*Paper No. 359. (quote when citing this article)*
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

# PILE-SOIL-PILE INTERACTION EFFECTS UNDER EARTHQUAKE LOADINGS

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## ABSTRACT

Piles are frequently used in groups to support structures in seismically active regions of the world. The behavior of a pile group may be related to that of a single pile by considering appropriate stiffness of piles, radiation and material damping of the piles, and pile-soil-pile interaction effects of the piles in the group. Several solutions, both analytical and experimental, have been obtained for pile-soil-pile interaction effects of the piles in the group. These studies show that the interaction factors strongly depend on pile spacing and some studies show their dependence on frequency of vibration also. A critical review of these studies is presented. Also an experimental study performed on model pile groups in low compressibility cohesive soil subjected to simulated earthquakes has been presented. A detailed comparison of *Efficiency Factors* obtained for a 2x2 pile group, using analytical and experimental studies, for frequencies of 1 Hz and 10 Hz, frequency range generally associated with earthquakes, shows that pile-group-interaction factors are independent of frequency and depends only on the spacing of piles.

## KEYWORDS

Efficiency factors; interaction factors; piles; pile groups

## INTRODUCTION

Piles are often used to transfer loads from superstructure to the underlying soils. During earthquakes a soil-pile element is subject to a complex system of stresses. Piles are generally used in closely spaced groups. The behavior of piles in a group is controlled by the existence of other, similarly loaded piles, in that group. This situation is popularly referred to as 'Pile-Soil-Pile Interaction'. Novak (1991) critically examined the existing analytical and experimental studies on pile groups and concluded that the dynamic pile-soil-pile interaction characteristics are very complex and non-linear, and the dynamic behavior of pile groups is significantly different from that of a single pile.

## FORCE-DISPLACEMENT CHARACTERISTICS OF PILE GROUPS

Force-displacement characteristics of pile groups are assessed through the use of *Interaction Factors*, by using the superposition approach (Poulos, 1971) and considering soil as an elastic material. In this approach, any two piles of a group are considered at a time and it is assumed that the other piles present in a group do not significantly affect the interaction between two piles under consideration. The interaction factor ($\alpha$) between two similarly loaded vertical piles in a group is defined as:

$$\alpha = \frac{\textit{Additional displacement of Pile}\,2\ \textit{caused by Pile}\,1}{\textit{Displacement of Pile}\,1\ \textit{under its own load}} \tag{1}$$

Some researchers reported their results in the form of *Efficiency Factor* ($\epsilon$), which is the ratio of the stiffness of pile group to the total stiffness of all piles, considered individually, i.e.

$$\epsilon = \frac{\textit{Group stiffness}}{N \times \textit{Single pile stiffness}} \tag{2}$$

where, N is the number of piles in a group. Efficiency factors have been used primarily in this study. However, the results from the previous studies in which interaction factors ($\alpha$) have been used, are presented as such.

The key parameters which control the value of interaction/efficiency factors are: (1) dimensionless frequency factor $a_o = \omega d/V_s$, where $V_s$ is the shear wave velocity of soil, d is the diameter of the pile, and $\omega$ is the frequency of vibration; (2) ratio of pile spacing, s to the diameter of the pile, d i.e. s/d; (3) ratio of the elastic modulus of pile, $E_p$ to the elastic modulus of soil, $E_s$ i.e. $E_p/E_s$; (4) the pile slenderness ratio L/d, where L is the length of the pile; (5) Poission's ratio ($\nu_s$); and (6) The departure angle, $\theta$ i.e. the angle between the line joining the pile centers and the direction of loading.

## PREVIOUS STUDIES ON INTERACTION/EFFICIENCY FACTORS

### 1. Analytical Studies

Poulos (1968), Poulos and Mattes (1971), Poulos (1971) and Poulos and Davis (1980), studied the effect of pile-soil-pile interaction under static loads by discretizing the piles into several segments and relating displacements of the segments to the corresponding forces in both the soil medium and piles. The solution was obtained by the introduction of the condition of displacement compatibility between the soil and the piles and imposing the appropriate boundary conditions.

Analytical studies by several authors have shown that the static interaction factors do not provide information on dynamic aspects of the problem. The significant solutions for dynamic analysis of pile groups have been developed by Wolf and Von Arx (1978), Kaynia and Kausel (1982, 1990), Dobry and Gazetas (1988), and Gazetas *et al.* (1991). Wolf and Von Arx (1978) used an axisymmetric finite element scheme to obtain Green's functions for ring loads which were used to form the soil flexibility matrix. They performed parametric study on single pile foundation, 2x2 pile group, and 10x10 pile group. Figure 1 shows the effect of frequency on the real and imaginary part of efficiency factors for 2x2 pile group and 10x10 pile group. Other soil and pile parameters used in the study are; s/d = 3, $E_p/E_s$ = 178, Poisson's ratio ($\nu_s$) = 0.4, and soil hysteric damping ($\beta$) = 0.05.

Kaynia and Kausel (1982, 1990), developed a formulation for the dynamic analysis of pile groups in semi-infinite layered soil media. Their formulation is in essence a boundary integral type method in which the Green's functions defining the displacement fields due to uniform barrel and disk loads associated with pile-soil interface tractions, are computed by solving the wave equations through Fourier and Hankel transformations (Gazetas *et al.*, 1991). They performed parametric study on 2x2, 3x3, and 4x4 pile groups for pile spacing to diameter (s/d) ratios of 3, 5, and 10. Figure 2, shows the variation of efficiency factors with frequency for a 2x2 pile group and s/d ratios of 2, 5, and 10. Other soil and pile parameters are; $E_p/E_s$=1000 $\nu_s$=0.4, L/d=15, and $\beta$=0.05.

A simple approximate method for calculating dynamic interaction factors for homogeneous soils was proposed by Dobry and Gazetas (1988). They assumed that the displacement field around a vibrating pile,

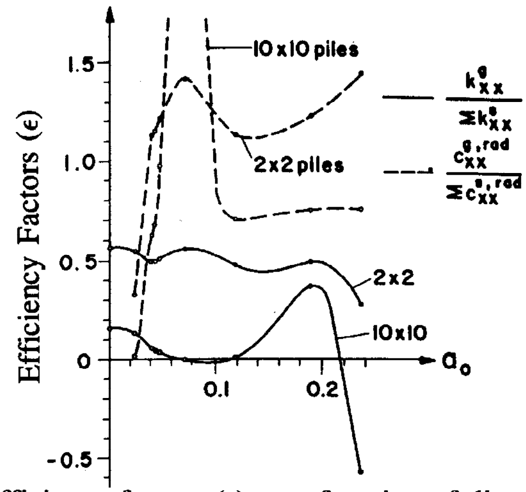



Fig. 1 Real and imaginary Efficiency factors ($\epsilon$) as a function of dimensionless frequency ($a_o$) for 2x2 and 10x10 pile groups (Wolf and Von Arx, 1978)

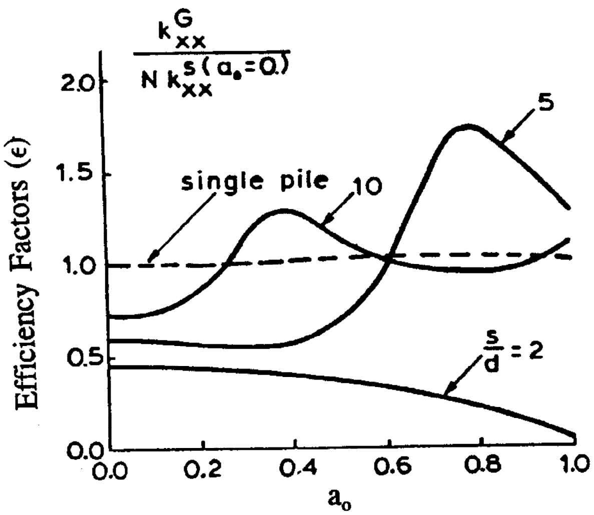



Fig. 2 Efficiency factors, $\epsilon$ (real part) as a function of dimensionless frequency factor, $a_o$ for 2x2 pile group (Kaynia and Kausel, 1982)

and thus, also the displacement of the neighboring pile, is governed by the law of cylindrical wave propagation. The interaction factor thus obtained for horizontal vibration is given by:

$$\alpha \approx 0.5\left(\frac{s}{d}\right)^{-\frac{1}{2}} \exp\left(\frac{-\beta\,\omega\,s}{V_{La}}\right) . \exp\left(\frac{-i\,\omega\,s}{V_{La}}\right) \qquad for\ \theta = 0° \tag{3}$$

$$\alpha \approx 0.53\left(\frac{s}{d}\right)^{-\frac{1}{2}} \exp\left(\frac{-\beta\,\omega\,s}{V_s}\right) . \exp\left(\frac{-i\,\omega\,s}{V_s}\right) \qquad for\ \theta = 90° \tag{4}$$

where, $\theta$ is the departure angle and $V_{La}$ is the Lysmer's analog wave velocity. For any other departure angle ($\theta$), interaction factor ($\alpha$) can be obtained with sufficient accuracy from the cosine law.

A closer look to the above equations reveals that for certain range of parameters, particularly for low frequencies, the interaction factor for $\theta = 90°$ is higher than for $\theta = 0°$. This is not consistent with the studies by others and is exactly opposite to the recommendations of Finn and Gohl (1992) which recommends that the interaction between piles for off-line shaking can be ignored for all practical purposes.

Gazetas *et al.* (1991), used the rigorous analytical-numerical formulation developed by Kaynia and Kausel (1982) to study the effect of frequency on interaction factors. Results of Wolf and Von Arx (1978) and Kaynia and Kausel (1982) show peaks and troughs occurring at different location for different values of s/d ratio. They observed that the picture clears up significantly when an alternative frequency parameter $b_o = a_o * s/d$ is used. Horizontal interaction factors for departure angle 0° and 90° are shown in Fig. 3. The parameters used for developing this plot are: $E_p/E_s = 1{,}000$; $L/d = 20$; $\beta = 0.05$; and $\nu_s = 0.4$.

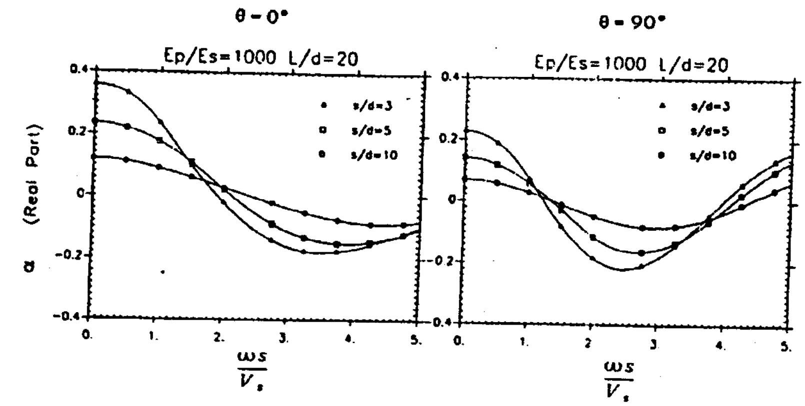



Fig. 3 Horizontal interaction factors (α) as function of dimensionless frequency factor, $b_o$ (Gazetas *et al.*, 1991)

2. Experimental Studies

Scott *et al.* (1982) conducted a centrifuge model study on single piles and two and four pile groups embedded in saturated silty beach sand. The effect of pile spacing on effective pile stiffness was studied from the pile group tests. The results given by Scott *et al.* (1982) were compared with other predictions and are given in Fig. 6.

Fin and Gohl (1992), performed model tests on shake table on two and four pile groups in sand at various pile spacings. They concluded that the interaction between piles in a group subject to in-line lateral base shaking is significant up to 6 pile diameter spacing (Fig. 6).

UMR-EXPERIMENTS

Model tests on two and four pile groups embedded in cohesive soil and subjected to simulated earthquakes of various amplitudes and frequencies were performed at University of Missouri-Rolla shake table (Sreerama, 1993). Total of 23 tests were performed on single piles and pile groups. Two types of pile groups (Two pile group and four pile group) at three different pile spacings (3d, 5d, and 8d) were tested. Single piles and pile groups were excited at base at three different amplitudes of excitation (0.03, 0.04, and 0.05 inch). In addition to these tests, one free vibration test and one static lateral load test was also performed on single pile. The limited results from pile group tests have only been presented here. For detail description of experimental set-up and other results see Sreerama (1993).

Prediction of efficiency factors for a 2x2 pile group using all the above recommendations have been included to study the variation in the predicted values using these methods and to study the effect of frequency at 1 and 10 Hz, frequency range typically associated with earthquakes.

Figures 4 and 5 show the displacement response curves of the two and four pile groups, respectively. Piles are spaced at a distance of three times the diameter of the pile (3d). Three curves correspond to three different amplitude levels, 0.03, 0.04, and 0.05 inches, respectively. Similar plots for two and four pile groups with piles spaced at distances of 5d and 8d are reported elsewhere (Sreerama, 1993). Each point on the curve represents the peak single amplitude absolute displacement of the pile cap under the influence of base shaking at the corresponding frequency. These and other similar figures clearly show that the natural frequencies of the pile group-soil system decrease with increased base motion amplitudes which indicates that the system behaved in a non-linear manner, even in this small sized model. Therefore, only non-linear analyses are recommended. Limited data from these experiments restrict to derive any definite conclusions on this aspect. However, further work is in progress (Arsoy, 1996).

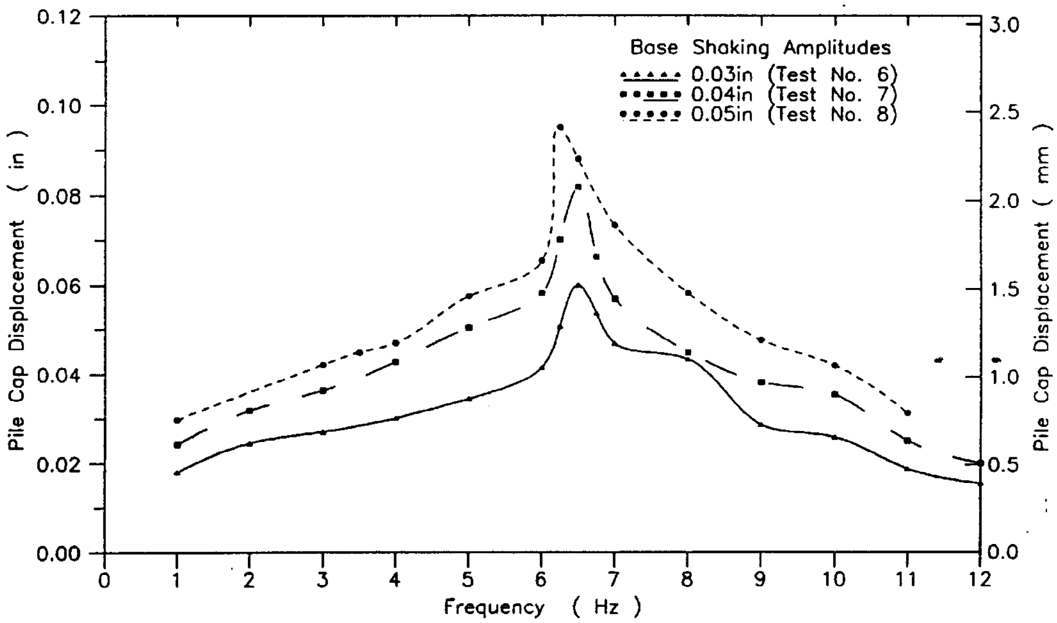



Fig. 4 Displacement response of a two pile group-3d spacing (Sreerama, 1993)

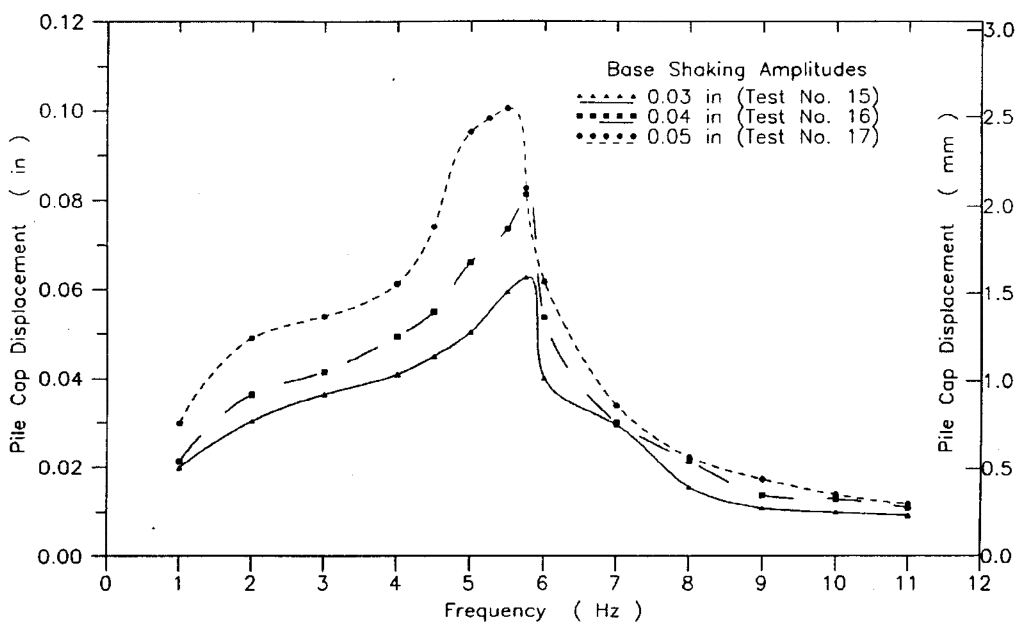



Fig. 5 Displacement response of a four pile group-3d spacing (Sreerama, 1993)

Efficiency Factors ($\epsilon$) developed from the present study along with the those from previous studies are shown in Figure 6. Following relationship was developed by Sreerama from the experimental data to determine the efficiency factor ($\epsilon$):

$$\epsilon = \left(\frac{1}{2}\right)^{\frac{3}{2}} \left(\frac{s}{d}\right)^{\frac{1}{2}} \left(\frac{1}{N}\right)^{\frac{1}{5}} \quad \leq 1 \tag{5}$$

where, s/d is the ratio of pile spacing to the diameter of the pile and N is the number of piles in a pile group. For N = 2 and s/d = 8, efficiency factor ($\epsilon$) = 0.87 and for N = 4 and s/d = 8, efficiency factor ($\epsilon$) = 0.76.

## DISCUSSION

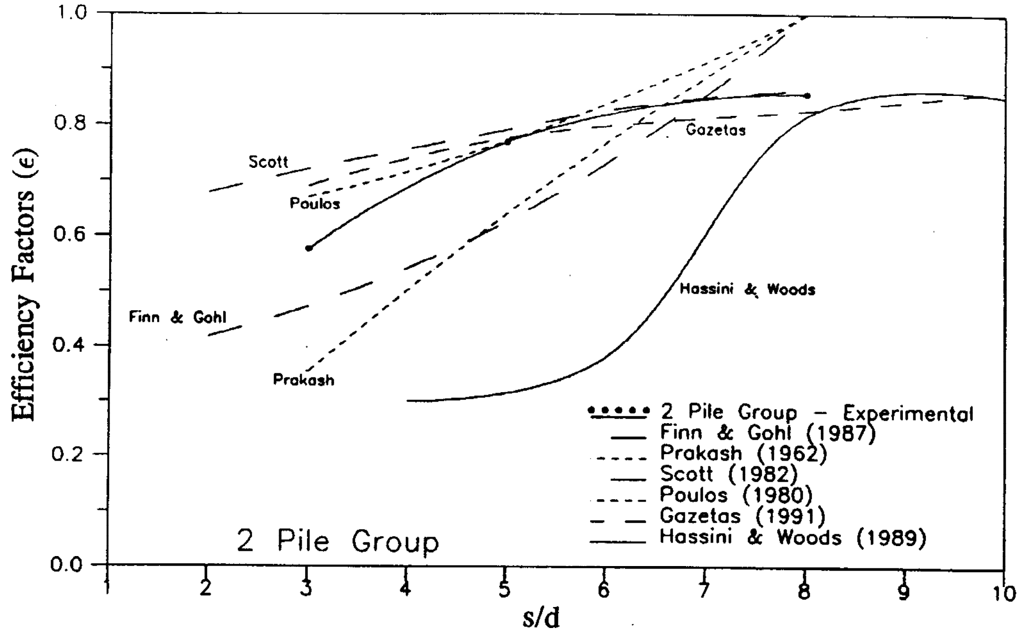
In order to study the variation in efficiency factors ($\epsilon$) for 2 and 4 pile groups by different methods, Figure 6 was prepared (Sreerama, 1993). The frequencies used to compute the efficiency factors ($\epsilon$) shown in Fig. 6 by Kaynia and Kausel (1982) and Gazetas *et al.* (1991), are the natural frequency observed in the experiments of Sreerama (1993). This figure gives an insight of the confusion on this subject and only generalized conclusions can be drawn from this figure.

To study the variation in efficiency factors from different methods and the effect of frequency of excitation on the efficiency factors ($\epsilon$), Table 1 was developed (Kumar, 1996). The values of efficiency factors ($\epsilon$) shown in the table are for a 2x2 pile group and vibration frequencies of 1 and 10 Hz. Piles are assumed at a spacing of 3d. This table shows that, for all practical purposes, all the studies give very similar results except that by Prakash (1962) which was the first attempt to predict the behavior of pile groups using the results from single piles. In fact, these recommendations are under revision based on the analysis of new data on pile groups. Slight variation in the results can be attributed to the difference in parameters used in different studies.

Table 1 also demonstrates that for the frequency range generally associated with the earthquakes, interaction/efficiency factors are independent of frequency of excitation. A closer look at the factors of Kaynia and Kausel (1982) and Gazetas *et al.* (1991) indicates that although the factors are frequency dependent but have negligible variation with dimensionless frequency factor within the frequency range of interest in case of seismic excitation. For very high frequencies of vibration, generally associated with loads from machine unbalances, the effect of frequency is important to be considered in the design.

TABLE 1. Comparison of efficiency factors ($\epsilon$) from different studies (Kumar, 1996)

| Reference | Efficiency Factor | | Soil and Pile Parameters Used |
|---|---|---|---|
| | f=1 Hz | f=10 Hz | |
| Prakash (1962) | 0.35 | 0.35 | Independent |
| Polous (1971) | 0.50 | 0.50 | $E_p/E_s=1000, \nu_s=0.5, L/d=25$ |
| Wolf and Von Arx (1978) | 0.56 | 0.56 | $E_p/E_s=178, \nu_s=0.4, L/d=20, \beta=0.05$ |
| Fin and Gohl (1982) | 0.48 | 0.48 | Independent |
| Scott *et al.* (1982) | 0.52 | 0.52 | Independent |
| Kaynia and Kausel(1982, 1990) | 0.53 | 0.53 | $E_p/E_s=1000, \nu_s=0.4, L/d=15, \beta=0.05$ |
| Dobry and Gazetas(1988) | 0.543 | 0.554 | $E_p/E_s=1000, \nu_s=0.35, \beta=0.05$ |
| Gazetas et al. (1991) | 0.56 | 0.56 | $E_p/E_s=1000, \nu_s=0.4, L/d=20, \beta=0.05$ |
| Sreerama, 1993 | 0.45 | 0.45 | Independent |



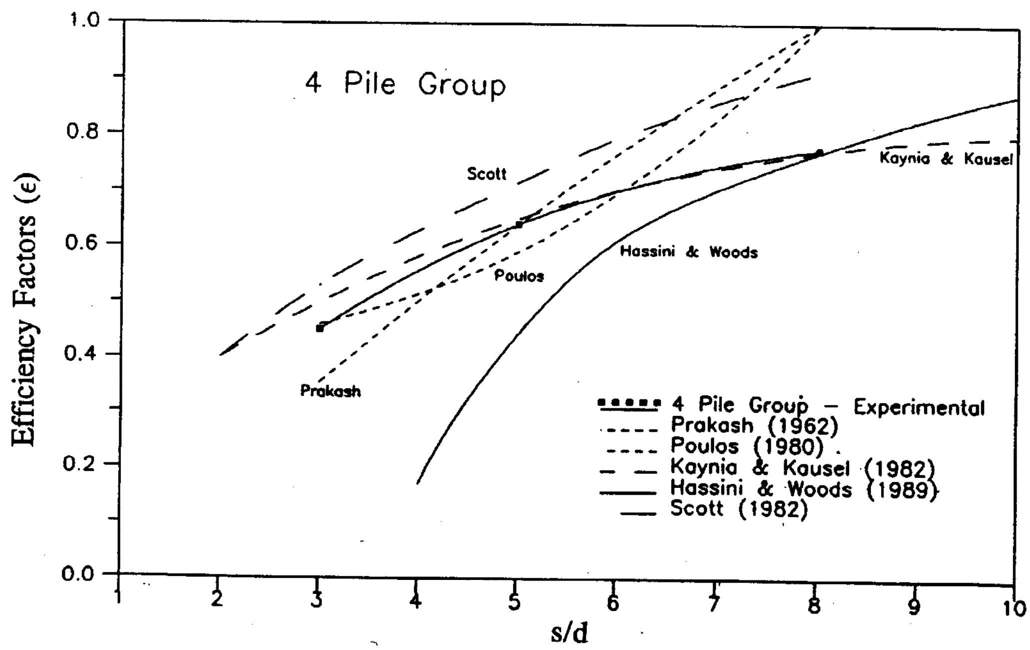




Fig. 6 Comparison of pile-soil-pile efficiency factors (a) two pile group (b) four pile group (Sreerama, 1993)

## CONCLUSIONS

The following conclusions are derived from this study:

1. For analysis of piles for earthquake excitation, the group interaction/efficiency factors are independent of frequency.
2. The efficiency factors approach unity as s/d increases and also depends on the number of piles in a pile group.
3. Pile group behavior is non-linear under earthquake loading.

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