses reveals that long-period forward directivity pulses can result in significant response amplification, especially when the pulse amplitude intensifies. In contrast, short-period forward directivity pulses with high amplitudes are significantly isolated. In addition, vibration transmissibility of nonlinear SSI is more period-dependent subject to forward directivity pulses compared to fling step ground shock. At last, it is concluded that more high-rise buildings subjected to near-fault pulses are more prone to acceleration response amplification due to nonlinear rocking motions.

REFERENCES

Alavi, B. and H. Krawinkler, 2004. Behavior of moment resisting frame structures subjected to near-fault ground motions. Earthq. Eng. Struct. D., 33: 687-706.

Alhan, C. and M. Sürmeli, 2011. Shear building representations of seismically isolated buildings. B. Earthq. Eng., 9: 1643-1671.

Anastasopoulos, I., G. Gazetas, M. Loli, M. Apostolou and N. Gerolymos, 2010. Soil failure can be used for seismic protection of structures. B. Earthq. Eng., 8: 309-326.

ASCE/SEI 7-10, 2010. Minimum Design Loads for Buildings and Other Structures. Published by American Society of Civil Engineers.

Fenves, G.L., S. Mazzoni, F. McKenna and M.H. Scott, 2004. Open System for Earthquake Engineering Simulation (OpenSEES). Pacific Earthquake Engineering Research Center, University of California, Berkeley, CA.

Gazetas, G., I. Anastasopoulos, O. Adamidis and T. Kontoroupi, 2013. Nonlinear rocking stiffness of foundations. Soil Dyn. Earthq. Eng., 47: 83-91.

Hall, J.F., T.H. Heaton, M.W. Halling and D.J. Wald, 1995. Near-source ground motion and its effects on flexible buildings. Earthq. Spectra, 11(4): 569-605.

Heaton, T.H., J.F. Hall, D.J. Wald and M.V. Halling, 1995. Response of high-rise and base-isolated buildings in a hypothetical Mw 7.0 blind thrust earthquake. Science, 267: 206-211.

Housner, G.W., 1963. The behavior of inverted pendulum structures during earthquakes. B. Seismol. Soc. Am., 53(2): 403-417.

Kalkan, E. and S.K. Kunnath, 2006. Effects of fling step and forward directivity on seismic response of buildings. Earthq. Spectra, 22: 367-390.

Koh, A. and C. Hsiung, 1991a. Base isolation benefits of 3-D rocking and uplift. I: Theory. J. Eng. Mech-ASCE, 117(1): 1-18.

Koh, A. and C. Hsiung, 1991b. Base isolation benefits of 3-D rocking and uplift. II: Numerical example. J. Eng. Mech-ASCE, 117(1): 19-31.

Naeim, F. and J.M. Kelly, 1999. Design of Seismic Isolated Structures: From Theory to Practice. Wiley, Chichester, England.

Piersol, A.G. and T.L. Paez, 2010. Harris' Shock and Vibration Handbook. 6th Edn., McGraw-Hill, New York.

Sasani, M. and V. Bertero, 2000. Importance of severe pulse-type ground motions in performance-based engineering: Historical and critical review. Proceedings of the 12th World Conference on Earthquake Engineering. New Zealand, No. 8.

Sehhati, R., A. Rodriguez-Marek, M. ElGawady and W.F. Cofer, 2011. Effects of near-fault ground motions and equivalent pulses on multi-story structures. Eng. Struct., 33: 767-779.

Skinner, R.I., W.H. Robinson and G.H. McVerry, 1993. An Introduction to Seismic Isolation. Wiley, Chichester, England.

Veletsos, A.S., 1997. Dynamic of Structure-Foundation Systems. Structural and Geotechnical Mechanics. Prentice-Hall, Englewood Cliffs, NJ, pp: 333-61.

Wolf, J.P., 1985. Dynamic Soil-Structure Interaction. Prentice-Hall, Englewood Cliffs, NJ.

Wolf, J.P., 1994. Foundation Vibration Analysis Using Simple Physical Models. Prentice-Hall, Englewood Cliffs, NJ, pp: 293-307.

Wolf, J.P. and A.J. Deeks, 2004. Foundation Vibration Analysis: A Strength-of-materials Approach. Elsevier, Amsterdam.