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CONTENT

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DEPENDENCE OF ENERGY ENTERING A BUILDING FROM THE INCIDENT ANGLE, THE LEVEL OF NONLINEARITY IN SOIL, AND THE FOUNDATION STIFFNESS

ALEKSANDRA RISTESKA-KAMCHESKI AND VLADO GICEV

Abstract. In this paper we analyze the distribution of energy in the interactive system of the ground-foundation-object for an arbitrary angle of incidence of the seismic wave into the model. The analysis is conducted using a numerical simulation of wave propagation. In our research we use a two-dimensional mathematical model of the system soil-foundation-object. The ultimate goal of the research was to determine how the angle of propagation of the wave affects the amount of seismic energy that enters the object at various stiffness of the foundation, various soil stiffness and the levels of nonlinear response in the soil.

1. **Introduction**

The research of the response of a soil-structure system using numerical models and numerical simulations became popular with the development of computers. The numerical models of the soil-structure system include material properties of the constitutive parts of the system as well as initial and boundary conditions.

Advanced large-scale numerical simulations have been developed for the analyses of dynamic response of soils, including nonlinear representation and complex geometry of foundations (Elgamal et al. 2008; Prevost 1993; Zhang et al. 2008). Large numerical models are necessary for engineering analyses in realistic settings, but detailed interpretations of some of the results become a challenge due to the simultaneous action of their many complex features. Useful results can be obtained even for the simplest 1-D numerical models (Kanai, 1965; Safak, 1998; Fujino and Hakuno, 1978, Risteska et al., 2013; Risteska and Gicev, 2018; Gicev and Trifunac, 2010).

In the last decade, one of the main concerns of the authors is the nonlinear response of the soil-structure system. For these studies, authors usually develop 2-D models and for assumed stress-strain relationship in the media obtain the response of the soil-structure system (Lee and Trifunac, 2010; Lee et al., 2014a,b; Gicev, 2009; Gicev and Trifunac, 2010; Gicev and Trifunac, 2012)

In this paper, with the aim of analyzing and interpreting only a subset of the phenomena—which accompany the nonlinear response of soil, foundation, and structure in the presence of soil-structure interaction—but without loss of accuracy and without reducing the completeness in describing the physical phenomenon, we analyze only the most elementary representation of wave motions and adopt a bi-linear yielding model for both the foundation and the soil.

It is assumed that the object is linear, while the ground and foundation can suffer nonlinear deformations. The input excitement is in the form of a semi-synousoid pulse. By changing the parameters that affect the distribution of energy in the system, we researched how the input seismic energy is distributed in the system depending on the input angle of the wave. Since the input energy through a given cut depends on the velocity of the intersection particles, in this paper we research how the input angle θ of the wave affects the velocity of the particles of the foundation (at different stiffnesses of the foundation and different level of non-linearity of the ground), and thus also of the seismic energy entering the building.

2. Numerical model

We analyzed a two-dimensional model of a soil-foundation-object system. The material properties of the model are assumed to be those of Holiday Inn hotel in Van Nuys, California which was severely damaged during the Northridge earthquake, 1994 (Todorovska et al., 2001; Gicev and Trifunac, 2006). To study the energy flow through the foundation-object interface, we define the mean particle velocity at this interface as:

$$v_{av} = \frac{\sum_{i=1}^{N_c} v_i}{N_c}, \qquad (2.1)$$

where N_c is the number of points of the contact foundation-object, and v_i is the velocity at point *i* of the contact in time step *k*. In this way, for each time step of our numerical simulation, we calculated the mean pulse excitation velocity with a dimensionless frequency η. For the largest absolute value of the mean velocity and the corresponding η, we obtain a point on the curve $v_{av,\max}(\eta,t)$. We conducted the research in the domain of the dimensionless frequency of excitation $0.06 \le \eta \le 3$ with a step $\Delta\eta = 0.02$. In this way we have $N_p = \frac{3-0.06}{0.02} + 1 = 148$ points on our curves $v_{av}(\eta)$. From the fact that the energy flow through a certain area perpendicular to the direction of the wave propagation is proportional to the square of particle velocity, in the following we study how the average particle velocity varies with changes of the incident angle, the level of soil nonlinearity and the foundation stiffness.

3. Results and discussion

Figures 1, 2, 3 and 4 show the normalized curves $v_{av,r}(\eta) = v_{av,\max}(\eta,t)/v_{\max,ff}$, where $v_{\max,ff}(\eta)$ is the highest velocity by absolute value that occurs on the free surface of the soil with absence of the foundation and the object. We compute it as $v_{\max,ff} = 2 \cdot \left| \left(\frac{d_{i+1} - d_i}{\Delta t} \right) \right|_{\max}$, where d_i is the *i*-th value of the filtered semi-sinusoidal pulse.

These curves are shown for three degrees of nonlinearity of the ground, at four different input angles, $\theta = 0^0, 30^0, 60^0$ and 85^0. It is obvious that in Figure 1, $v_{av,r}(\eta)$ for the model of ground with the lowest level of nonlinearity, C = 1.5 (blue line), has the largest ordinates.

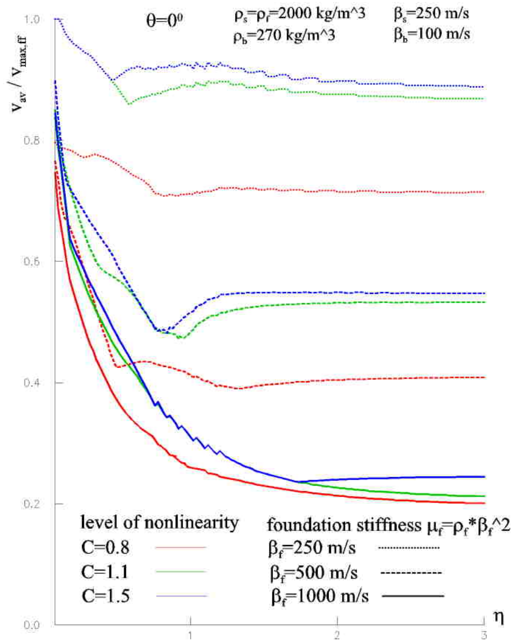

Figure 1. *Peak average velocity v_{av} at structure-foundation interface normalized by peak free-field velocity $v_{max,\,ff}$ vs. η for three foundation stiffness and three levels of nonlinearity of soil. $\theta = 0^0$*

For the longest pulses, η = 0.06, $v_{av,r}(\eta)$ has an ordinate one and as η increases to η = 0.48, it decreases. At η = 0.48 the relative mean velocity has a minimum, $v_{av,r}(\eta)$= 0.89. As η continues to grow, $v_{av,r}(\eta)$ begins to grow slightly and reaches values between 0.92 and 0.93 in the interval $0.6 \le \eta \le 1.2$. With further growth of η, $v_{av,r}(\eta)$ decreases slightly and at the largest considered value of the dimensionless frequency η = 3 gets a value $v_{av,r}(\eta)$= 0.89.

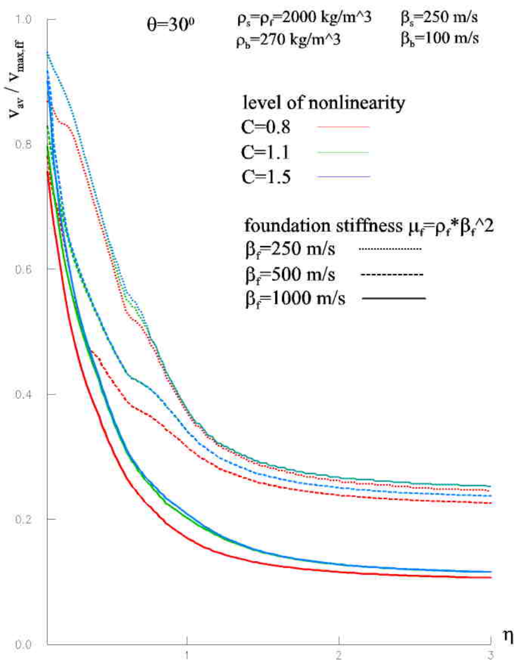

Figure 2. *Same as Fig.1 but for $\theta = 30^0$*

The soil model with the nonlinearity level C = 1.1 (green line), for the longest pulses, η = 0.06 to η = 0.48, has the same ordinates as the soil model with the nonlinearity level C = 1.5, which has a local minimum at this η. The model with C = 1.1 has a minimum $v_{av,r}(\eta)$= 0.859 for η = 0.58, and further by increasing η, it goes parallel to the curve with the level of nonlinearity C = 1.5. The maximum $v_{av,r}(\eta)$= 0.898 occurs at η = 1.2, and $v_{av,r}(\eta)$= 0.868 for η = 3. The model with the largest nonlinearity on the ground, C = 0.8 (red line), follows the trend of the previous two curves, by not starting from 1 for the smallest considered dimensionless frequency, η = 0.06, but from $v_{av,r}(\eta)$ = 0.8. This is because in the previous two curves, for the smallest dimensionless frequencies, the ground is linear and there is no permanent deformation in it, which is not the case with the model with large nonlinearity, C = 0.8, when permanent deformations occur at the smallest η. Models with low nonlinearity on the ground have larger ordinates than models with higher nonlinearity. The model with the highest level of nonlinearity in the ground C = 0.8 (red line) has the smallest ordinates of $v_{av,r}(\eta)$ for all η, which leads to the conclusion that the models with high nonlinearity in the soil, i.e. small ε_m, i.e. small C in equation (2), prevent (do not allow) much of the energy to reach the object (to the foundation-object contact). This insight allows us to understand why many of the buildings on weak soil (with a high level of nonlinearity) and close to the epicenter of the 1994 Northridge earthquake remained completely undamaged. As the input angle θ increases, for high frequencies (Figures 2 to 4), the curves approach. Figure 2 shows the corresponding input angle curves $\theta=30^0$. As η increases, the curves $v_{av,r}(\eta)$ approach each other.

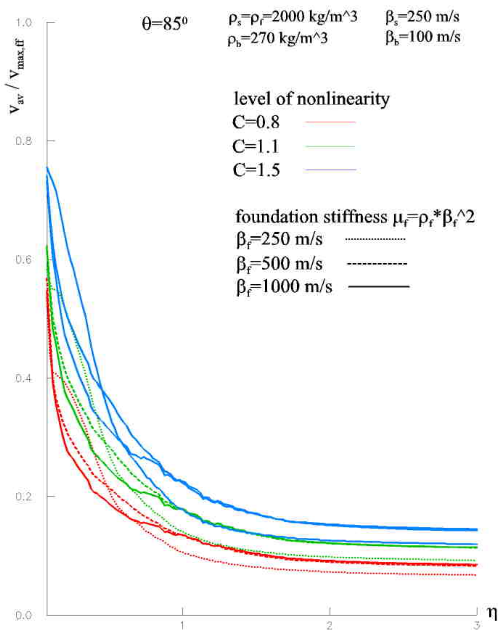

Figure 3. *Same as Fig.6.6 but for $\theta = 60^0$*

In Figure 2, it can be seen that for lower nonlinearity, C = 1.1 and C = 1.5 (green and blue lines), the curves $v_{av,r}(\eta)$ almost match, especially at high dimensionless frequencies. Otherwise, for this input angle, θ = 30^0 the curves for large nonlinearity C = 0.8, have different, always smaller ordinates than the curves for C = 1.1 and C = 1.5. Figure 3 shows the curves $v_{av,r}(\eta)$ for input angle θ = 60^0. The figure shows that for small η the model with the lowest level of nonlinearity on the ground C = 1.5 has the highest value for the average velocity. For $\eta = 0$, i.e., for the longest pulses, $v_{av,r}(\eta)$ has the ordinate close to 0.86 and as the dimensionless frequency increases, $v_{av,r}(\eta)$ decreases sharply.

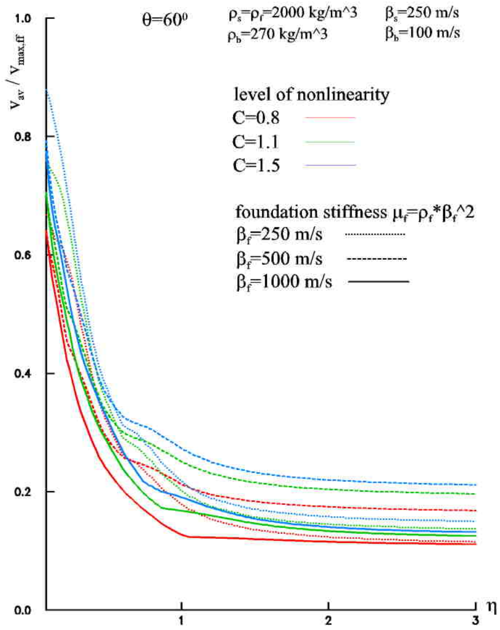

Figure 4. *Same as Fig.1 but for θ = 85^0*

At $\eta = 0.5$ the relative velocity of the model with the lowest level of nonlinearity on the ground C = 1.5, becomes greater than the same for C = 1.5. For $\eta > 0.5$, the relative velocities for this model are the highest and reach the lowest value in the considered interval, about 0.25. The model with the level of nonlinearity on the ground C = 1.1 for $\eta = 0$ has a maximum ordinate for the relative velocity 0.8. The curve of this model runs parallel to the curve with the nonlinearity level C = 1.5 and the minimum occurs for $\eta = 3$, $v_{av,r}(\eta) = 0{,}24$. The model with the largest nonlinearity on the ground (red line) behaves similarly to the previous curve, in that the minimum value for the mean velocity reaches the same for $\eta = 3$, $v_{av,r}(\eta) = 0{,}2$. It is observed that the increase of the input angle leads to the approximation of the curves $v_{av,r}(\eta)$.

Figure 4 shows the curves of the previous mathematical models, but at the input pulse angle θ = 85^0. It is obvious that the maximum value for the relative velocity is lower than that at the input angle θ = 60^0, $v_{av,r}(\eta) = 0{,}75$. This value reaches the curve of the model for the lowest nonlinearity of the ground C = 1.5 (blue line). The curve with the level of nonlinearity C = 1.1 behaves similarly, with a small difference in the maximum and minimum of the relative velocity. Curves with large nonlinearity on the ground (C = 0.8) have the lowest value for velocity, about 0.58. As η increases, they decrease and for $\eta = 3$ reach the minimum, about 0.1. Figure 4 also shows that as the pulse input angle θ increases, as the frequency increases, the curves $v_{av,r}(\eta)$ decrease and move closer to each other (some of them even coinciding). This shows that at higher η the degree of nonlinearity of the ground is almost irrelevant to the values of the relative velocity of the foundation-object contact, $v_{av,r}(\eta)$. It is also obvious that these velocities for larger η become almost constant, i.e., they no longer depend on the frequency.

Conclusion

We determined under which conditions and where maximum responses of finite-dimension elements occur during seismic excitations. We come to the conclusion that with the increase of the incident angle of the pulse, the relative particle velocity and consequently the energy at the foundation – object interface decreases. Further, the models with stiffer foundation and higher level of nonlinearity of the soil have the smallest ordinates for $v_{av,r}(\eta)$, i.e, as the foundation becomes stiffer, most of the input energy is scattered from the foundation and a smaller part enters the building.

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