

**Numerical Analysis of Soil-Structure Interaction at Seismic Fault Pulses**Hetal D. Pandya¹, D.A.Shah²¹LDRP-Institute of Technology & Research, Gandhinagar, Gujarat, INDIA – 382015; veddhumi@yahoo.com²Sardar Vallabhbhai Patel Institute of Technology, Vasad, Gujarat, INDIA – 388306; dinubaheti@yahoo.co.in

Abstract — Numerical analysis of soil–structure systems at seismic fault pulses has investigated. Vibration transmissibility of the soil–structure interaction has analyzed for super-structures with different aspect ratios positioned on various soil types and different foundations have studied. Soil structure interaction with geometric nonlinearity has been considered with forward directivity and fling step types of mathematical seismic fault pulses. It has been analyzed that nonlinear SSI is tend to amplify the acceleration responses when subjected to low frequency incident pulses below normalized threshold frequencies. These thresholds associate with soil classification, so that different soil type has various shear wave velocity. With increased shear wave velocity of the underlying soil makes the threshold frequency increases.

Keywords- Nonlinear soil–structure interaction; response analysis; seismic fault; ground shock; rocking isolation

I. 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 [1]. 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 [2]. 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 [3]. Alternatively, base displacements in those systems, especially under near–fault ground motions, are increased [4]. 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 [5]. 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 [6]. 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 [7] can benefit from energy absorbing capacity of the underlying soil namely rocking isolation. This context motivated Koh and Hsiung [8], [9] 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 paper is shock response analysis of the soil– structure systems induced by near–fault pulses. 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.

II. MATHEMATICAL 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 figure 1. Different types of seismic acceleration pulse have considered in model a) forward-directive pulse b) fling step pulse.

2.1. 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 [10]. In this study, the superstructure is a 3D shear building regular in plan and height to avoid the effects of geometrical asymmetry. Requirements for including near-field effects are considered according to ASCE7-10 [11]. Dead and live loads are assumed 600 and 200kg/m², respectively. The story height of 3.0m and number of stories equal to 10, 15, and 20 are selected in order to represent medium to high rise buildings that can rationally have shallow foundations on different types of soil medium. First mode natural periods of fixed base structure are 1.0, 1.5, and 2.0s for 10, 15 and 20 story buildings respectively. These natural periods are consistent with approximate fundamental period formulas introduced in ASCE7-10. The analyses have been performed using Open SEES software [12]. Rayleigh model with damping ratio equal to 5% of critical damping is assigned to the superstructure. In this case, superstructure elements are assumed with no ductility and P-Delta geometrical nonlinearity is included.

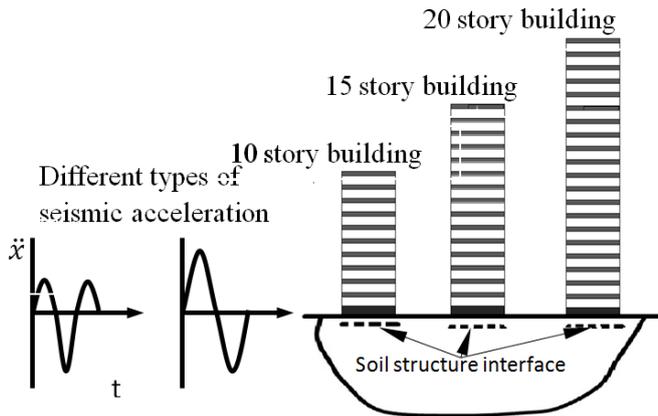


Figure.1 SSI near fault ground acceleration

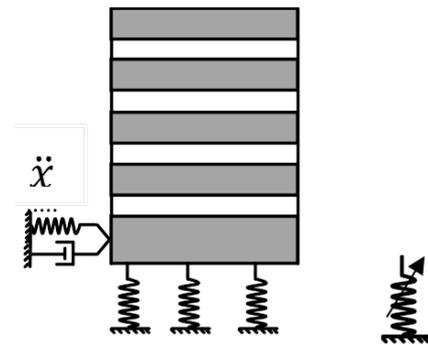


Figure.2 linear & Non linear SSI interacting system

2.2. Interacting System

The interacting system called substructure consists of soil foundation ensemble which induces base-isolating effects to the structure. The foundation is a square mat with thickness of 1.0, 1.5, and 2.0m for 10, 15 and 20 story buildings, respectively. Brick elements are used to model the foundation. Dimensions of the foundation plan were designed according to vertical load bearing capacity of soil medium. Thus, different foundation plan dimensions are calculated regarding to different soil types as well as different safety factors. The foundation is assumed to be inflexible and no embedment is considered in this study. In order to consider soil effects, four types of soil media with a wide range of shear wave velocity (v) were considered to cover soft to very dense soil in accordance with site classification introduced in ASCE7-10 [11]. The soil is considered as a homogenous half-space medium and is not modeled directly in this study. Simplified models are used to impose substructure effects including soil flexibility, radiation damping, tension cut-off, and soil yield on the foundation. The horizontal (sway) impedances can be directly obtained using Cone model formulas [13]. However, rocking and vertical impedances, because of contribution of foundation uplift and soil yield nonlinear effects, could not be directly calculated using lumped model in vertical and rocking directions. In vertical and rocking directions, the foundation area is discretized over a sufficient number of nodes. The discretization of foundation plan area has been done in accordance with so called sub-disk method recommended by Wolf [14] to calculate vertical and rocking dynamic impedance of soil. In order to let the foundation uplift and soil yield phenomena contribute in finite element modelling of soil structure system the vertical nonlinear elastic perfectly plastic gap material is assigned to the vertical contact elements as shown in figure 2.

III. MATHEMATICAL MODEL NEAR FAULT PULSES

Idealized pulses, used in this study, are described by sinusoidal functions proposed by Sasani and Bertero as well as Kalkan and Kunnath that represent fling step and forward directivity type of ground motions [15], [16]. The mathematical formulations of the acceleration time history of fling step and forward directivity pulses are presented in (1), and (2), respectively.

Fling-Step Pulse

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

Forward Directivity Pulse

$$a(t) = \frac{2\pi A}{T_p^2} \sin \left[\frac{2\pi}{T_p} (t - T_i) \right]; t \in (T_i + 0.5\tau, T_i + T_p)$$

$$\frac{\pi A}{T_p^2} \sin \left[\frac{2\pi}{T_p} (t - T_i) \right]; t \in (T_i, T_i + 0.5T_p) \cup (T_i + \tau, T_i + 1.5T_p)$$
(2)

Where, A denotes the maximum amplitude of the ground displacement derived by double time integration of ground acceleration, $a(t)$, T_p and T_i denote pulse period and pulse arrival time, respectively. Pulse amplitude and pulse period are the two fundamental input parameters of the idealized pulse models. In this research, pulse to fixed base structure period ratio (T_p/T) is assumed to fall within 0.5 to 2.5 where T is considered as natural periodic rocking response time interval. Within this range, real near field records can be replaced by idealized pulses and salient properties of structural response are captured with reasonable approximation [17], [18]. Moreover, pulse amplitude corresponding to different excitation levels varies from moderate to very strong ground motions in this study. For this purpose, Maximum ground response (MGR) in velocity mode varies from 0.20 to 2.20 m/s to represent moderate to very strong ground motions, respectively. In this study, unidirectional excitation is exerted to the base when the simplified pulse models of fling step and forward directivity are used.

IV. PARAMATRIC STUDY

It is well known that the response of soil–structure system depends on geometric and dynamic properties of the structure and the beneath soil. These effects can be incorporated into the studied model by the following non dimensional parameters [19], [20]:

$$a_0 = \frac{\omega_{fix} H}{v} \qquad \qquad \qquad \text{Slenderness Ratio} = \frac{H}{W}$$
(3)

Where, a_0 , ω_{fix} , H , v , and W stand for non dimensional frequency, circular frequency of base structure, superstructure height, shear wave velocity of soil and width of the superstructure, in the same order. Non dimensional frequency parameter a_0 , is introduced as an index for the structure to soil stiffness ratio. In this study, this parameter is assumed 0.25, 0.5, 1 and 2 to cover different levels of soil flexibility. According to equation (1), the a_0 equals to 0.25, 0.5, 1.0, and 2.0 is corresponding to shear-wave velocity of soil 754, 377, 188, and 94 sm , respectively.

Regarding to equation (3), SR parameter stands for slenderness of the superstructure. In this paper, values of 2 and 4 are assigned to SR parameter in order to represent low as well as high a and SR , are typically considered as the key parameters of the soil–aspect ratio. These two mentioned parameters, Ostructure system [19]. Besides, with regard to nonlinear SSI incorporated in this parametric study, the following non– dimensional parameter is also considered:

$$FOS = \frac{C_{bs}}{P_v}$$
(4)

where C_{bs} , P_v and FOS indicated the static bearing capacity of soil under purely vertical loading, the vertical applied load, and factor of safety against vertical load bearing of the foundation, respectively. FOS is set equal to 1.2, 1.85, and 2.5 to represent severely–loaded, heavily–loaded and lightly–loaded foundations, respectively [21].

For shock response analysis of the soil–structure system, maximum amplitude at a given i^{th} story (MA) is defined as time–domain extreme value of absolute response acceleration of the i^{th} floor. Peak value of MA_i along height of the structure is defined as PMA . 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:

$$R_{acc} = \frac{PMA_{Non-linear}}{PMA_{Linear}}$$
(5)

where R_{acc} denotes maximum response acceleration ratio which is equal to PMA at nonlinear SSI condition to PMA at linear SSI condition.

V. SHOCK RESPONSESPECTRA (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 Figs. 3 and 4, the ordinate of each SRS curve represents the R_{acc} ratio as introduced in (6). The abscissa (T_p/T) of the SRS represents the ratio of the excitation pulse duration T_p 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 Figs. 3 and 4 represent mean and standard deviation (s) of the primary SRS curves ensemble, respectively. The SRS pairs are plotted with respect to different incident pulse periods T_p to show the effect of shock intensity.

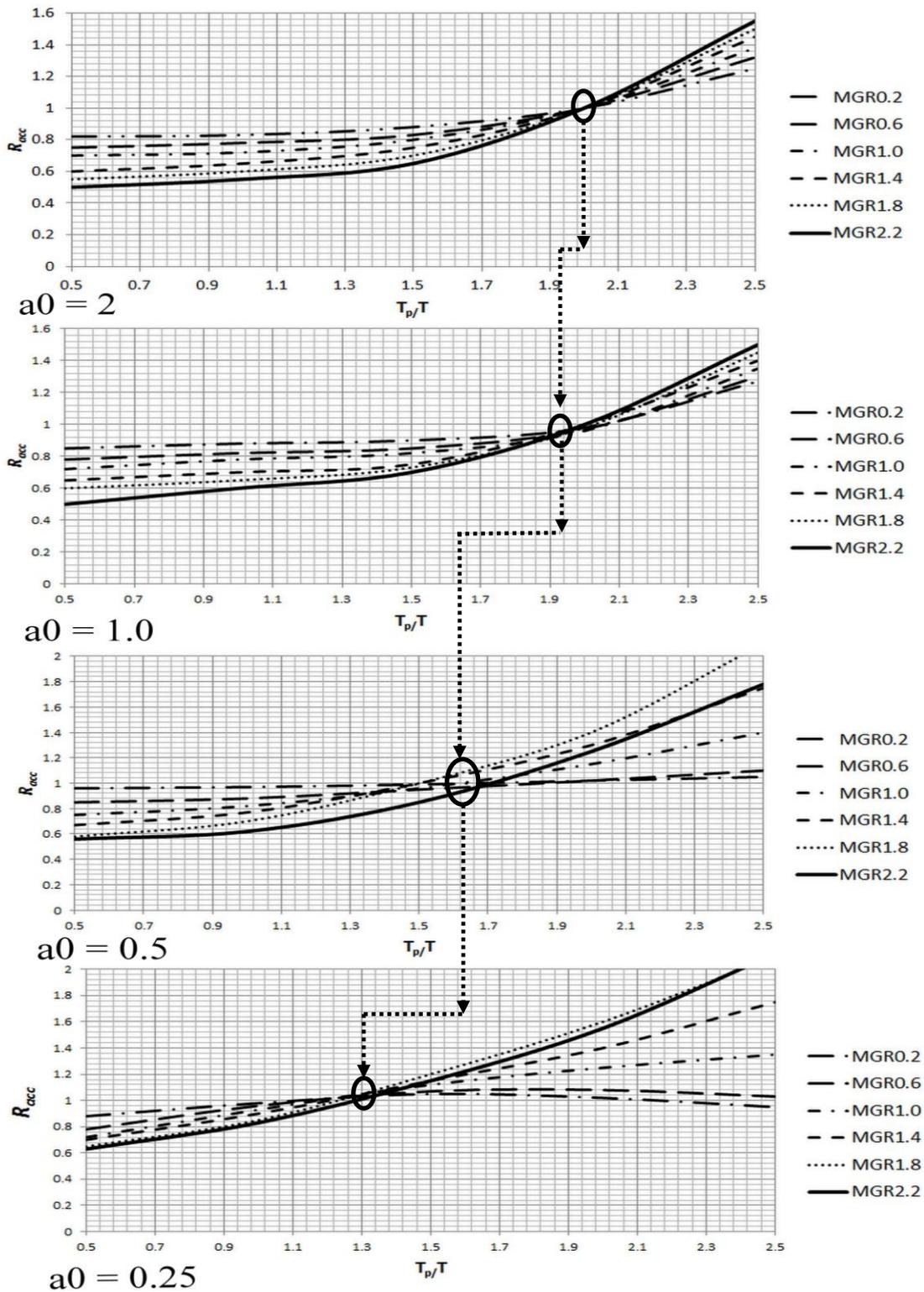
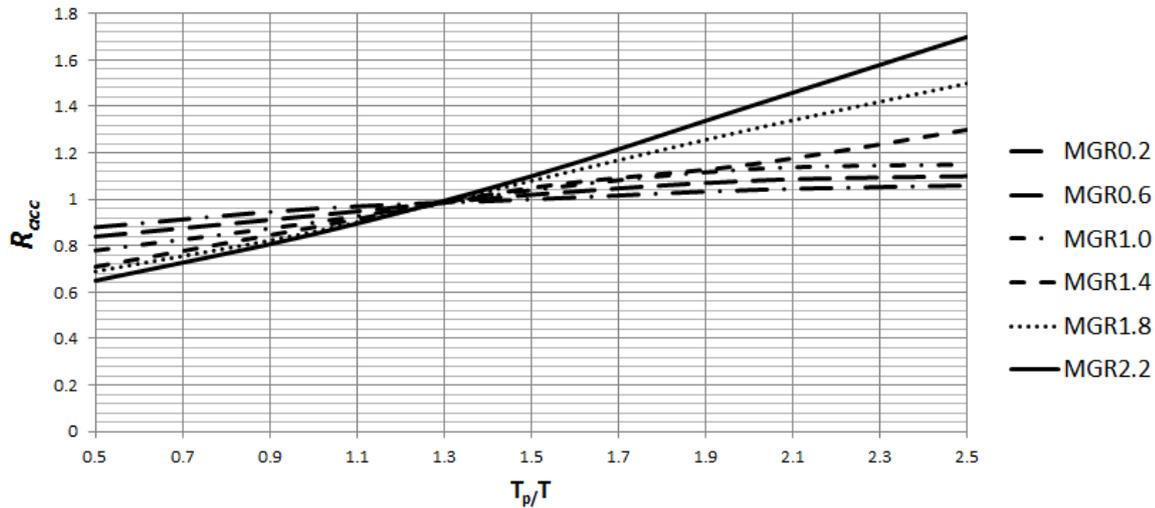


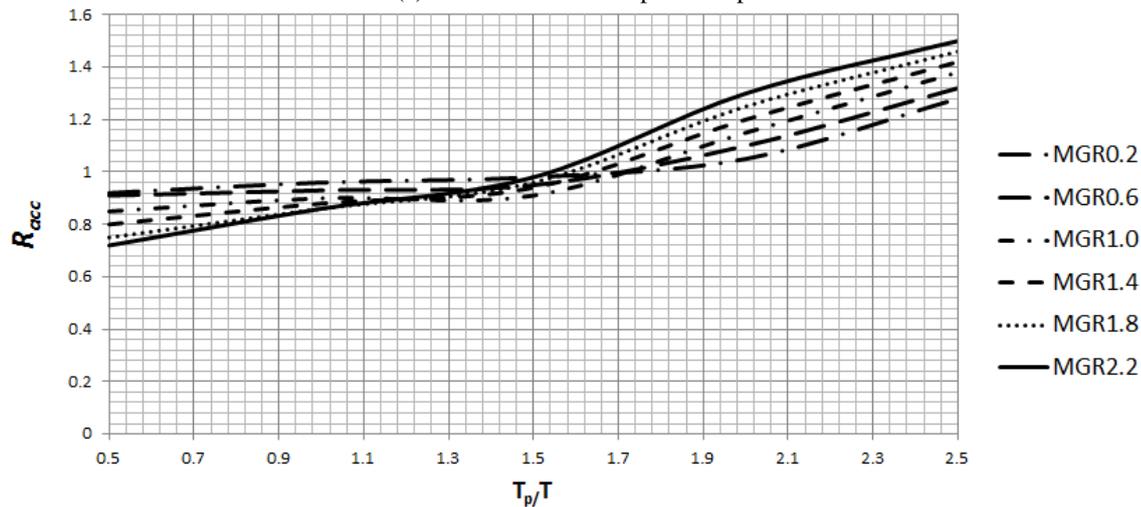
Fig. 3 Shock responses of 10 story building located on different soil types along with different MGR ranging from 0.2 to 2.2 m/s

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 , (3). The results show that nonlinear SSI is likely to amplify the acceleration responses when subjected to long–period incident pulses with normalized period T_p/T exceeding a threshold. It is shown that this threshold T_p/T correlates with soil type. In more precise words, when a decreases (i.e. at more dense sites) the threshold T_p/T moves to left as displayed in Fig. 3. For instance, the incident pulse with normalized period

greater than the threshold, $T_p/T = 1.25$, leads to response amplification in a 10-story building located on very dense site ($a=0.25$). On the other hand, comparing individual SRS curves on each graph of Fig. 3 reveals that increasing the ground shock intensity results in steeper slopes of SRSs. This fact shows that nonlinear SSI is more activated subject to incident pulses with greater amplitudes.



(a) Forward directive pulse responses



(b) Flip step pulse responses

Fig. 4 Shock response for 15 story building at different MGR ranging from 0.2 to 2.2 m/s

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.

VI CONCLUSION

This paper concerns shock response analysis of the soil structure interaction 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 studies 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 R_{acc} 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 T_p/T exceeding a threshold. This threshold T_p/T correlates with soil type, so that increasing shear-wave velocity of the underlying soil, the threshold T_p/T decreases. On the other hand, increase in ground shock intensity results in steeper slopes of SRSs, 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.

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