KINEMATIC SOIL-STRUCTURE INTERACTION EFFECTS ON MAXIMUM INELASTIC DISPLACEMENT DEMANDS OF SDOF SYSTEMS

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ABSTRACT :

This paper presents a statistical study of the kinematic soil-foundation-structure interaction effects on the maximum inelastic deformation demands of structures. Discussed here is the inelastic displacement ratio defined as the maximum inelastic displacement demands of structures subjected to foundation input motions divide by those of structures subjected to free-field ground motions. The displacement ratio is computed for a wide period range of elasto-plastic single-degree-of-freedom (SDOF) systems with various levels of lateral strength ratios and with different sizes of foundations. Seventy-two earthquake ground motions recorded on firm soil with average shear wave velocities between 180 m/s and 360 m/s are adopted. The effects of period of vibration, level of lateral yielding strength and dimension of foundations are investigated. The results show that kinematic interaction will reduce the maximum inelastic displacement demands of structures, especially for systems with short periods of vibration, and the larger the foundation size the smaller the maximum inelastic displacement becomes. In addition, the inelastic displacement ratio is nearly not affected by the strength ratio of structures for systems with periods of vibration greater than about 0.3 s and with strength ratios smaller than about 3.0. Expressions obtained from nonlinear regression analyses are also proposed for estimating the effects of kinematic soil-foundation-structure interaction from the maximum deformation demand of the inelastic system subjected to free-field ground motions.

KEYWORDS: inelastic deformation demands, kinematic interaction, foundation input motion, free-field motion, strength ratio.

1. INTRODUCTION

For the analysis of the dynamic response of a structure subjected to earthquakes, the ground motions are inputted from the base of this structure and are commonly assumed to be the free-field motions. Actually, the input motions should be the base-slab motions (foundation input motions) if there is a foundation in the structure. Differences between the free-fields motion and the foundation input motion result from kinematic interaction. The presence of stiff foundations on or in soil will cause the base-slab motion to deviate from the free-field motion. Kinematic interaction reduces foundation motions relative to the free-field due to the differences in stiffness between the foundation and surrounding soil (Todorovska and Trifunac 1992, Aviles and Perez-Rocha1998, Stewart et al. 1998, Aviles et al. 2002). For shallowly embedded foundations, the primary factor contributed to such deviation is the base-slab averaging effect in which free-field motions associated with inclined or incoherent incident wave fields are averaged within the footprint area of the base-slab due to the kinematic constraint of essentially rigid-body motion of the slab. It has been shown that kinematic interaction is most noticeable at high frequencies of excitation. This feature may imply that short-period structures are easier than long-period ones to be affected by kinematic interaction since stiff structures are sensitive to high frequency motions.

The purpose of this paper is to discuss the effects of kinematic soil-foundation-structure interaction on the maximum deformation demands of nonlinear SDOF systems with known relative strength. Results of a statistical study of the ratio of maximum inelastic displacement responses derived from the foundation input motion to those derived from the free-field motion are presented. Seventy-two earthquake ground motions recorded on free-field stations located on stiff soil are used. The effects of dimensions of foundations, periods of vibration and levels of lateral strength are investigated. In addition, for design practice, expressions obtained from nonlinear regression analyses are also proposed.

2. FOUNDATION INPUT MOTIONS

The effects of kinematic interaction are, in general, quantified by transfer functions H(f), the ratio of the foundation input motion to the free-field motion in frequency domain. The transfer function is actually a kind of low pass filters (Holloway 1958, Hudson 1979). When the free-field motion runs through foundations, the high frequency waves of the free-field motion will be filtered by the foundations. The foundation input motion can be determined by the following steps. (a) Calculate Fourier transforms of the free-field motion; (b) Multiply the amplitude obtained from Step (a) by H(f); (c) Perform an inverse Fourier transform with the modified amplitude, and then the base-slab motion can be obtained. Although the foundation input motion can be derived from the above procedure, in this paper it will be approximately estimated by conducting an equally-weighted running average to the free-field motion in time domain. It has been shown that doing a running average to the free-field motion in time domain is exactly equal to using the following low pass filter in frequency domain.

$$|H(f)| = \left|\frac{\sin(\pi f T_w)}{\pi f T_w}\right| \tag{1}$$

where $f = \omega/2\pi$ = the natural frequency (Hz) of the harmonic component of the ground motion considered, T_w= the filtering interval which depends on the size of foundations as follows.

$$T_w = 0.251(1 - e^{-0.009 b_e}) \tag{2}$$

According to Eq. 2, the only variable (T_w) needed in the approximate running average method can be acquired from the foundation size (b_e). Fig.1 presents the foundation motions derived from the free-field motion of the 1952 Kern County earthquake. In this figure, square foundations with widths of 20 and 72 m are used. The two base-slab motions are smoother than the free-field motion. Fig.2 depicts the Fourier amplitudes of the foundation input and free-field motions. It can be observed that the base-slab motion has less high frequency content than the free-field one. High frequency motions decreases as the dimension of foundations increases. Therefore, the existence of foundations can restrict the high frequency ground motions to be imported into structures.

3. STUDY MODEL

Once the foundation input motion is obtained, the following term (inelastic displacement ratio, K_R) is implemented for studying the effects of kinematic interaction on the maximum inelastic displacement demands of structures.

$$K_R = \frac{\Delta_{i,b}}{\Delta_{i,f}} \tag{3}$$

where K_R is defined as the maximum lateral inelastic displacement for structures subjected to the foundation input motion ($\Delta_{i,b}$) divided by that for structures subjected to the free-field motion ($\Delta_{i,f}$) on systems with the same mass and initial stiffness (i.e., same period of vibration, T). In Eq. 3, $\Delta_{i,b}$ and $\Delta_{i,f}$ are computed in systems with constant yielding strength relative to the strength required to maintain the system elastic (i.e., constant relative strength). Here the relative lateral strength is measured by the strength ratio (R) defined as

$$R = \frac{m S_a}{F_y} \tag{4}$$

in which m= the mass of the system, S_a = the acceleration spectral ordinate, and F_y= the lateral yielding strength of the system. The numerator in Eq. 4 represents the lateral strength required to maintain the system elastic, which sometimes is also referred to as the elastic strength demand.

In this study, $\Delta_{i,b}$ and $\Delta_{i,f}$ are calculated for SDOF systems having elasto-plastic hysteretic behavior, a viscous damping ratio of 5%, and seven levels of strength ratios (R=1, 1.5, 2, 3, 4, 5 and 6). For each earthquake record and each strength ratio, the inelastic displacement ratio (K_R) is computed for a set of 57 periods of vibration from 0.15 to 3.0 s with an increment of 0.05 s. In addition, the foundations discussed here are limited to be square and have width (b_e) equal to 20, 43 and 72 m.

According to the free-field and foundation input motions of Fig.2, Fig.3 shows the displacement response histories for the system with vibration period of 0.2 s and strength ratio of 5, respectively. In the case, the deformation trace derived from the base-slab motion is smaller than that derived from the free-field motion. The inelastic displacement response spectra with R= 1 and 5 for the free-field and foundation input motions of the Kern County earthquake are presented in Fig.4. From this figure, the inelastic displacement ratio (K_R) can be obtained by Eq. 3 as shown in Fig.5.

4. EARTHQUAKE GROUND MOTIONS USED IN THE STUDY

A total of 72 earthquake acceleration time histories recorded in the state of California from 9 different earthquakes are used as the free-field motions in this investigation. These ground motions have the following characteristics: (a). They are recorded on accelerographic stations where enough information exists on the geological and geotechnical conditions at the site that enables the classification of the recording site in accordance to recent code recommendations; (b) They are recorded on firm sites with average shear wave velocities between 180 and 360 m/s.; (c) They are recorded on free-field stations or in the first floor of low-rise buildings with negligible soil-structure interaction effects; (d) They are recorded in earthquakes with surface wave magnitudes (M_s) larger than 6.1; and (e) At least one of the two horizontal components had a peak ground acceleration (PGA) larger than 40 cm/s^2.

5. STATISTICAL RESULTS

Fig.6 depicts the ratios of $S_{a,foundation}/S_{a,free\text{-}field}$ which are derived from the mean normalized elastic response spectra (S_a) computed from the free-field and foundation motions (b_e=20, 43, and 72 m) of the 72 earthquake records. It is clear that the kinematic soil-foundation-structure interaction obviously reduces the maximum elastic acceleration response of the short-period (stiff) systems (T<0.3 s for b_e=20 m, T<0.5 s for b_e=43 m, and T<0.8 s for b_e=72 m). The greater the size of foundations the smaller the acceleration response becomes. In other words, the kinematic interaction is beneficial to lowrise buildings with large foundations. For instance, if a structure has a period of vibration of 0.2 sec, the maximum acceleration response can be decreased in percentage of 5% (b_e=20 m), 19% (b_e=43 m) and 39% (b_e=72 m) with respect to their free-field ones. Long-period systems are not sensitive to the kinematic interaction.

Fig.7 shows the mean inelastic displacement ratios ($\Delta_{i,b}/\Delta_{i,f}$) corresponding to all of the 72 ground motions for systems with different levels of strength ratios and different sizes of foundations. The mean maximum inelastic deformation demands derived from the foundation input motions for all systems are smaller than those derived from the free-field ones (i.e., all $\Delta_{i,b}/\Delta_{i,f} < 1.0$). This means that the kinematic soil-foundation-structure interaction would not increase the maximum inelastic displacement demands of all structures. As indicated in the elastic acceleration response spectra (the preceding paragraph), the reduction of maximum deformation demands is obvious as systems with periods of vibration less than about 0.3 s for b_e=20 m, 0.5 s for b_e=43 m, and 0.8 s for b_e=72 m. Although increasing the size of foundations results in the decrease of displacement demands, the kinematic interaction effects can almost be ignored for long-period (soft) structures ($T \geq 0.5$ s for b_e=20 m, $T \geq 0.8$ s for b_e=43 m, and $T \geq 1.2$ s for b_e=72 m). In addition, for systems with strength ratios less than 3.0 and periods of vibration greater than about 0.3 s (Fig.7), the inelastic displacement ratios ($\Delta_{i,b}/\Delta_{i,f}$) are nearly independent of the inelastic hysteretic characteristic of structures (i.e., $\Delta_{i,b}/\Delta_{i,f}$ for $R \leq 3.0$ and $T \geq 0.3$ s is almost identical to each other).

The mean inelastic displacement ratio is very important because they represent what can be expected on average. However, it is equally important to quantify the level of dispersion in the inelastic displacement ratio. A common and effective way to quantify the dispersion is through the coefficient of variation (COV), which is defined as the ratio of the standard deviation to the mean. Fig.8 presents COVs of the inelastic displacement ratios corresponding to all ground motions considered here for various strength ratios (R) and foundation widths (b_e). It can be seen that dispersion increases as the dimension of foundations and the level of strength ratios increase. The elastic case (R=1.0) always has the smallest errors. Dispersion is high for systems with short periods of vibration (T< 0.3 s for b_e=20 m, 0.4 s for b_e=43 m, and 0.5 s for b_e=72 m) regardless of the lateral strength ratio. Furthermore, for a given level of strength ratios, the COVs decrease as increasing the periods of vibration of structures.

6. NONLINEAR REGRESSION ANALYSES

For earthquake-resistant design, it is desirable to have a simplified expression of the inelastic displacement ratios to estimate the maximum inelastic displacement demands of the systems subjected to the foundation input motion from those of the systems subjected to the free-field motion (i.e., to predict $\Delta_{i,b}$ from $\Delta_{i,f}$). For the objective, the Levenberg-Marquardt method (Bevington and Robinson 1992) is conducted for obtaining the expression. The proposed equation is given as follows.

$$\frac{\Delta_{i,b}}{\Delta_{i,f}} = 1 - \frac{1}{aT^{1.6}}, \quad a = (0.032R\,T_w^{-1.653} - 0.057T_w^{-1.757})^2 + 0.710T_w^{-1.777} \tag{5}$$

where T = the period of vibration of systems, R= the strength ratio of systems, and T_w = the filtering interval as shown in Eq. 2, which is the function of foundation size (b_e). Eq.5 is plotted in Fig.9. In the short-period region, this equation is primarily controlled by the variable of natural period (T) with an exponential tendency. These curves converge and keep almost constant as periods of vibration of systems increase. Eq.5 corresponds to a surface in the $\Delta_{i,b}/\Delta_{i,f}$ -T-R-b_e space that provides estimates of mean inelastic displacement ratios as functions of T, R and b_e. Since the inelastic displacement ratios for $R \le 3.0$ and $T \ge 0.3$ s are almost independent of the strength ratios (Fig.10a), Eq.5 can be further simplified in the range as Eq.6 shown in Fig.10b.

$$\frac{\Delta_{i,b}}{\Delta_{i,f}} = 1 - 2.23T_w^{2.01}T^{-1.6} \tag{6}$$

7. CONCLUSIONS

Through the inelastic displacement ratio, a statistical study of the kinematic soil-foundation-structure interaction on the inelastic displacement demands of elasto-plastic SDOF systems has been carried out by a large number of free-field and foundation input motions. The inelastic displacement ratio is defined as the maximum lateral inelastic displacement of structures subjected to foundation input motions divided by that of the same structures subjected to free-field motions. This ratio depends on the period of vibration of systems (T), the strength ratio of systems (R), and the dimension of foundations (b_e). From the investigation of the study, the following conclusions can be drawn.

(1) The foundation input motions always have less high frequency contents than the free-field ones because of the presence of foundations (Fig.2). High frequency ground waves are filtered by foundations, and only the long-period motions can be passed into structures.
(2) Kinematic interaction will reduce the maximum inelastic displacement demands of structures, especially for short-period systems (Fig.7). The reason is that short-period systems are more sensitive to the high frequency excitation than long-period ones. The reduction in displacement demands due to kinematic interaction is apparent when systems have periods of vibration less than about 0.3 s for foundations with width (b_e) of 20 m, 0.5 s for b_e=43 m, and 0.8 s for b_e=72 m. Long-period systems are almost not affected by the kinematic soil-foundation-structure interaction.
(3) Increasing the dimension of foundations (b_e) results in a decrease of the maximum inelastic deformation demands of structures (Fig.7) because the larger the dimension of foundations the more the high frequency motions are filtered (Fig.2).
(4) Coefficients of variation of inelastic displacement ratios increase with decreasing the periods of vibration of systems and with increasing the width of foundations (Fig.8). Dispersion is large for systems with periods

smaller than 0.3 s (b_e=20 m), 0.4 s (b_e=43 m), and 0.5 s (b_e=72 m).

(5) Simplified equations have been derived from nonlinear regression analyses for estimating the maximum inelastic displacement demands of systems subjected to foundation input motions from those of systems subjected to free-field motions.

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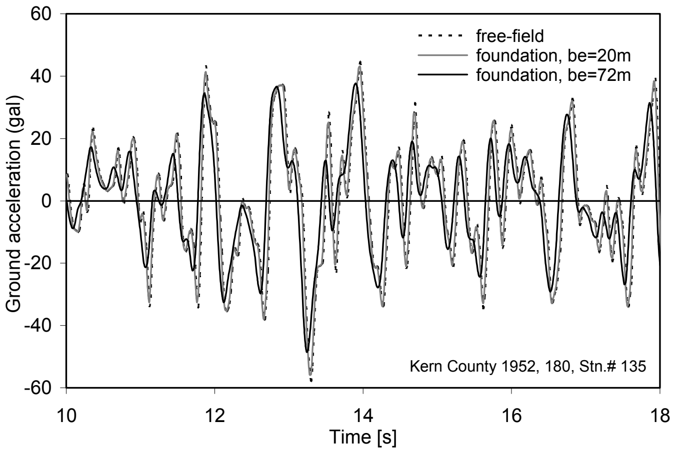

Fig.1 Comparison between the free-field motions and the foundation input motions derived from the 1952 Kern County earthquake (b_e=20 and 72 m).

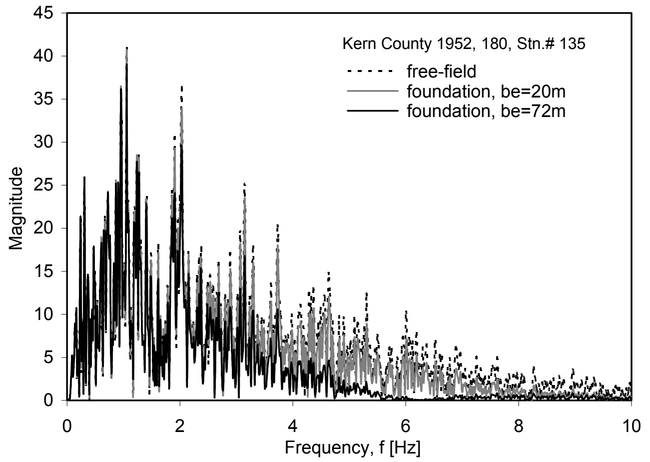

Fig.2 Fourier amplitude of the free-field and foundation input motions (b_e=20 and 72 m) for the 1952 Kern County earthquake.

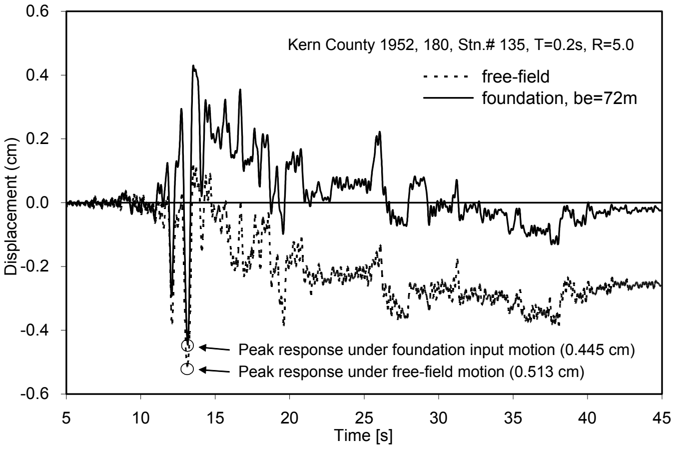

Fig.3 Displacement response histories derived from free-field and foundation input motions of the 1952 Kern County earthquake for T=0.2 s and R=5.0.

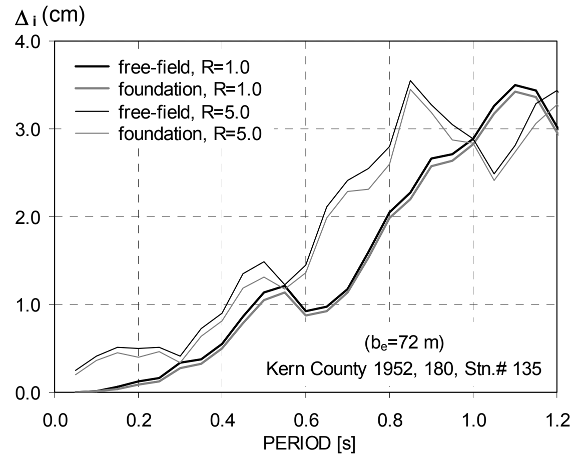

Fig.4 Displacement response spectra derived from free-field and foundation input motions of the 1952 Kern County earthquake for R=1.0 and 5.0.

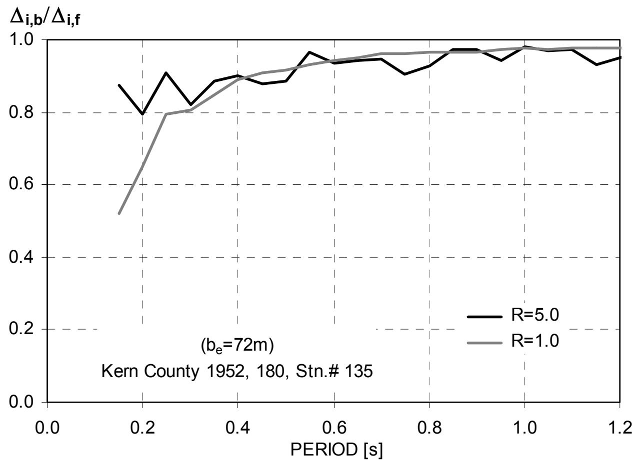

Fig.5 Inelastic displacement ratios ($\Delta_{i,b}/\Delta_{i,f}$) for the 1952 Kern County earthquake (R=1.0 and 5.0).

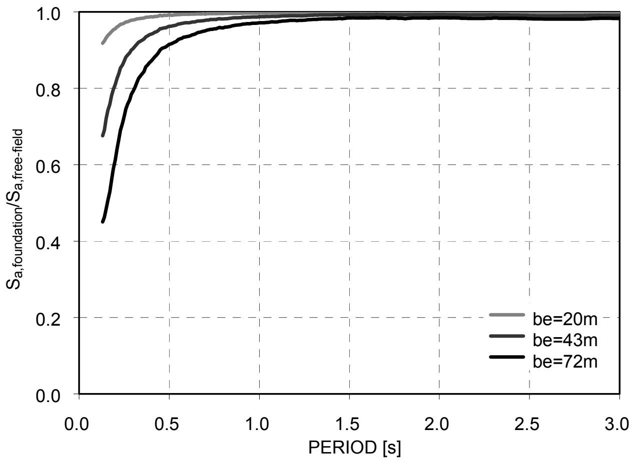

Fig.6 Ratios of mean elastic response spectra derived from free-field motions to those derived from foundation input motions.

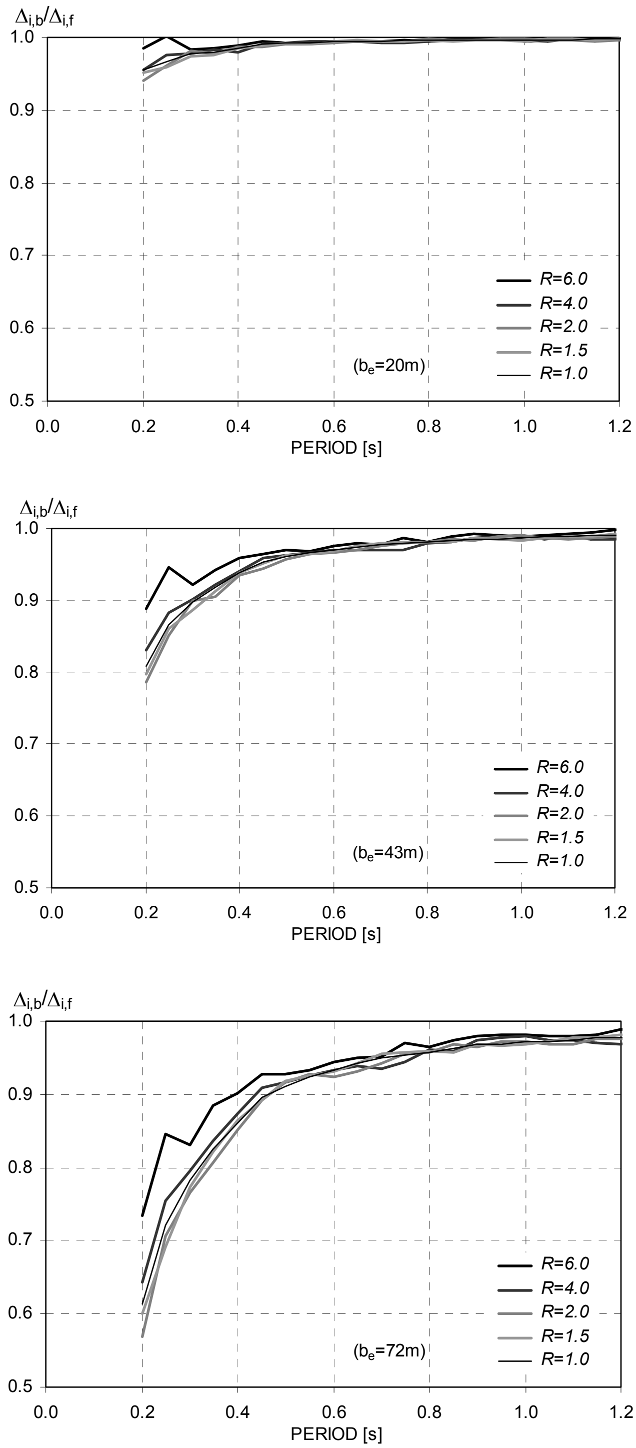

Fig.7 Mean inelastic displacement ratios ($\Delta_{i,b}/\Delta_{i,f}$) against periods for square foundations with width (b_e) equal to 20, 43 and 72 m.

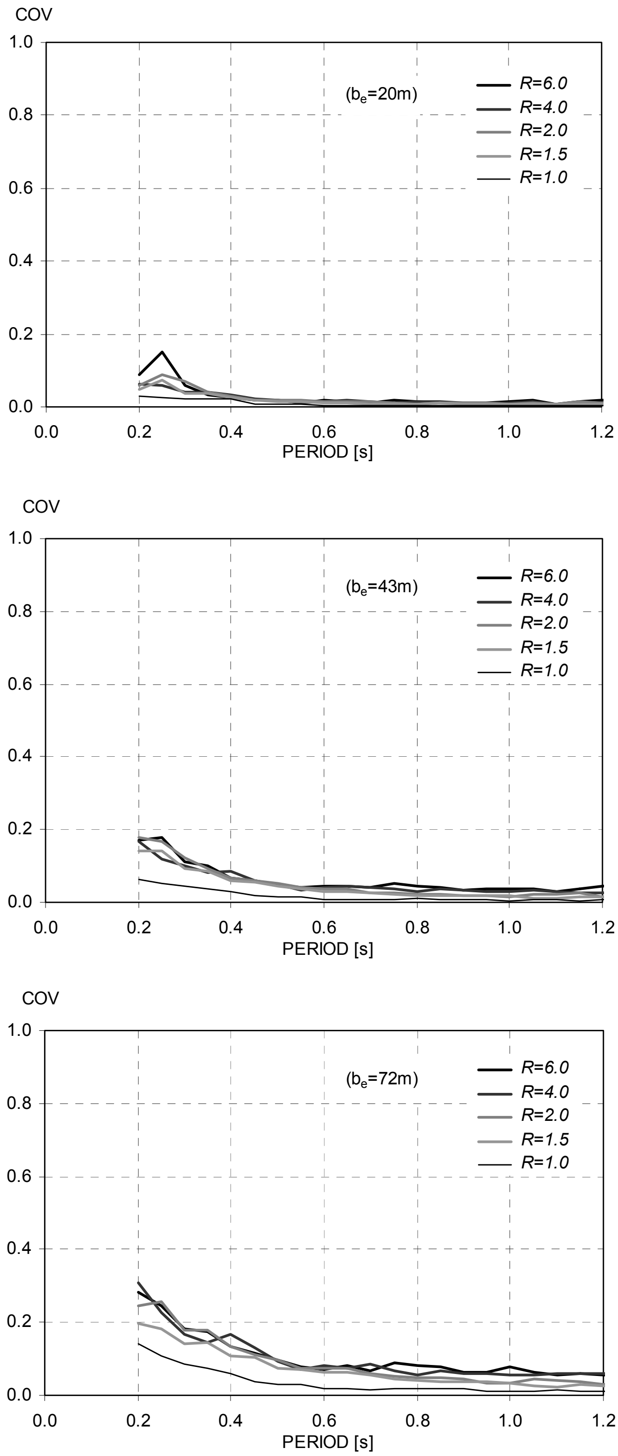

Fig.8 Coefficients of variation of inelastic displacement ratios for all 72 earthquakes.

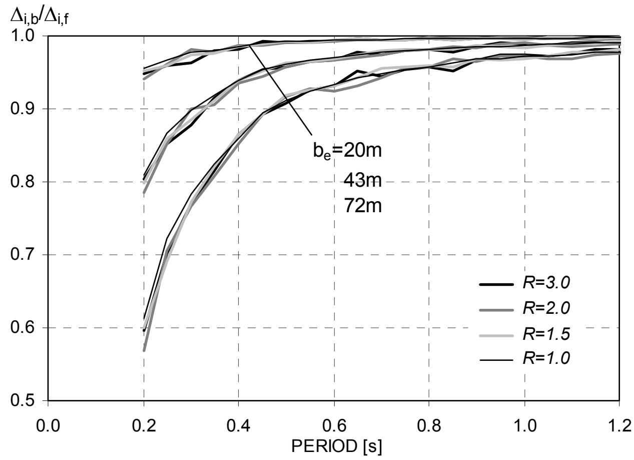

Fig.10a Mean inelastic displacement ratios derived from all 72 earthquake records for systems with $T \geq 0.3$ s and $R \leq 3.0$.

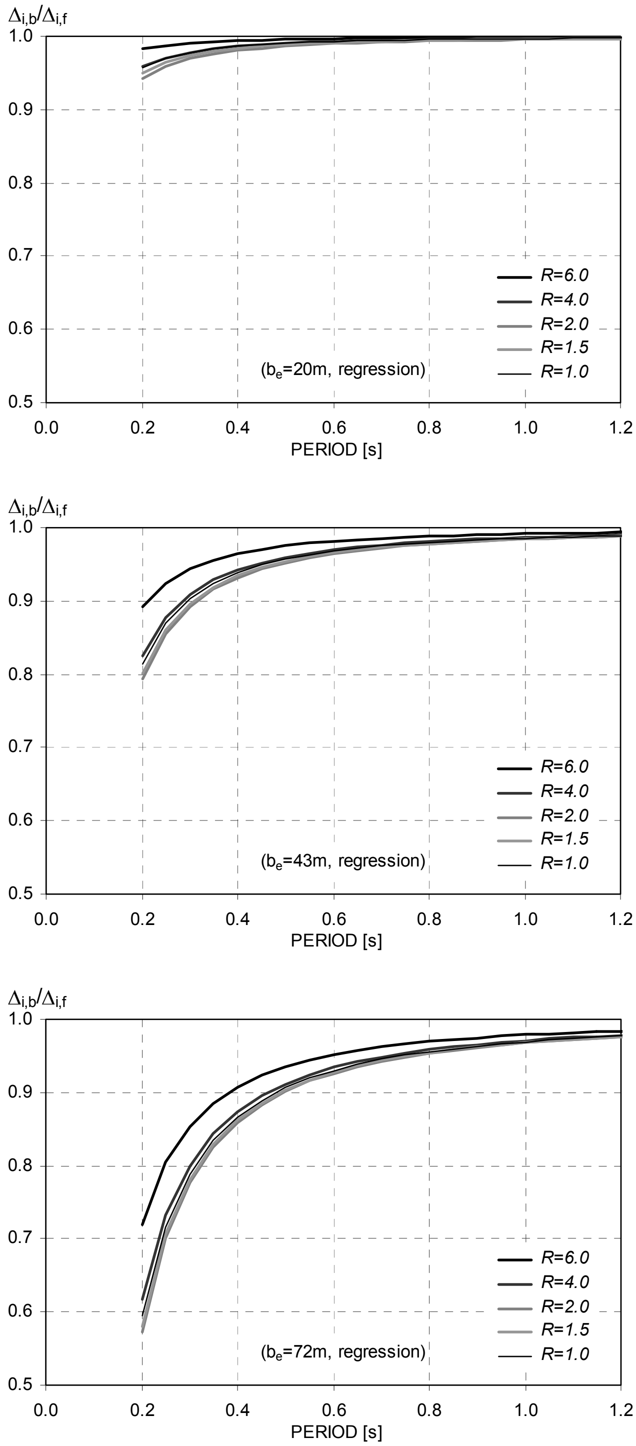

Fig.9 Proposed inelastic displacement ratios for computing kinematic interaction of square foundations.

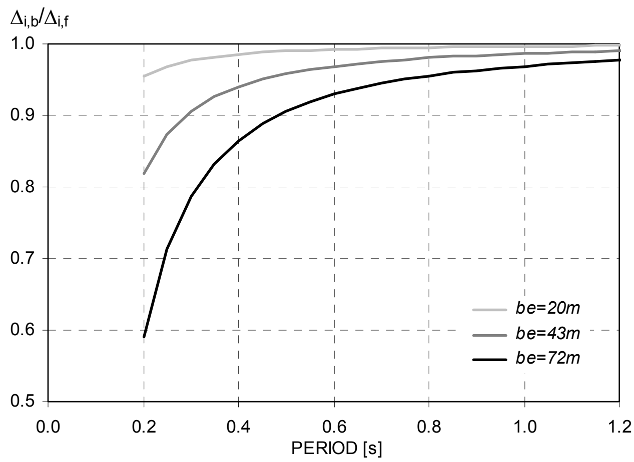

Fig.10b Simplified inelastic displacement ratios proposed for systems with $T \geq 0.3$ s and $R \leq 3.0$.