Seismic Response of
Single Piles and Pile Groups

by

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A numerical study is presented on the kinematic response of groups of floating piles connected through rigid massless caps and subjected to vertically-propagating harmonic S waves. Pile-soil and pile-pile interaction effects are modeled rigorously. Parametric results for the effective seismic input motion at the pile cap, normalized by the free-field ground-surface motion, are displayed in dimensionless form for a number of typical pile-group configurations, in three idealized soil profiles. Pile-head fixity conditions and the pile/soil modulus ratio are found to affect appreciably the seismic response of both single piles and pile groups. The presented results can be utilized in assessing the influence of piles on the effective seismic excitation at the base of a structure.

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PILE PILE INTERACTION.
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PREFACE

The National Center for Earthquake Engineering Research (NCEER) is devoted to the expansion and dissemination of knowledge about earthquakes, the improvement of earthquake-resistant design, and the implementation of seismic hazard mitigation procedures to minimize loss of lives and property. The emphasis is on structures and lifelines that are found in zones of moderate to high seismicity throughout the United States.

NCEER's research is being carried out in an integrated and coordinated manner following a structured program. The current research program comprises four main areas:

- Existing and New Structures
- Secondary and Protective Systems
- Lifeline Systems
- Disaster Research and Planning

This technical report pertains to Program 3, Lifeline Systems, and more specifically to the study of dams, bridges and infrastructures.

The safe and serviceable operation of lifeline systems such as gas, electricity, oil, water, communication and transportation networks, immediately after a severe earthquake, is of crucial importance to the welfare of the general public, and to the mitigation of seismic hazards upon society at large. The long-term goals of the lifeline study are to evaluate the seismic performance of lifeline systems in general, and to recommend measures for mitigating the societal risk arising from their failures.

In addition to the study of specific lifeline systems, such as water delivery and crude oil transmission systems, effort is directed toward the study of the behavior of dams, bridges and infrastructures under seismic conditions. Seismological and geotechnical issues, such as variation in seismic intensity from attenuation effects, faulting, liquefaction and spatial variability of soil properties are topics under investigation. These topics are shown in the figure below.

Program Elements and Tasks

Dams	Bridges	Infrastructures
• Fragility Curves • Computer Codes • Risk Assessment and Management	• Evaluate and Recommend Response Modification Factor (RMF) • Develop Probabilistic Load and Resistant Factor Design (LRDF) Format	• Inspection, Maintenance and Repair • Non-destructive Tests (NDT) and Inspection • Develop On-line System Identification Techniques (INTELAB) • Evaluate Seismic Effects on Metropolitan New York Transit Facilities

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This report investigates the nature of seismic pile-soil-pile interaction. A comprehensive set of dimensionless graphs is presented, which depict three pile configurations: single piles; groups of piles in a row; and square pile groups. Each pile configuration is embedded in three different soil deposits: homogeneous halfspace, halfspace with modulus proportional to depth, and a two-layered stratum.

Each pile-foundation soil system is excited by vertically propagating harmonic shear (S) waves. The Kaynia and Kausel (1982) formulation is used for the combination of incident waves, reflected-at-surface waves, and waves diffracted by the piles and propagating in a primarily-horizontal direction. The results show that, whereas the influence of the nature of the soil profile is profound at all frequencies, the effects of pile-group configuration, number of piles in the group, and relative spacing between piles are usually insignificant. Pile-head "fixity" conditions and the pile/soil modulus ratio are found to appreciably affect the seismic response of both single piles and pile groups.

ABSTRACT

A numerical study is presented on the kinematic response of groups of floating piles connected through rigid massless caps and subjected to vertically-propagating harmonic S waves. Pile-soil and pile-pile interaction effects are modeled rigorously. Parametric results for the **"effective seismic input motion"** at the pile cap, normalized by the **"free-field"** ground-surface motion, are displayed in dimensionless form for a number of typical pile-group configurations, in three idealized soil profiles: a homogeneous halfspace, a halfspace with modulus proportional to depth, and a two-layered stratum. It is shown that, whereas the influence of the nature of the soil profile is profound at all frequencies, the effects of pile-group configuration, number of piles in the group, and relative spacing between piles are usually insignificant. Pile-head "fixity" conditions and the pile/soil modulus ratio are found to affect appreciably the seismic response of both single piles and pile groups. The presented results can be utilized in assessing the influence of piles on the effective seismic excitation at the base of a structure.

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SECTION 1
INTRODUCTION

Consider a piled foundation supporting a structure and subjected to upward propagating ("incident") seismic waves. While an extremely flexible pile might simply follow the seismic motion of the ground, real piles "resist" and, hence, modify soil deformations. As a result, the incident seismic waves are "scattered" and the seismic excitation to which the structure base is **effectively** subjected differs from the **free-field** motion and may generally include rotational (in addition to translational) components. In turn, piles experience bending, axial and shearing stresses, in function of their overall rigidity relative to the soil. This wave-induced interplay between soil and piles is also affected by the kinematic constraints imposed at the head of the piles from the cap and the super-structure, and will be called hereafter **kinematic soil-piled-foundation seismic interaction**, or simply kinematic/seismic interaction.

While, in real-life situations, rigorously modeling all the factors influencing the kinematic response is a formidable task, (especially if non-vertical seismic waves are expected to impinge on the piles, or if substantial soil nonlinearities are likely to develop) practically useful results and valuable insight to the mechanics of soil-pile interaction during earthquake shaking can be obtained from proper linear analyses of simple idealized systems. A series of such analyses conducted by the authors have led to the parametric study reported in this paper.

Analyses of the kinematic seismic response of single piles and of pile groups have been reported in the last fifteen years by a number of researchers, including Blaney et al (1976), Takemiya & Yamada (1981), Flores-Berrones & Whitman (1982), Wolf & Von Arx (1978, 1982), Kaynia & Kausel (1982), Gazetas (1984), Barhouthi (1984), and Tazoh et al (1988). Continuum as well as Winkler-type models were developed/used in these studies. It appears, however, that the amount of published parametric results on this subject is very limited, especially for pile groups, and a number of questions remain unanswered. By contrast, a wealth of data is presently available for the response of piles and pile groups under dynamic force-and-moment loading **at the top**; such a loading arises during earthquakes from the inertial forces developing on the superstructure and the pile-cap.

To help close this apparent gap in the literature, this report presents a comprehensive set of dimensionless graphs which is expected to be readily utilized in practical applications. Moreover, a comparative study of these graphs leads to some interesting conclusions that may contribute towards an improved appreciation of the nature of seismic pile-soil-pile interaction.

SECTION 2
PROBLEM DEFINITION AND METHODS OF SOLUTION

Three categories of groups of floating piles are studied in this report:

- single free-head or fixed-head pile
- rigidly-capped pile group consisting of 2, 3, 4, 6, or 9 piles in a **row**
- rigidly-capped **square** group of 2x2, 4x4, or 6x6 piles

All piles, of diameter d and length L, are considered to be linear elastic beams with constant Young's modulus, E_p, and mass density, ρ_p. They are embedded in three different soil deposits (Fig. 3-1) in which the Young's modulus: (a) is a constant (E_s), (b) is proportional to depth [$E_s(z) = E_s(L).z/L$], or (c) has two distinct values (E_{s1} and E_{s2}) above and below a depth $z = L/2$, respectively, with $E_{s1}=0.10E_{s2}$ or $E_{s1}=0.30E_{s2}$. In all cases, the soil is assumed to be a linear hysteretic continuum with constant Poisson's ratio ν_s, constant material density ρ_s, and constant hysteretic damping β_s.

Each piled-foundation-soil system is excited by vertically propagating harmonic shear (S) waves, which would produce a horizontal oscillation $\mathbf{U_{ff}\ exp(i\omega t)}$ at a "free-field" point of the ground surface, i.e. at a location unaffected by the presence of the piles. Around the piles the "perturbed" wave field is a complicated combination of incident (upward propagating) waves, reflected-at-the-surface (downward propagating) waves, and waves diffracted by the piles and propagating in a primarily-horizontal direction. A rigorous method of solution to this 3-Dimensional dynamic boundary-value problem has been developed by Kaynia and Kausel (1982). This method is in essence a boundary-integral type formulation in which the Green's Functions, defining the displacement fields due to uniform **barrel** and **disk** unit loads associated with pile-soil interface tractions, are computed by solving the wave equations through Fourier and Hankel transformations (Kausel 1981). These Functions yield the dynamic soil flexibility matrix which is combined with the analytically-derived pile flexibility matrix, while enforcing compatibility of deformations at the pile-soil interface. For an arbitrary pile group the method gives the horizontal translation and rotation of the massless cap, both of which are complex-valued functions of frequency, for a given soil profile. The Kaynia & Kausel (1982) formulation was used to obtain most of the results presented herein. In addition, a finite-element (Blaney et al 1976) and a boundary-element (Ahmad 1985) formulations were used in a few cases for obtaining the response of single piles, and for establishing the very small sensitivity of the results to using different numerical solution procedures. A simple model developed for the problem at hand by Makris & Gazetas (1990) is also used for qualitatively explaining some of the trends observed in the numerical results.

SECTION 3
RESULTS AND DISCUSSION

The effects of soil-piled-foundation kinematic interaction are portrayed in the form of two **kinematic response factors**

$$I_u = \frac{|U_p|}{U_{ff}} \quad \text{and} \quad I_\phi = \frac{|\Phi_p|\ d}{U_{ff}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3\text{-}1)$$

plotted as functions of the frequency factor

$$a_o = \frac{\omega d}{V_s^*} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3\text{-}2)$$

where $V_s{}^*$ is a charateristic value of the soil S-wave velocity profile (in this paper $V_s{}^*$ is taken equal to V_s for the homogeneous profile, to $V_s(L)$ for the linearly inhomogeneous profile, and to V_{s1} for the two-layered profile). The horizontal displacement, U_p, and angle of rotation, Φ_p, at pile cap level constitute the **"effective input motion"** ; they are complex numbers because of the generation of both radiation damping (due to diffracted waves spreading away from each pile) and material damping (due to hysteretic action in the soil). Only the amplitudes (absolute values) of U_p and Φ_p are used in the definitions of kinematic response factors (Eqs. 3-1).

The dimensionless problem parameters whose influence on I_u and I_ϕ is investigated for a given pile group and soil profile include:

- The ratio of the effective pile modulus to a characteristic soil Young's modulus

  $$\frac{E_p}{E_s},\ \frac{E_p}{E_s(L)},\ \frac{E_p}{E_{s1}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3\text{-}3)$$

  for the homogeneous, inhomogeneous, or layered profiles of Fig. 3-1, respectively
- The ratio of the spacing between the closest piles to the diameter of the piles, s/d (hereafter called simply spacing ratio), and

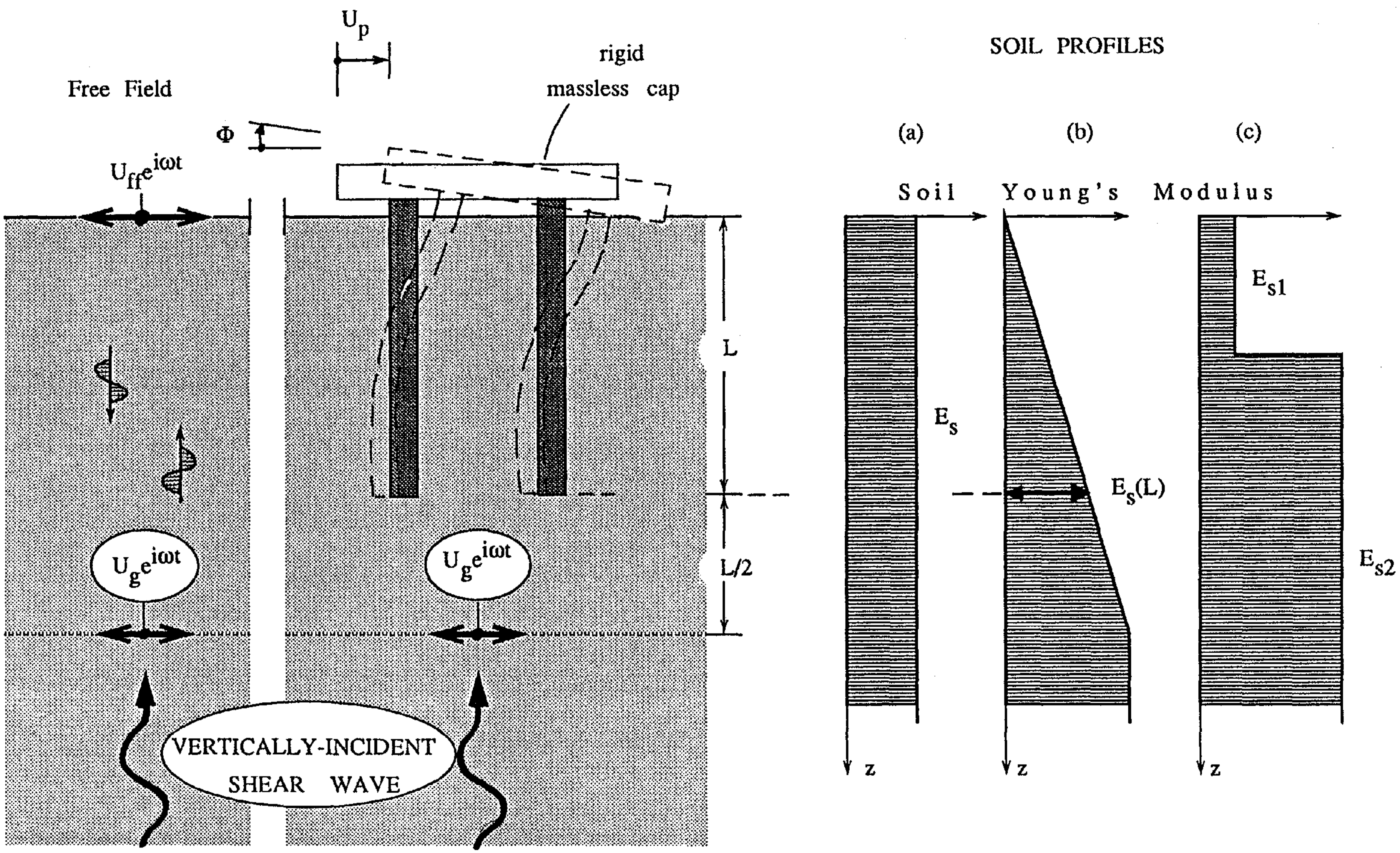

Fig.3-1 Sketch of the System and Soil Profiles Studied

- The pile slenderness ratio, L/d.

A few results are also displayed in the form of distributions along the depth of kinematic pile displacements and free-field soil displacements.

The dimensionless graphs are arranged according to pile configuration as follows:

- Figs 3-3 - 3-9 display results for a *single* pile
- Figs 3-10 - 3-19 are for groups of piles in a *row*
- Figs 3-20 - 3-24 are for *square* pile groups.

These graphs can be utilized to quickly assess the kinematic response of piled-foundations, without a need for detailed job-specific numerical analyses. The presented figures (in conjunction with the results of Kaynia-Kausel 1982, of Gazetas 1984, and of additional analyses by the present authors), reveal the following significant trends:

1. The *general shape* of the kinematic displacement factor, $I_u = I_u(a_o)$, is idealized in the sketch shown in Fig. 3-2. It consists (for single piles *and* pile groups) of three distinct regions in the frequency range of greatest interest for earthquake loading ($a_o < 0.5$):

- A low-frequency region ($0 < a_o < a_{o1}$) in which $I_u \approx 1$ -- the end result of the pile(s) following closely the relatively-large-wavelength deformations of the ground, as illustrated in Fig. 3-7 for a pile in the two-layered soil with E_{s1}/E_{s2}=0.10

- An intermediate-frequency region ($a_{o1} < a_o < a_{o2}$) characterized by I_u declining rapidly with frequency -- a direct consequence of the progressively-increasing incompatibility between the "wavy" pattern of soil movements and the flexurally-deforming pile(s), as illustrated in Fig. 3-9 for a pile in the two-layered soil with E_{s1}/E_{s2} = 0.10

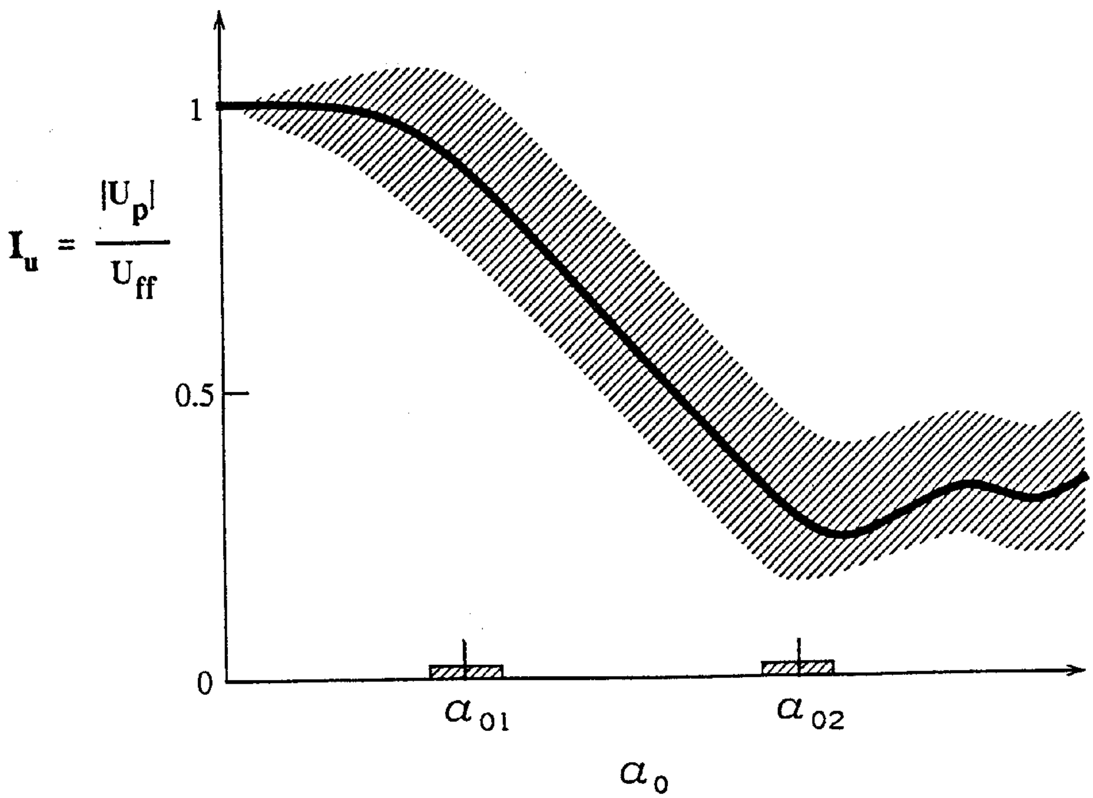

Fig.3-2 Idealized General Shape of the Kinematic Displacement Factor, $I_u = I_u(a_0)$, Explaining the Transition Frequency Factors a_{01} and a_{02}.

- A relatively-high-frequency region $a_o > a_{o2}$ in which $I_u(a_o)$ fluctuates around an essentially-constant value of about 0.20 to 0.40 -- since at such frequencies the increasing "waviness" of the soil deformations is largely counterbalanced by the generally-decreasing amplitude of the ground surface motion. Indeed, $a_o > a_{o2}$ corresponds to seismic-excitation frequencies, f, being of the order of five-to-ten-times greater than the natural frequency, f_n, of the soil deposit in S-waves; and it is well known from the 1-Dimensional Soil Amplification Theory (Roesset 1976) that a linearly-hysteretic soil would experience at such frequencies U_{ff} values not very different from the values of the base-rock displacement.

The reader should recall that kinematic displacements induced on **rigid shallow foundations** by seismic waves impinging at an angle (with or without random phase "incoherence") follow a qualitatively similar trend versus frequency with that discussed above for the kinematic displacements atop piles and pile groups. Excellent presentations on this subject for shallow foundations can be found in Scanlan (1976), Luco & Wong (1986), Pais & Kausel (1985) and Veletsos & Prasad (1988).

2. Whereas this general shape of $I_u(a_o)$ is approximately valid in all studied cases, four factors seem to significantly affect the transition frequencies a_{o1} and a_{o2}: (i) the type of soil profile; (ii) the relative rigidity of the pile; (iii) the pile-head fixity conditions; and (iv) the pile slenderness. Specifically:

The significant factor controlling the magnitude of a_{o1} and a_{o2}, and thereby the kinematic response of single piles and pile groups, is the nature of the soil profile as expressed by the variation of soil modulus, E_s, versus depth. In strongly non-homogeneous deposits, as the one having modulus proportional to depth, a_{o1} is very small -- of the order of merely 0.05 (e.g. Fig. 3-4,3-12,3-13,3-16,3-17,3-18,3-22,3-23, and 3-24), depending of course on the value of the other three factors. By contrast, in a homogeneous stratum or in a stratum with a thick homogeneous top layer a_{o1} may be as high as 0.20-0.30 (e.g. Fig. 3-3, 3-5, 3-6,3-10, and 3-20). (Thus, in terms of actual frequencies, ω, in deposits with the same **average** wave velocity the decaying branch of I_u will start earlier -- by a factor of about 2 -- in the nonhomogeneous profile.) Similarly, a_{o2} is about 0.10-0.20 in the linear-modulus profile "b" compared to a_{o2} usually exceeding 0.40 in the two other profiles "a" and "c". The practical implications of these differences are worthy of note: in nonhomogeneous profiles, piles and pile groups will **depress** a much wider spectrum of the harmonic components of the incident seismic excitation (and thereby their heads will experience smaller "effective" horizontal input motions) than pile(s) in a homogeneous soil.

The relative rigidity of the pile(s), expressed through the aforementioned moduli ratios (Eq. 3-3) also affects a_{o1} and a_{o2}. As expected, the stiffer pile(s) are more effective in depressing a seismic soil movements and, hence, their kinematic response is characterized by smaller values of a_{o1} and a_{o2}, compared with those of the softer piles (e.g. see Figs. 3-3,3-4,3-5, and compare Fig. 3-10 with Fig. 3-11, and Fig. 3-20 with Fig. 3-21).

Increasing, the degree of fixity at the pile-cap level (from "hinged"- or "free"-head to "fixed"-head piles) has an effect similar to the effect of increasing E_p/E_s: a_{o1} and a_{o2} tend to decrease and, hence, the "effective" pile-cap input motion in an earthquake excitation will tend to be less severe (see Fig. 3-5). An additional influence of pile-head fixity conditions has been observed with pile(s) embedded in homogeneous deposits and in deposits with a homogeneous top layer (like profile "c"): "free"-head single piles and "hinged"- at-the-cap piles and pile groups embedded in such soils experience in the low to intermediate frequency range I_u values exceeding unity. This appears to be the only case where a small deviation from the aforescribed general shape of $I_u(a_o)$ has been observed. It implies an "effective" pile top motion, $|U_p|$, greater than the free-field U_{ff}; Fig. 3-8 elucidates this possibility by comparing the pile and soil displacement profiles (both real, i.e. in-phase, and imaginary, i.e. 90°-out-of-phase, components of displacement) for the two-layered profile with $E_{s1}/E_{s2} = 0.10$. With "fixed"-head piles this tendency for larger pile-top motion is completely suppressed, as evidenced in Fig. 3-5 for a single pile and in numerous additional results for pile groups (not shown herein).

3. Pile group configuration ("row" versus "square"), number of piles in the group (1, 2, 3, 36), and pile-spacing ratio (s/d = 3, 5 and 10) make little difference on I_p, in the low ($a_o < a_{o1}$) and intermediate ($a_{o1} < a_o < a_{o2}$) frequency ranges. This remarkable conclusion is valid (within engineering accuracy, of course) for most studied soil profiles and relative pile rigidities. It implies that with seismic excitation there is **little pile-to-pile interaction** at this frequency range, even for close pile spacing. By contrast, with inertial excitation at the top, pile-to-pile interaction has been shown in the literature to play a dominant role in the response of pile groups. (The only small deviation from this general trend is depicted in Fig. 3-11 for two piles in a homogeneous half-space.)

There is a straightforward explanation for this lack of interaction between the piles of a group for **very low** frequency factors: seismic wavelengths are then so large that piles follow almost exactly the free-field ground movements, and there is hardly any scattering of the vertically-propagating seismic waves. In other words, at the pile-soil interface, no waves originate that would spread outward and affect the neighboring piles; hence no influence of one pile on another, and no interaction.

However, the explanation is not as simple for low and intermediate frequency factors, at which pile and (free-field) soil motions **are** different and the incident seismic waves **are** therefore diffracted by the piles. A qualitative explanation is suggested herein (refer to Fig. 3-9) which compares the seismic displacement profiles of the two-layered soil deposit with $E_{s1}/E_{s2} = 0.10$ and of a pile embedded in it, at a frequency $a_o \approx a_{o2}$. We notice that the difference $(U_u - U_{ff})$, which is responsible for the generation of waves at the pile-soil interface ("diffraction"), is practically zero within the bottom stiff layer. In the top soft layer, however, this difference is **positive** from the ground surface down to $z \approx 4d$ and **negative** for greater depths. Therefore, the diffracted waves start with similar amplitudes but **opposite phases** from the two parts of the pile -- a situation reminiscent of rocking, which is conducive to considerable **"destructive wave interference"** and hence to rapidly-diminishing amplitudes away from the source pile, leading eventually to only a small influence of one pile on another.

On the other hand, at high frequencies ($a_o > a_{o2}$), pile spacing, total number of piles and pile-group configuration appear to affect (although perhaps not significantly from a practical viewpoint) the fluctuations of the $I_u(a_o)$ curves.

4. Although the foregoing discussion focused only on horizontal displacements, it is important to recognize that both "hinged"- and "fixed"-head pile groups will experience cap rotations during seismic-wave excitation. Thus, a rocking component of "effective" input motion develops, the significance of which in rocking oscillations of slender structures must be properly evaluated. Understandably, the amplitude of this kinematic rotation is quite sensitive to pile spacing ratio s/d, pile-group configuration, total number of piles in the group, and pile-soil modulus ratio E_p/E_s -- as all these factors affect the overall rotational stiffness of the group.

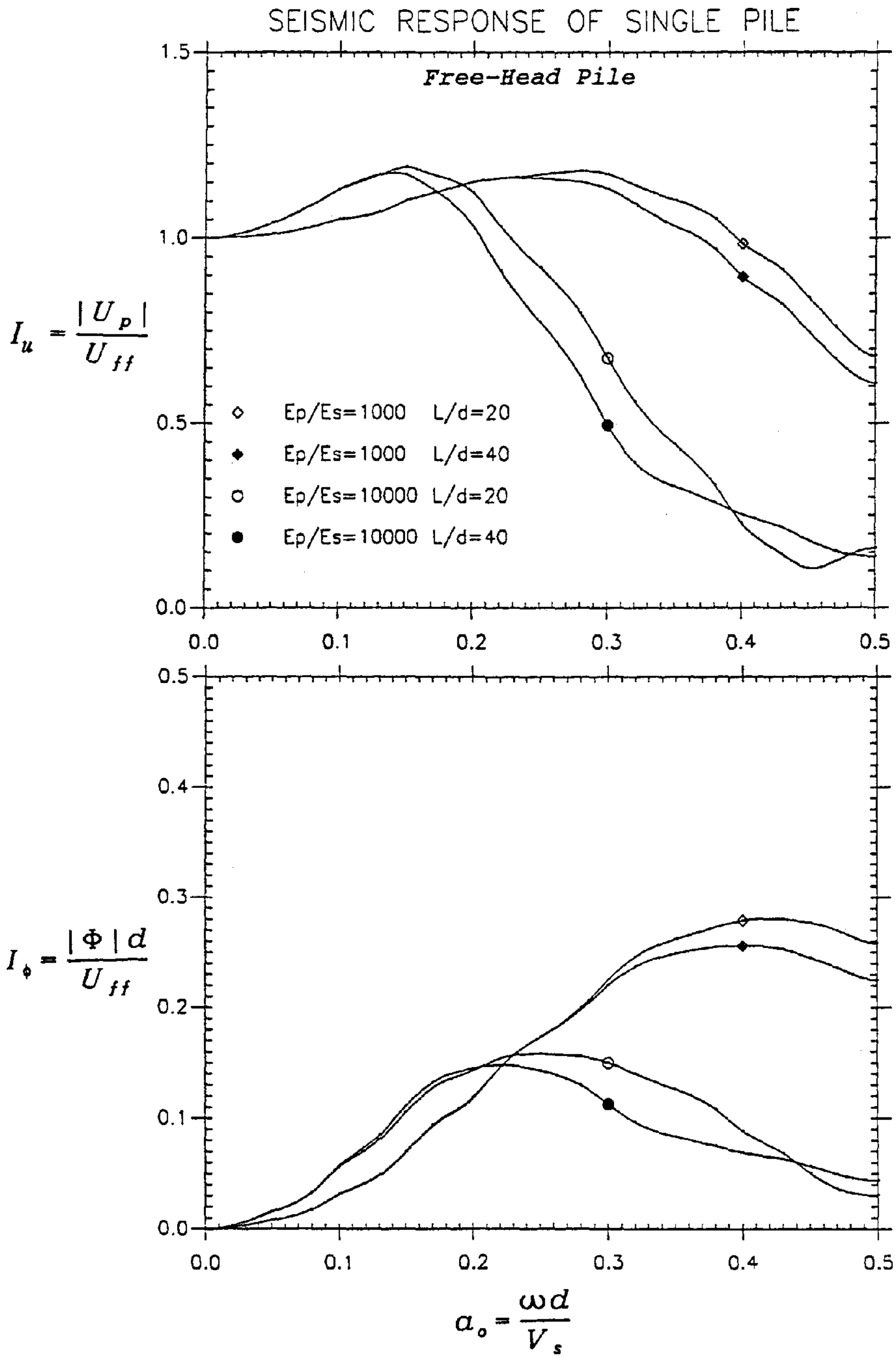

Fig.3-3 Effect of L/d and E_p/E_s on Kinematic Seismic Response of Single Free-head Piles in Homogeneous Soil ($\rho_s/\rho_p = 0.7$, $\beta = 0.05$ and $\nu_s = 0.4$)

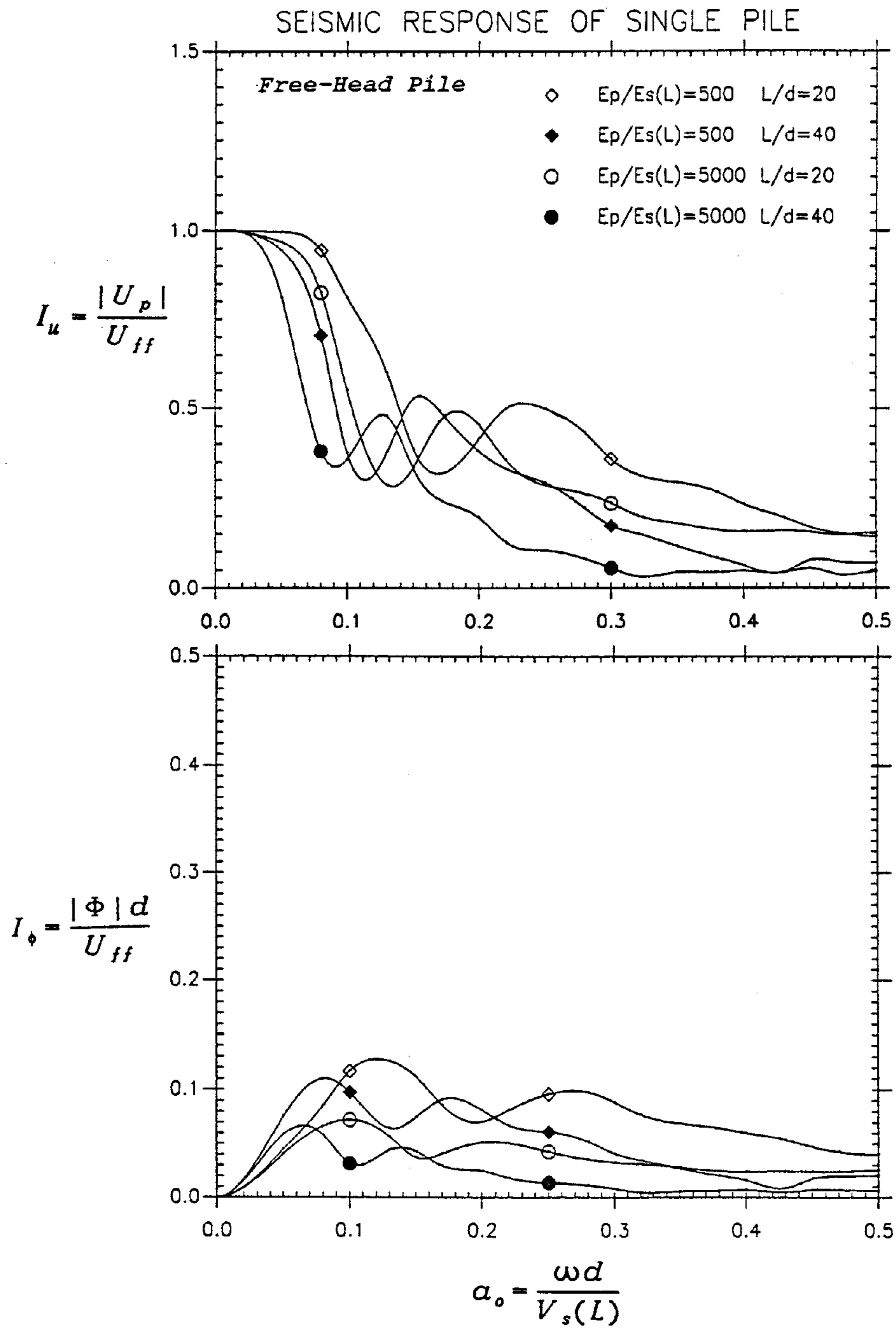

Fig.3-4 Effect of L/d and $E_p/E_s(L)$ on Kinematic Seismic Response of Single Free-head Piles in Nonhomogeneous Soil ($\rho_s/\rho_p = 0.7$, $\beta = 0.05$ and $\nu_s = 0.4$)

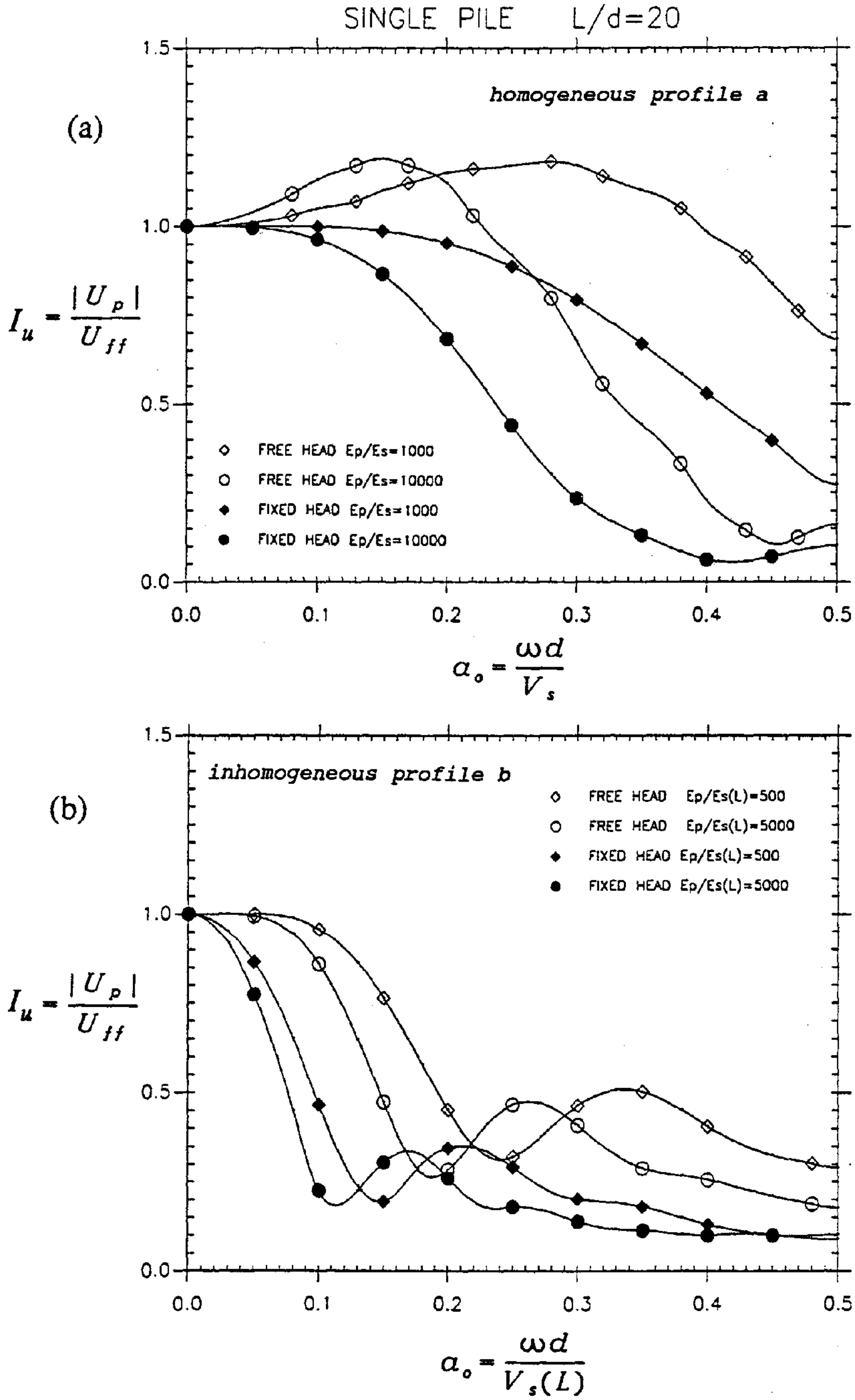

Fig.3-5 Influence of Pile Fixity on Kinematic Seismic Response of Single Piles in (a) Homogeneous, and (b) Nonhomogeneous Soils. ($L/d = 20$, $\rho_s/\rho_p = 0.7$, $\beta = 0.05$ and $\nu_s = 0.4$)

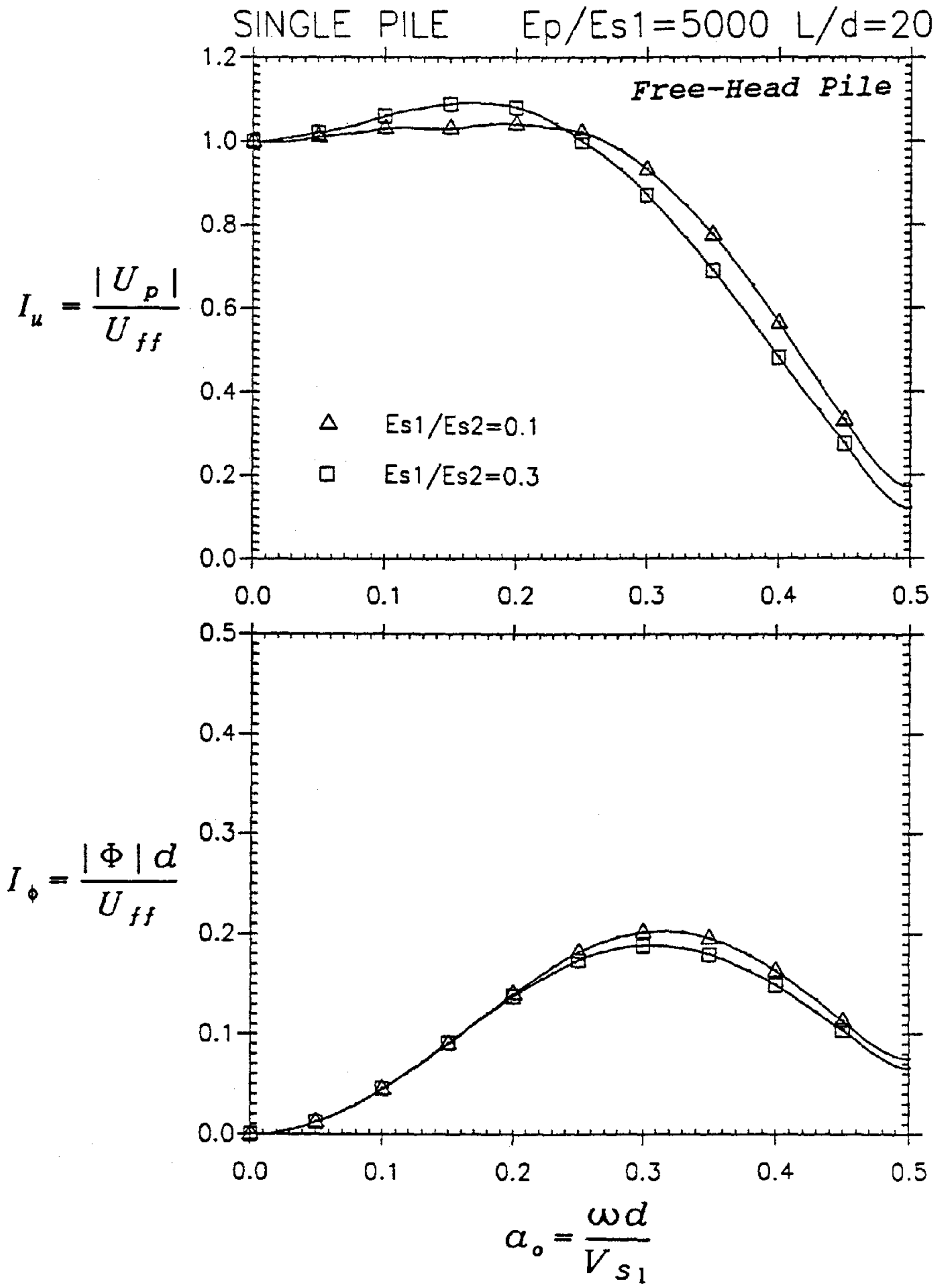

Fig.3-6 Kinematic Seismic Response of Single Free-head Pile in Two-Layered Soil with Different E_{s1}/Es_{s2} ($E_p/E_{s1} = 5,000$, $L/d = 20$, $\rho_s/\rho_p = 0.7, \beta = 0.05$ and $\nu_s = 0.4$)

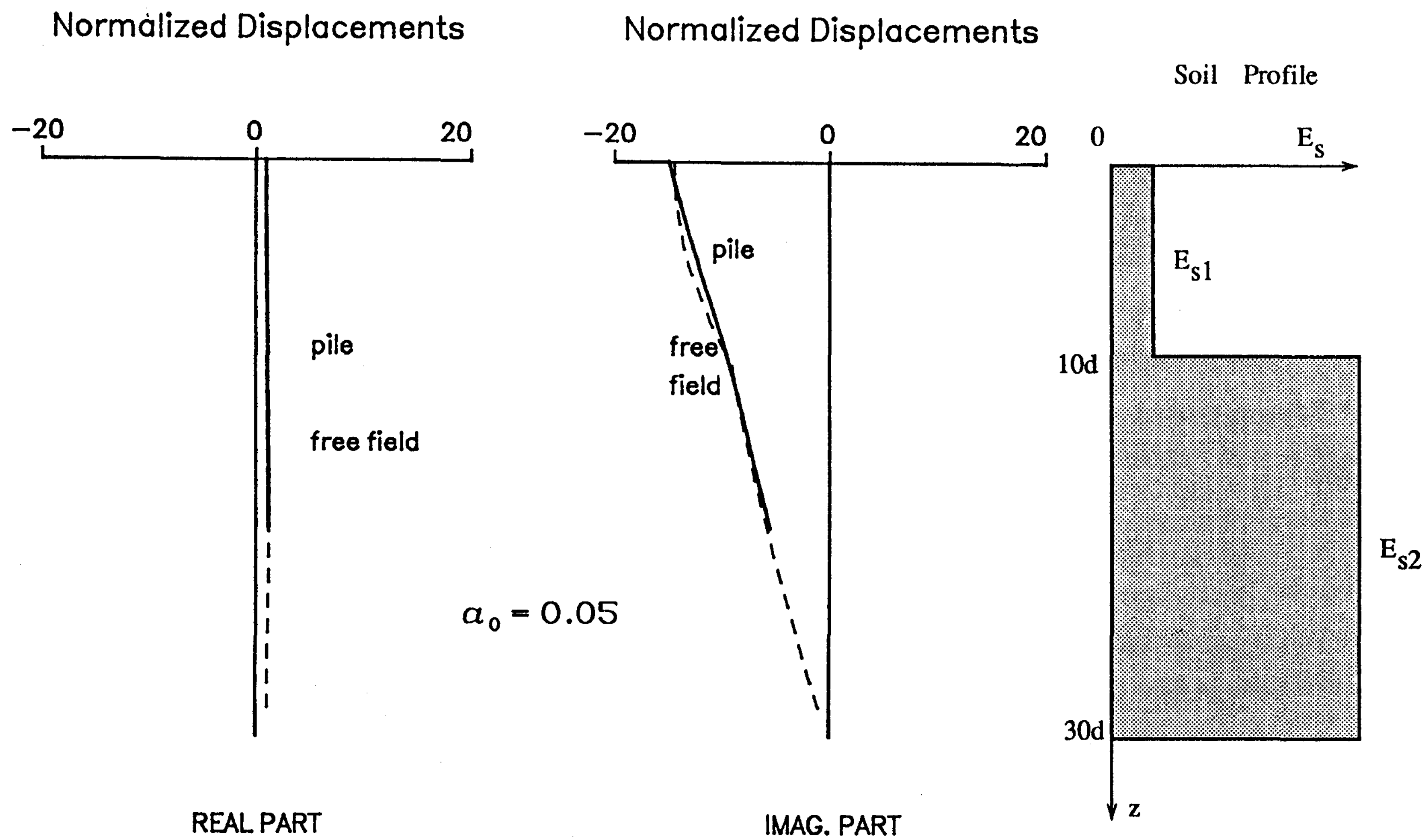

Fig.3-7 Distributions of Free-Field-Soil and Pile Displacements along the Depth of Two-Layered Soil ($E_{s1}/E_{s2} = 0.1$, $L/d = 20$, $\rho_s/\rho_p = 0.7$, $\beta = 0.05$ **and** $\nu_s = 0.4$) $a_0 = 0.05$

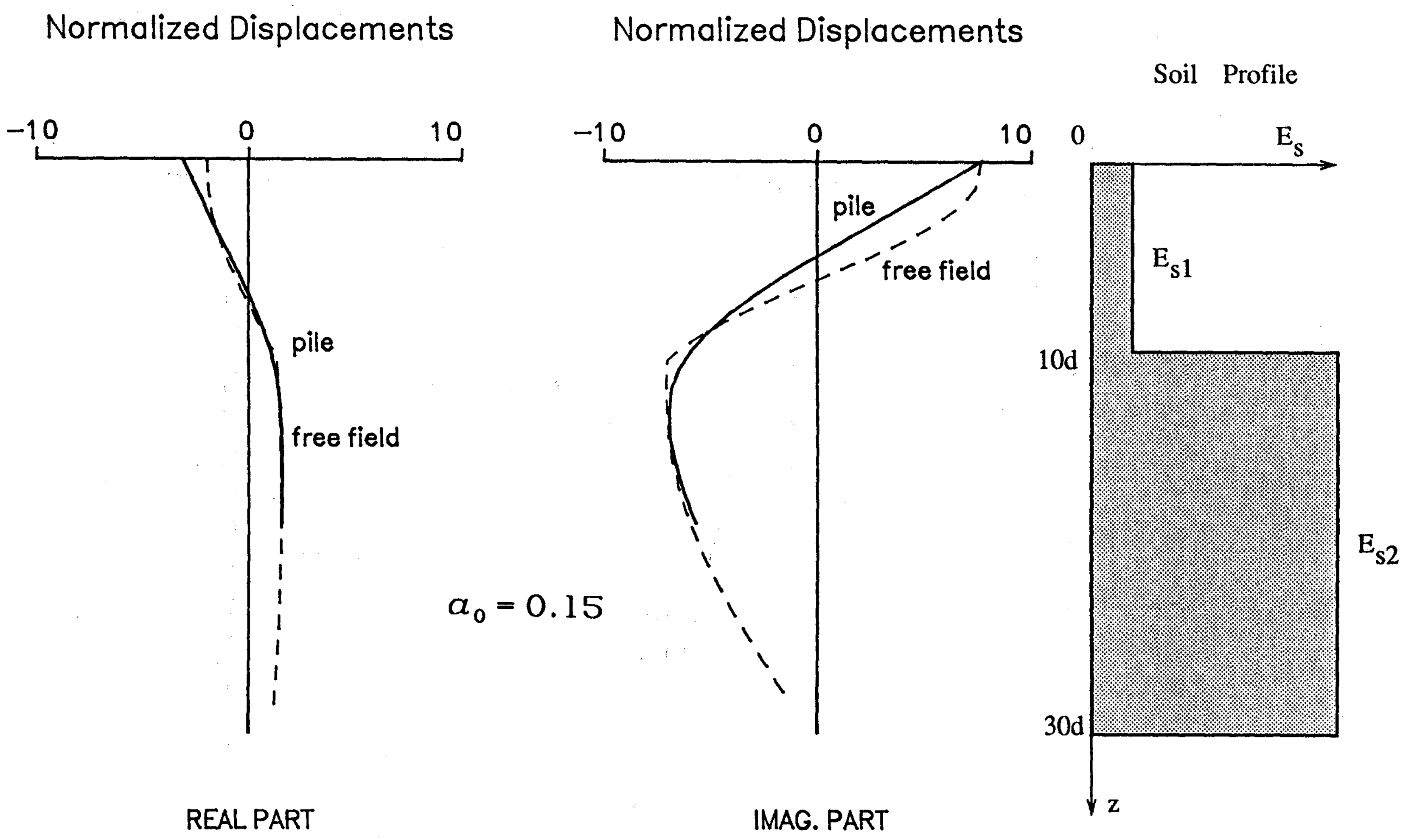

Fig.3-8 Distributions of Free-Field-Soil and Pile Displacements along the Depth of Two-Layered Soil ($E_{s1}/E_{s2} = 0.1$, $L/d = 20, \rho_s/\rho_p = 0.7, \beta = 0.05$ **and** $\nu_s = 0.4$) $a_0 = 0.15$

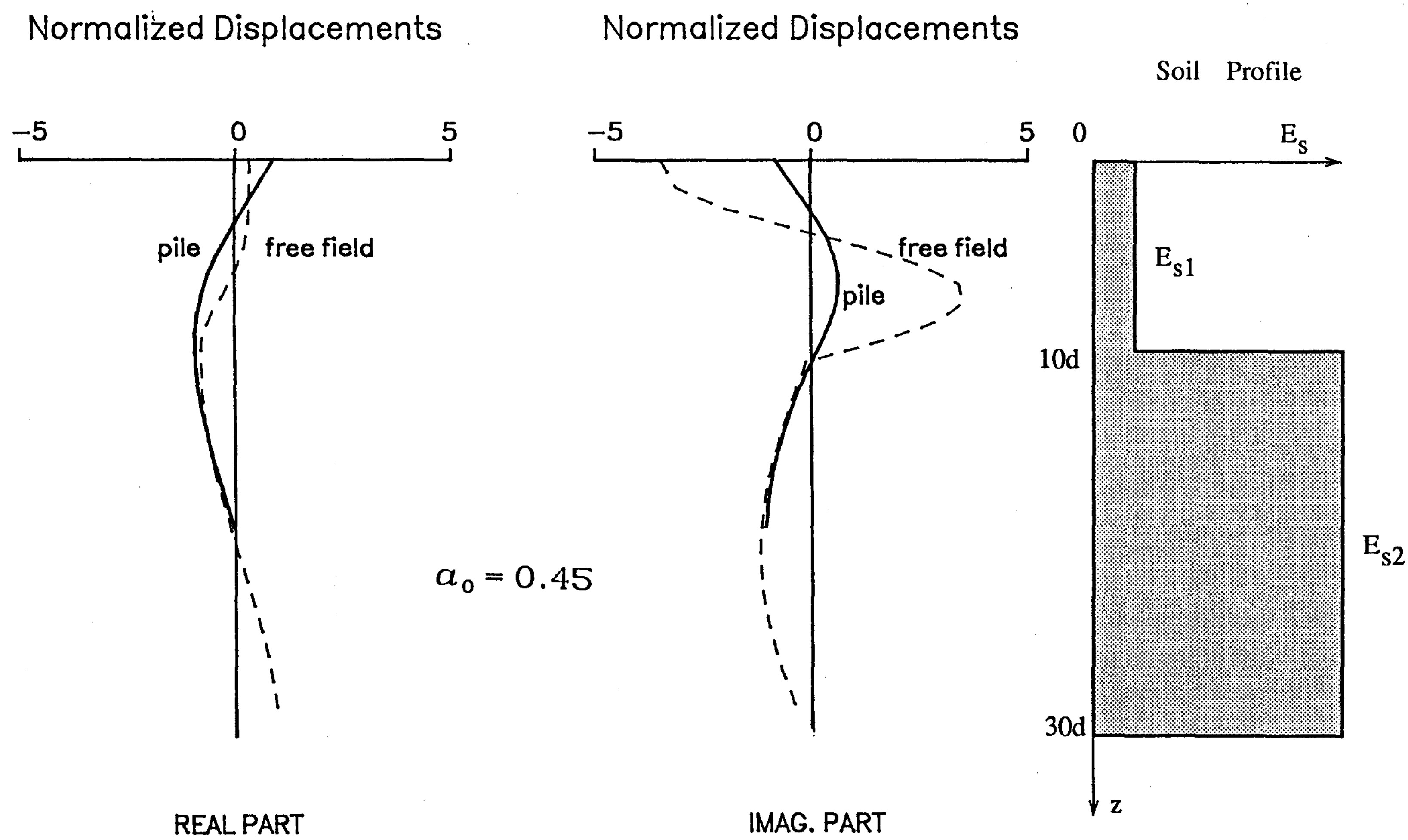

Fig.3-9 Distributions of Free-Field-Soil and Pile Displacements along the Depth of Two-Layered Soil ($E_{s1}/E_{s2} = 0.1$, $L/d = 20, \rho_s/\rho_p = 0.7, \beta = 0.05$ and $\nu_s = 0.4$) $a_0 = 0.45$

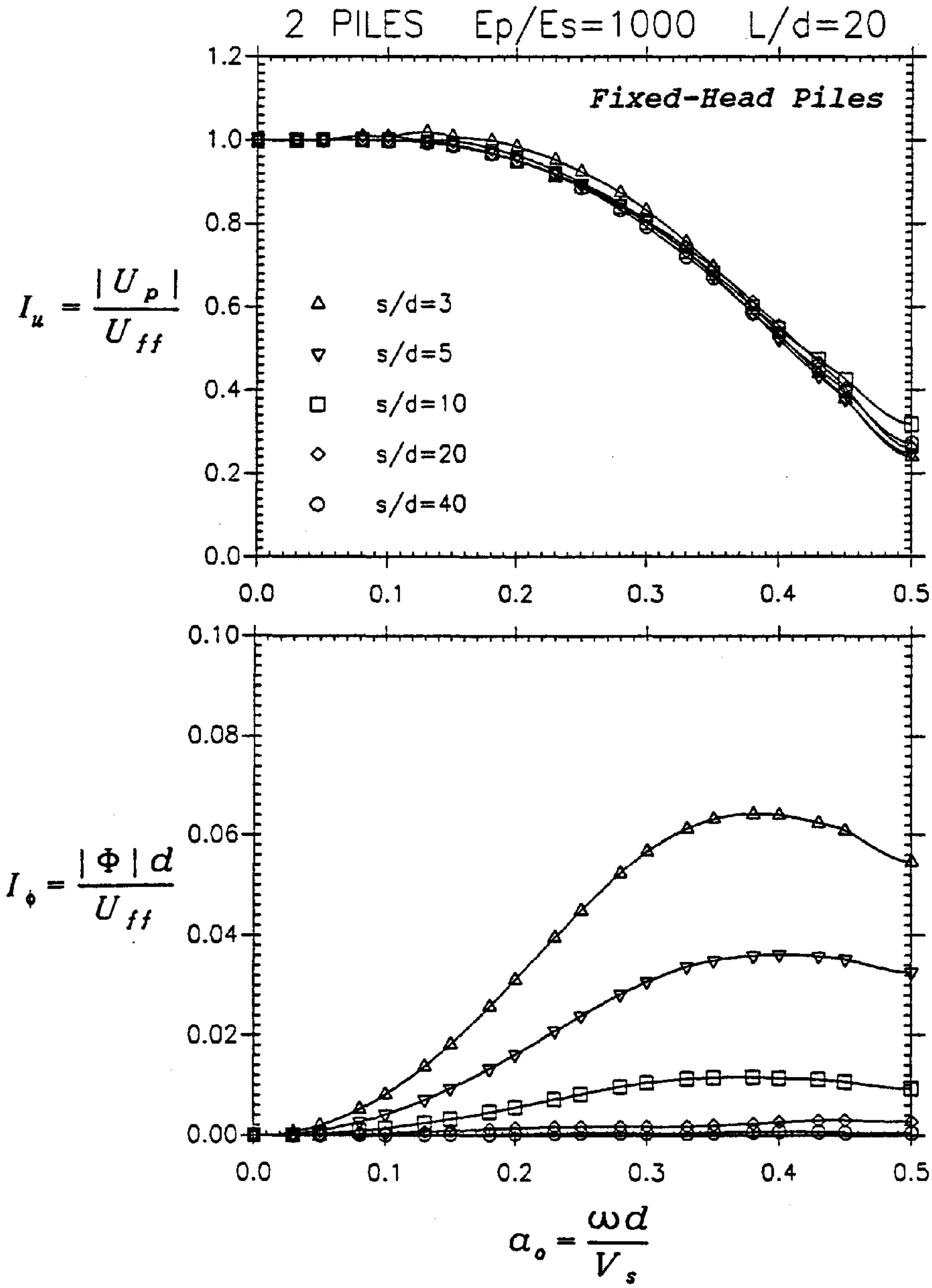

Fig.3-10 Effect of Pile Spacing on Kinematic Interaction of Relatively-Compressible Fixed-head Piles in Homogeneous Soil ($E_p/E_s = 1,000$, $L/d = 20$, $\rho_s/\rho_p = 0.7, \beta = 0.05$ and $\nu_s = 0.4$)

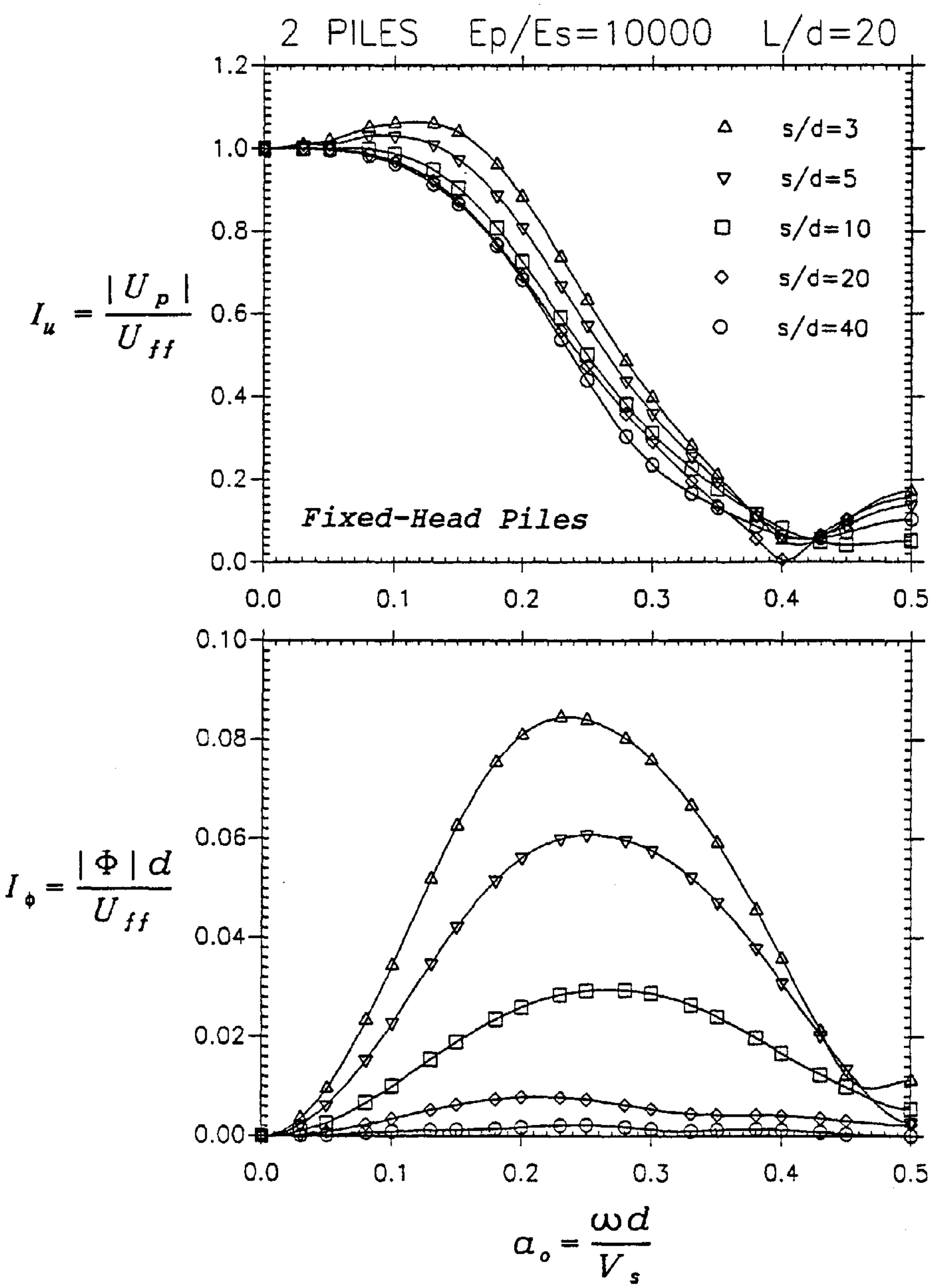

Fig.3-11 Effect of Pile Spacing on Kinematic Interaction of Relatively-Rigid Fixed-head Piles in Homogeneous Soil ($E_p/E_s = 10,000$, $L/d = 20$, $\rho_s/\rho_p = 0.7, \beta = 0.05$ **and** $\nu_s = 0.4$)

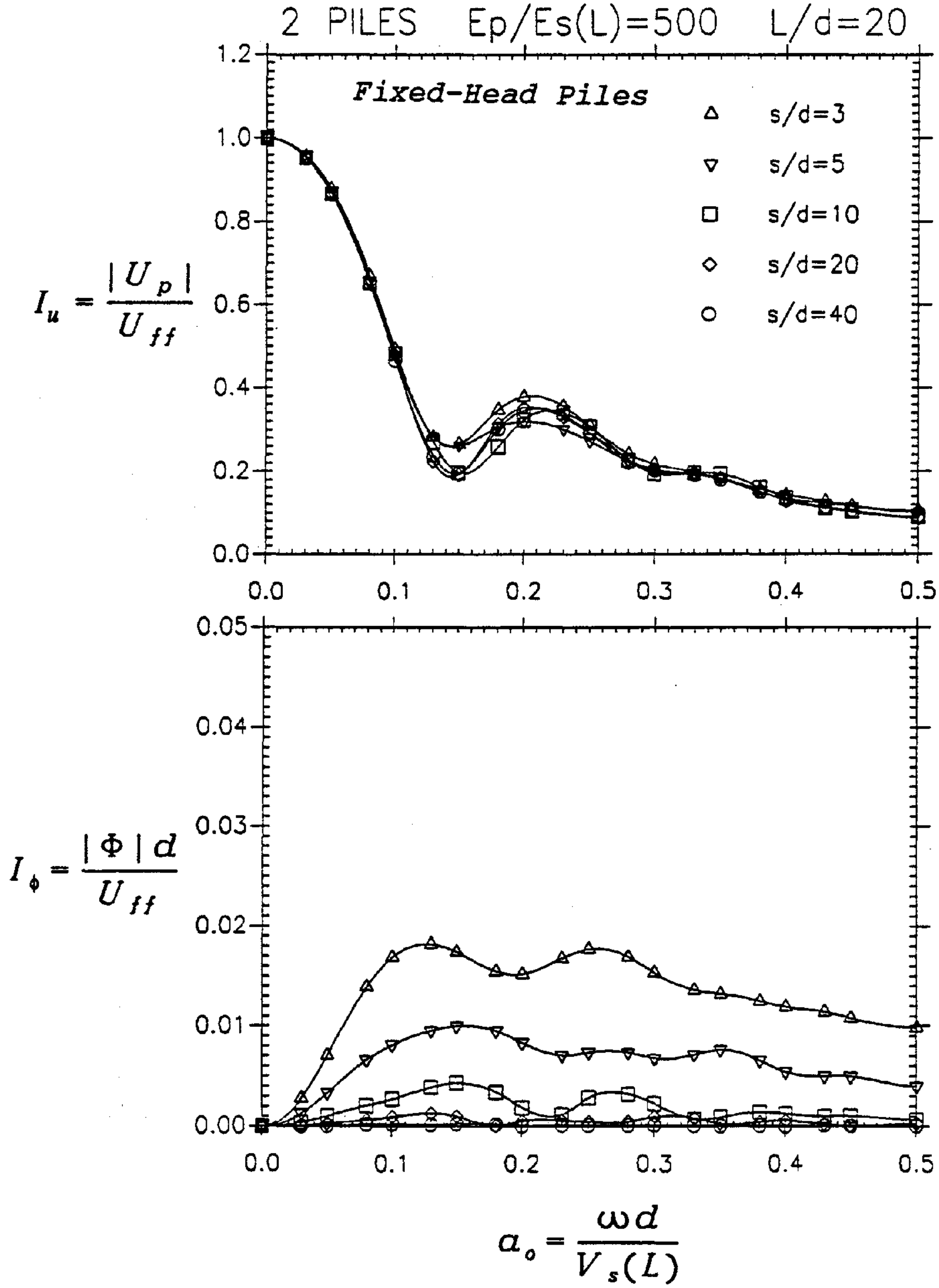

Fig.3-12 Effect of Pile Spacing on Kinematic Interaction of Relatively-Compressible Fixed-head Piles in Nonhomogeneous Soil ($E_p/E_s(L) = 500$, $L/d = 20$, $\rho_s/\rho_p = 0.7, \beta = 0.05$ and $\nu_s = 0.4$)

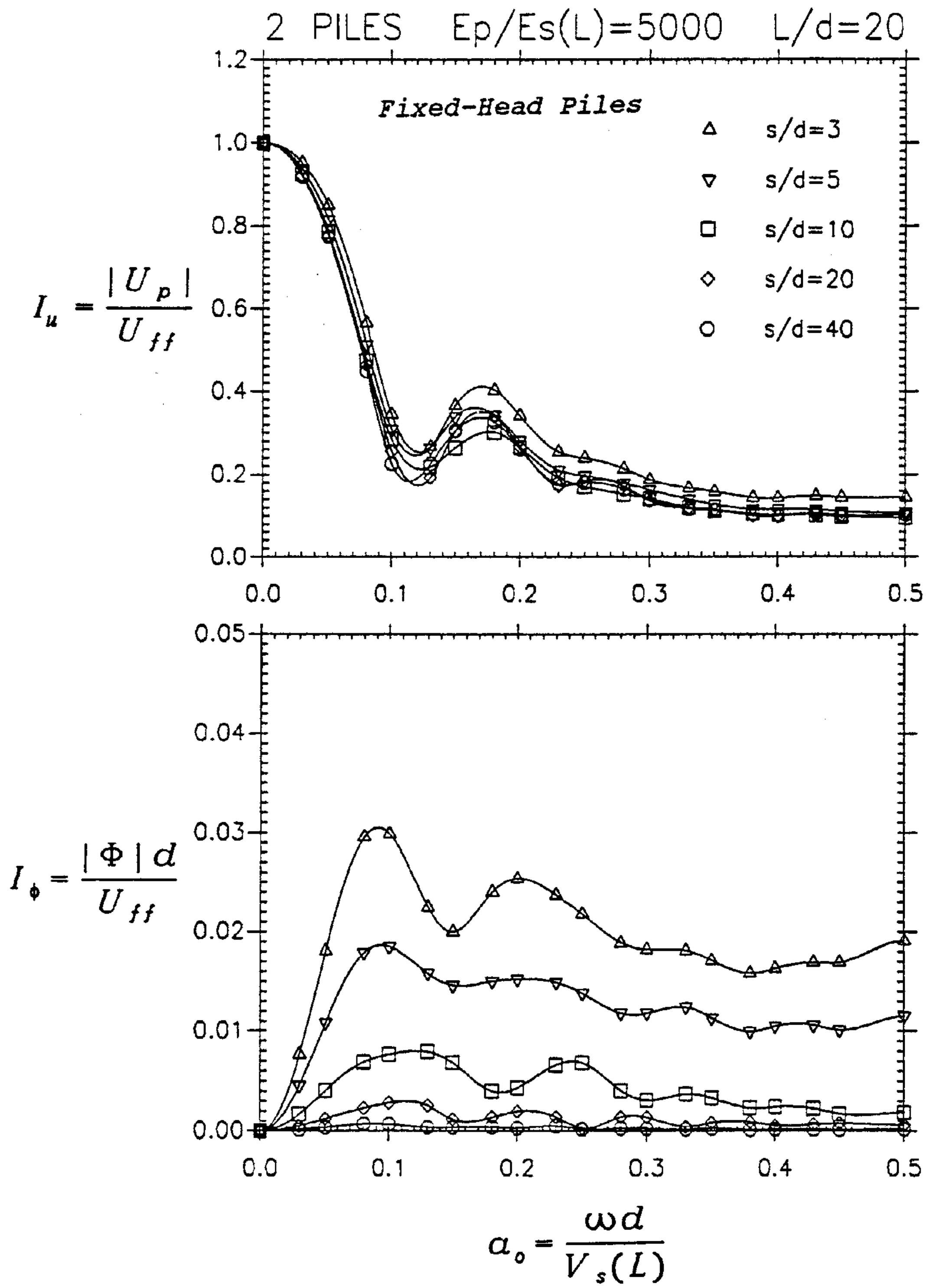

Fig.3-13 Effect of Pile Spacing on Kinematic Interaction of Relatively-Rigid Fixed-head Piles in Nonhomogeneous Soil ($E_p/E_s(L) = 5,000$, $L/d = 20$, $\rho_s/\rho_p = 0.7, \beta = 0.05$ and $\nu_s = 0.4$)

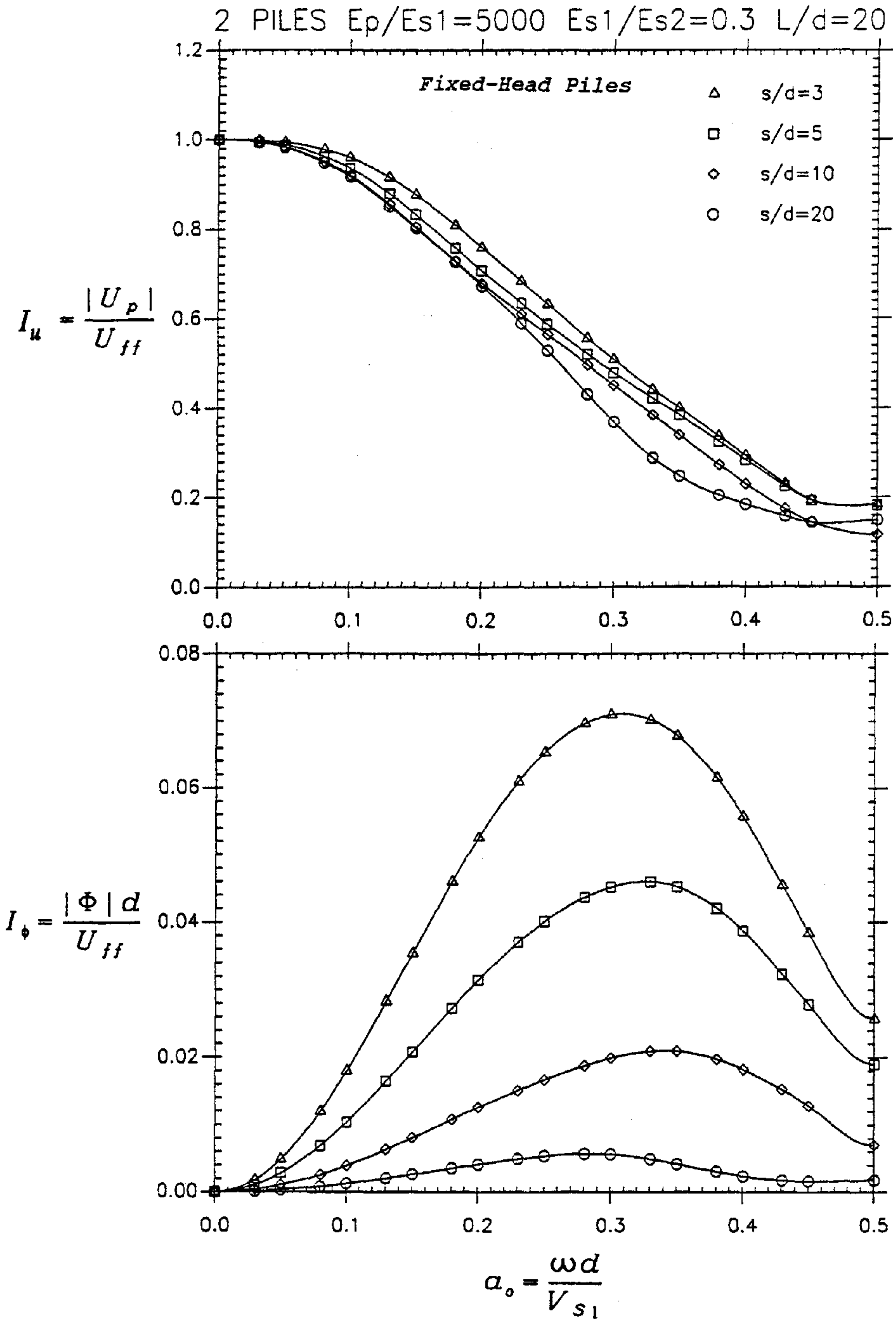

Fig.3-14 Effect of Pile Spacing on Kinematic Interaction of Relatively-Rigid Fixed-head Piles in Two-Layered Soil ($E_p/E_{s1} = 5,000$, $L/d = 20$, $\rho_s/\rho_p = 0.7, \beta = 0.05$ **and** $\nu_s = 0.4$) $E_{s1}/E_{s2} = 0.3$

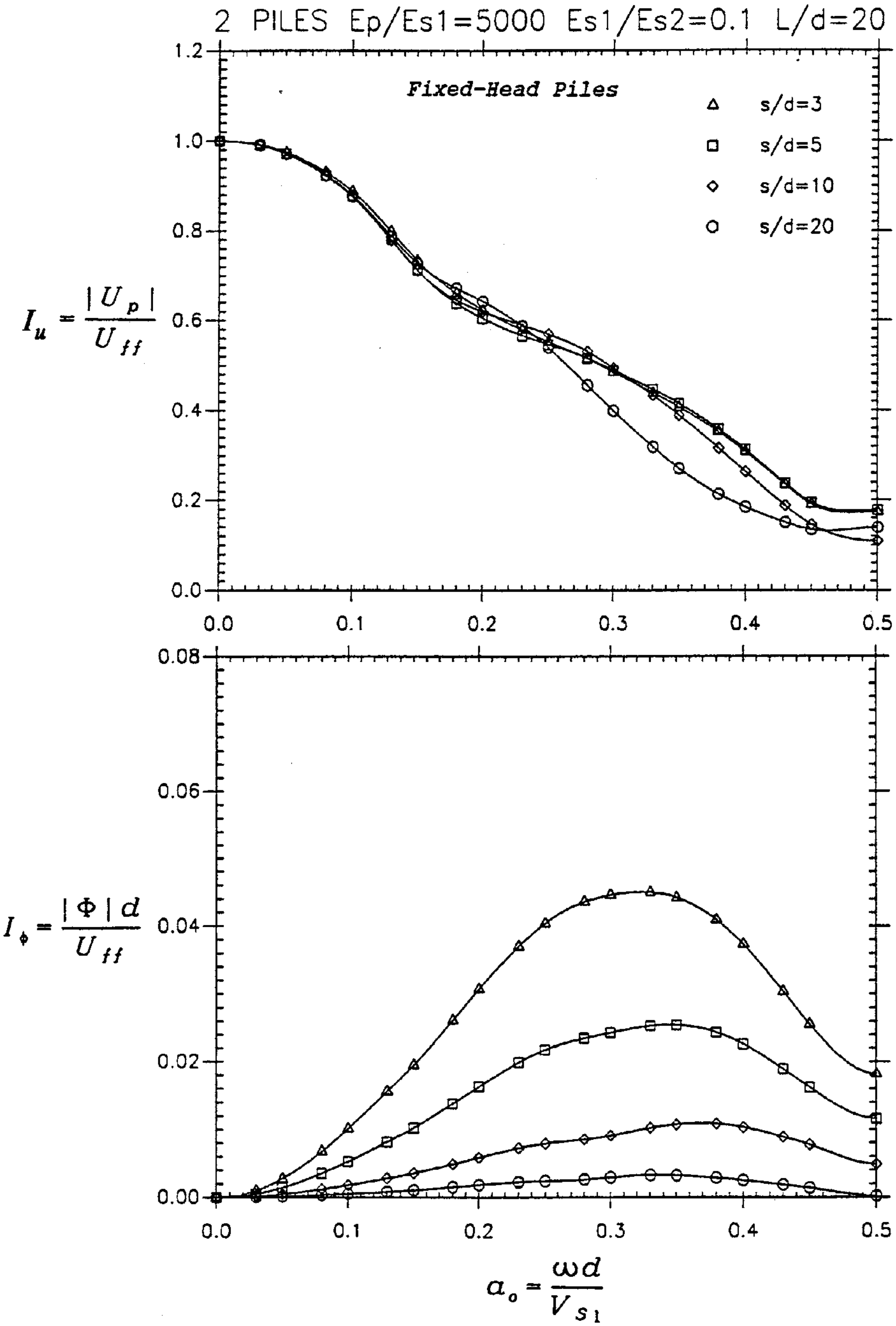

Fig.3-15 Effect of Pile Spacing on Kinematic Interaction of Rigid Fixed-head Piles in Two-Layered Soil ($E_p/E_{s1} = 5,000$, $L/d = 20$, $\rho_s/\rho_p = 0.7, \beta = 0.05$ and $\nu_s = 0.4$) $E_{s1}/E_{s2} = 0.1$

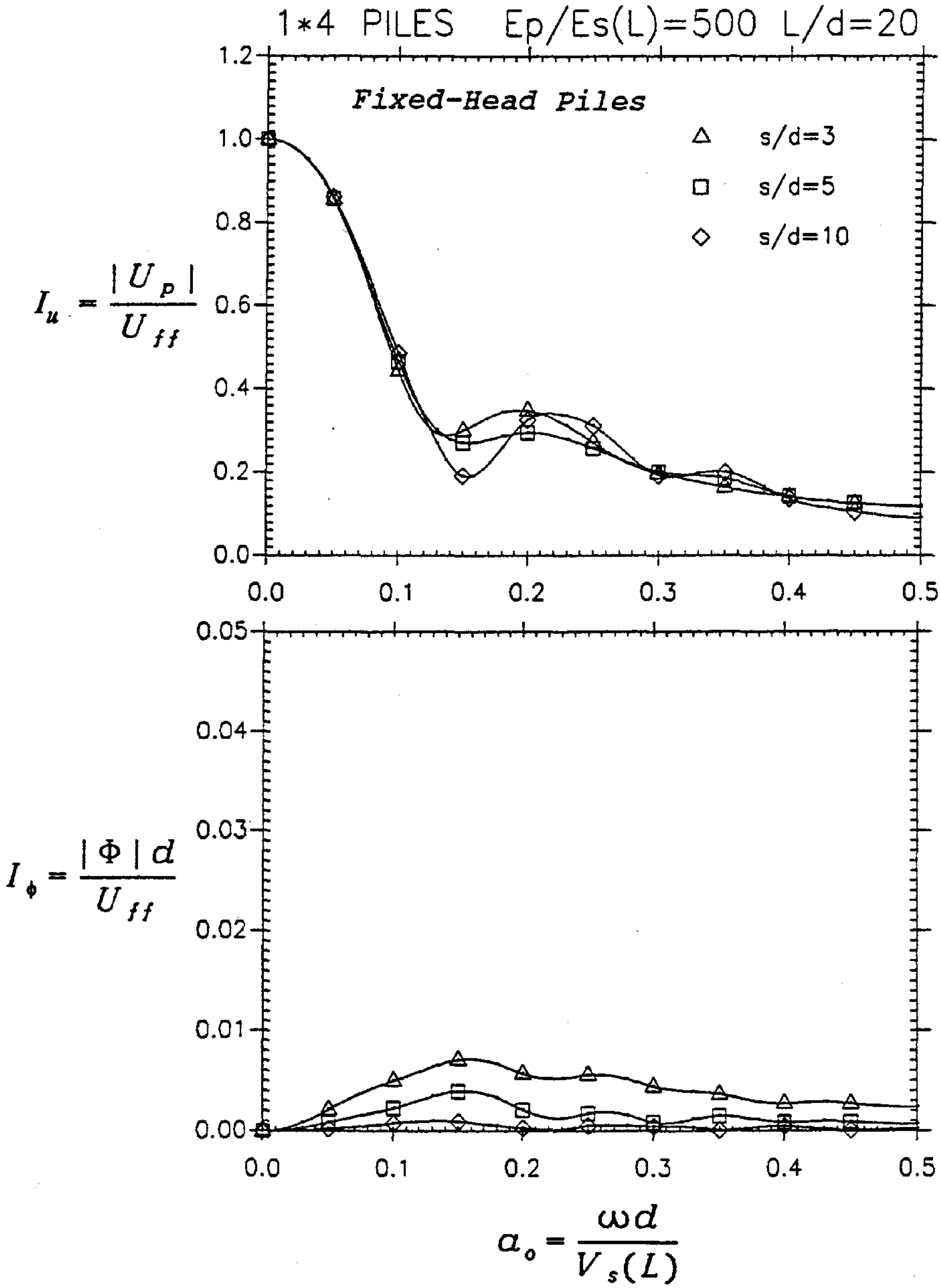

Fig.3-16 Kinematic Seismic Response of 1×4 **Relatively-Compressible Fixed-head Pile Groups in Nonhomogeneous Soil** ($E_p/E_s(L) = 500$, $L/d = 20$, $\rho_s/\rho_p = 0.7, \beta = 0.05$ **and** $\nu_s = 0.4$)

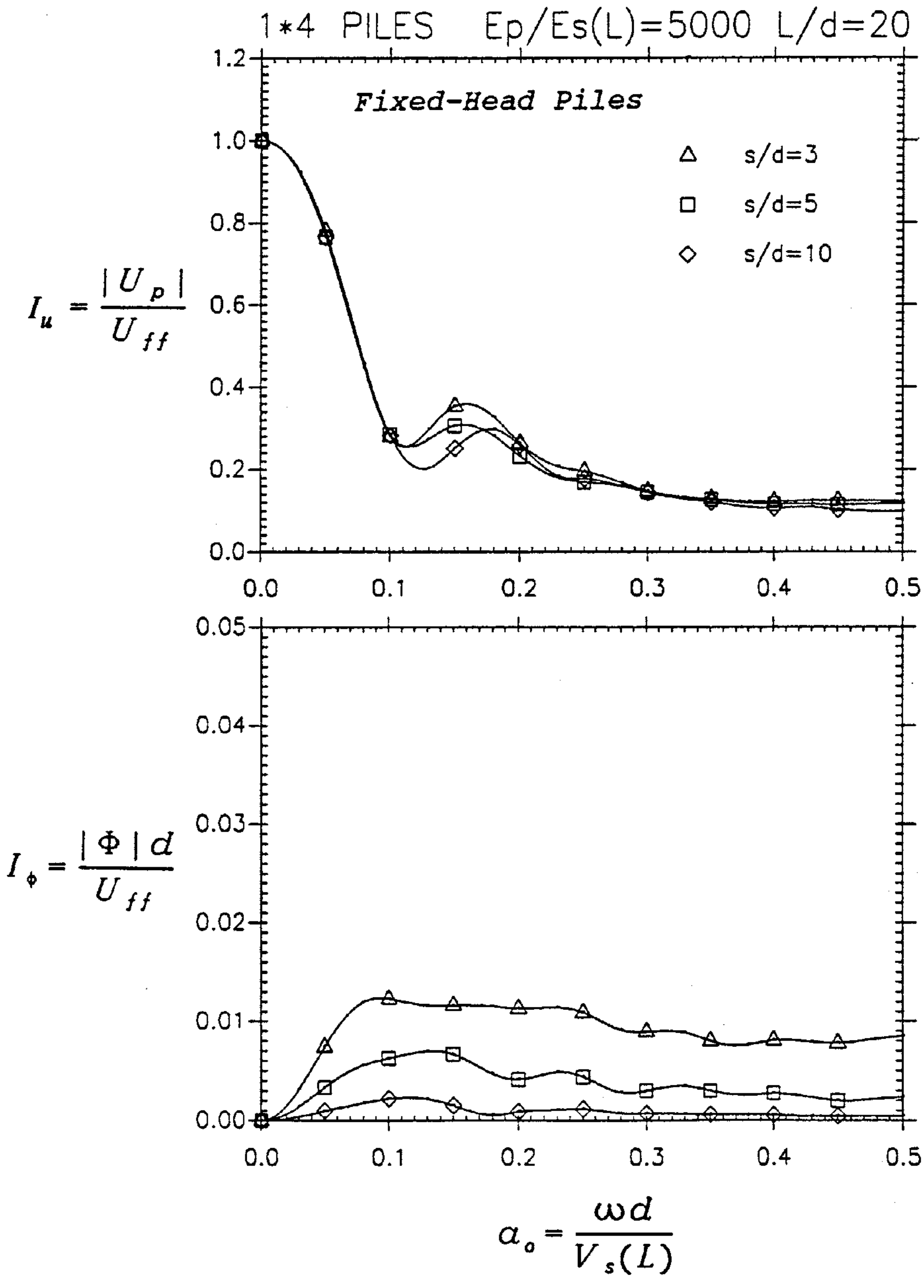

Fig.3-17 Kinematic Seismic Response of 1×4 Relatively-Rigid Fixed-head Pile Groups in Nonhomogeneous Soil ($E_p/E_s(L) = 5,000$, $L/d = 20$, $\rho_s/\rho_p = 0.7, \beta = 0.05$ and $\nu_s = 0.4$)

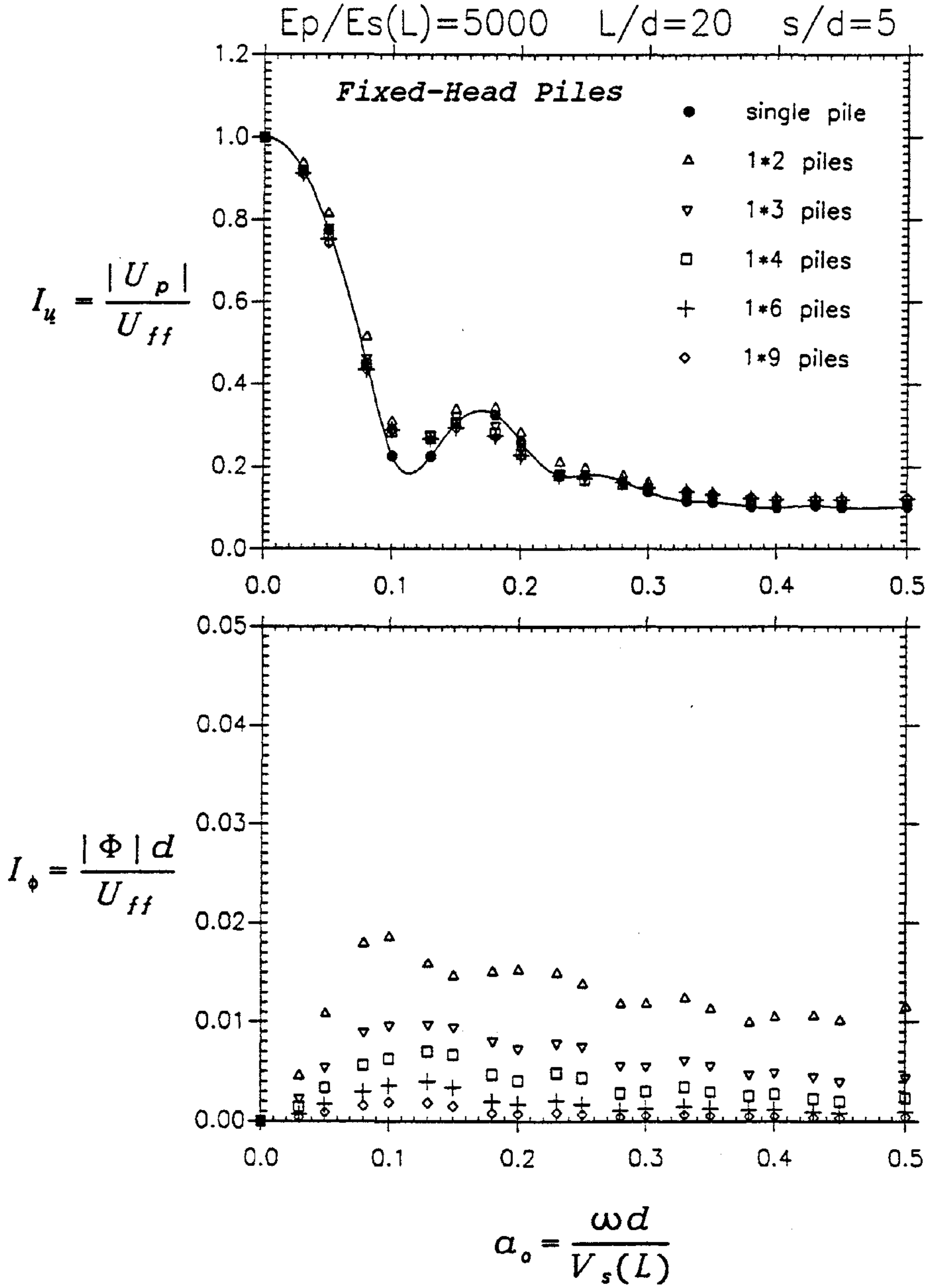

Fig.3-18 Kinematic Seismic Response of $1 \times N$ Relatively-Rigid Fixed-head Pile Groups in Nonhomogeneous Soil ($E_p/E_s(L) = 5,000$, $L/d = 20$, $\rho_s/\rho_p = 0.7, \beta = 0.05$ and $\nu_s = 0.4$; $N = 1, 2, 3, 4, 6,$and 9)

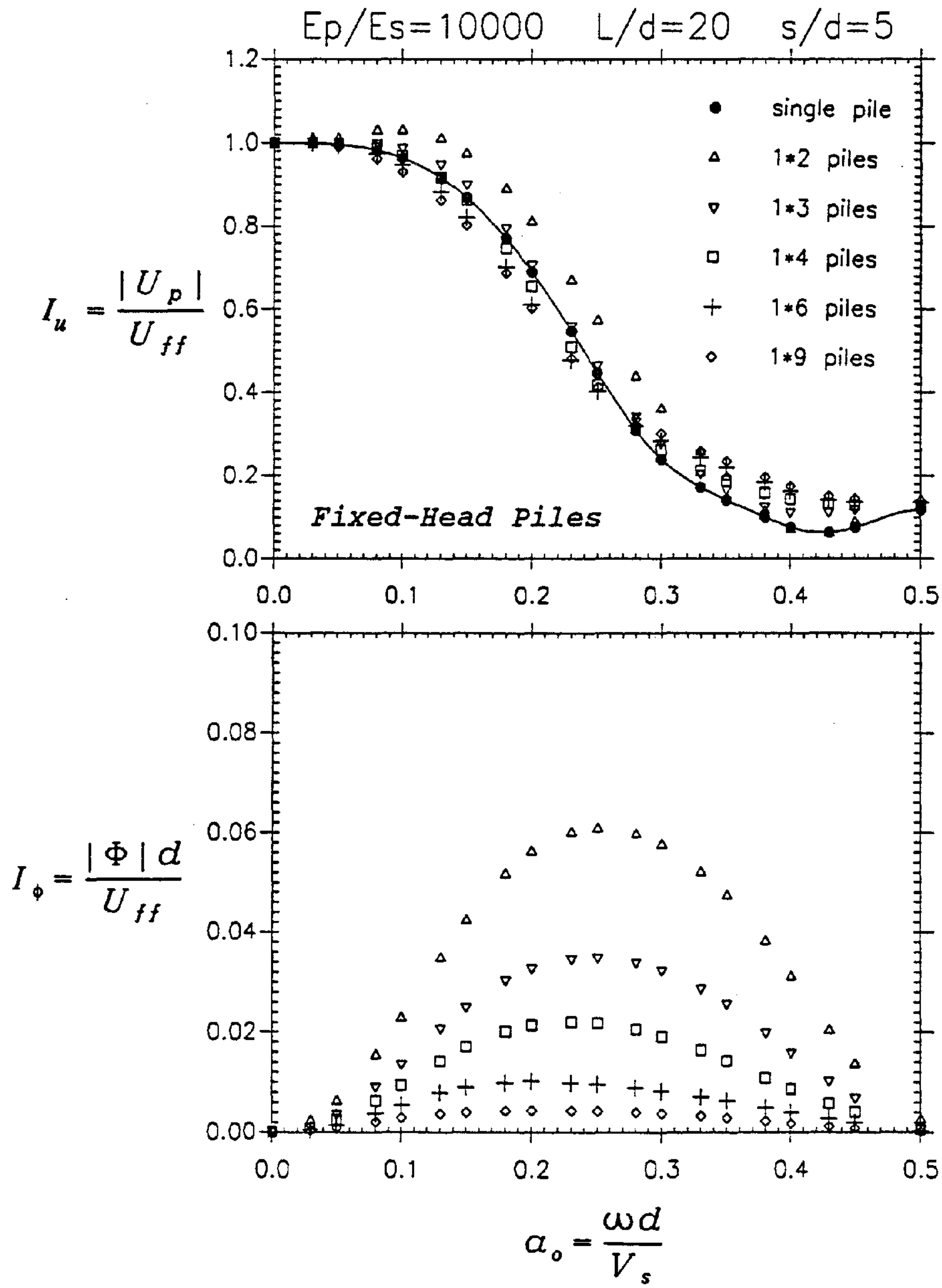

Fig.3-19 Kinematic Seismic Response of $1 \times N$ Relatively-Compressible Fixed-head Pile Groups in Homogeneous Soil ($E_p/E_s = 1,000$, $L/d = 20$, $\rho_s/\rho_p = 0.7, \beta = 0.05$ and $\nu_s = 0.4$; $N = 1, 2, 3, 4, 6,$and 9)

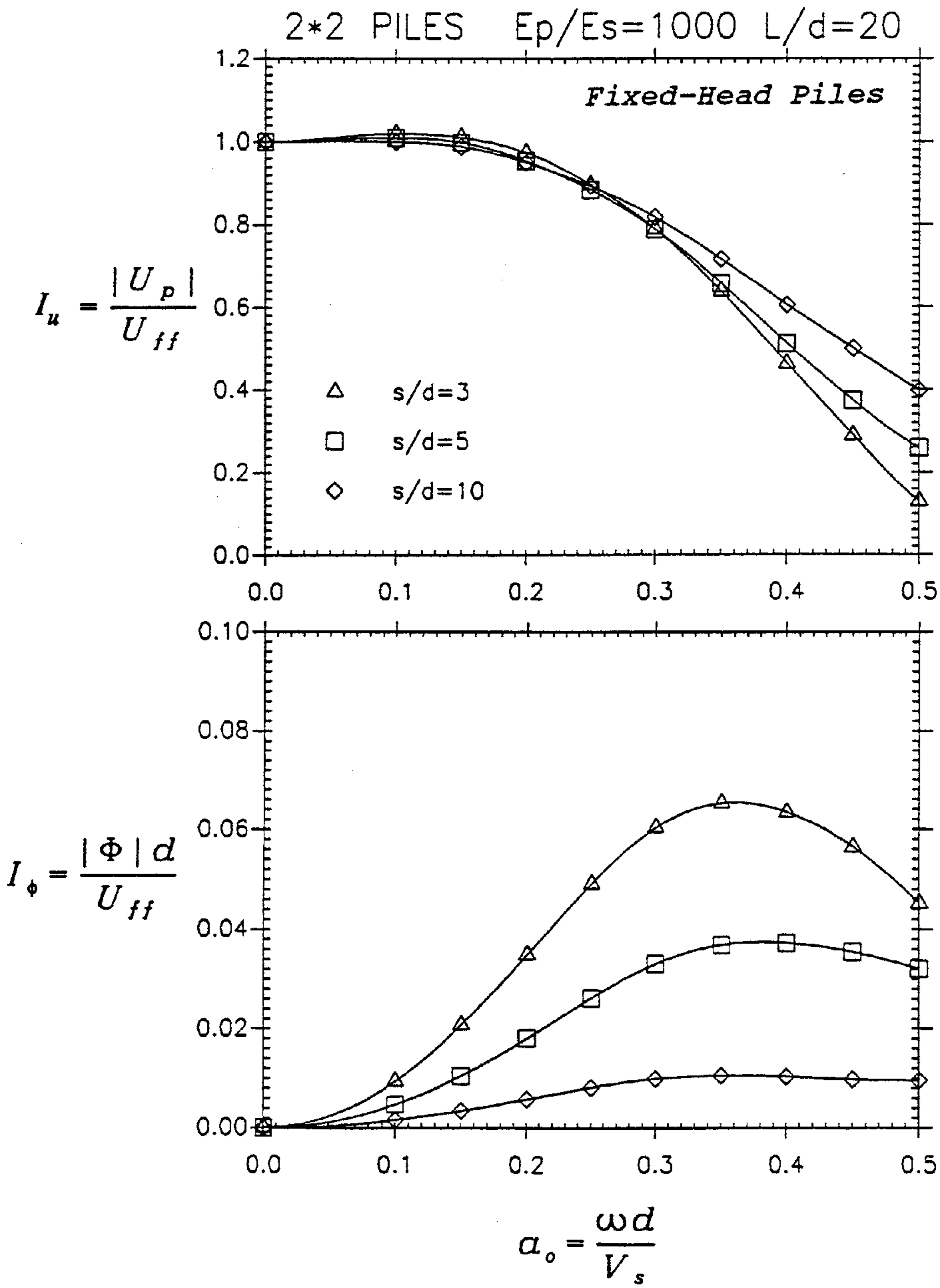

Fig.3-20 Kinematic Seismic Response of 2×2 Relatively-Compressible Fixed-head Pile Groups in Homogeneous Soil ($E_p/E_s = 1,000$, $L/d = 20$, $\rho_s/\rho_p = 0.7, \beta = 0.05$ and $\nu_s = 0.4$)

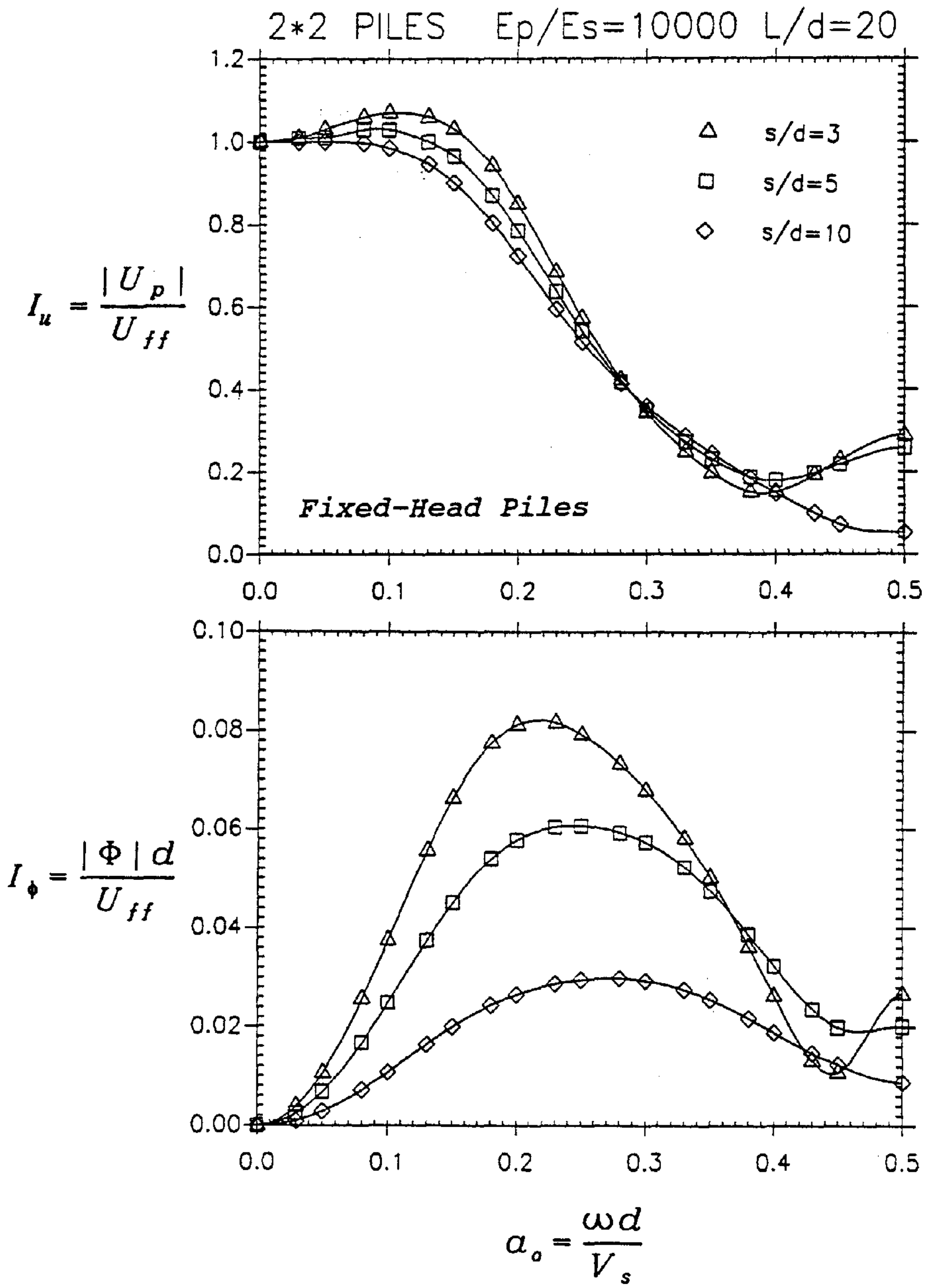

Fig.3-21 Kinematic Seismic Response of 2×2 Relatively-Rigid Fixed-head Pile Groups in Homogeneous Soil ($E_p/E_s = 10,000$, $L/d = 20$, $\rho_s/\rho_p = 0.7, \beta = 0.05$ and $\nu_s = 0.4$)

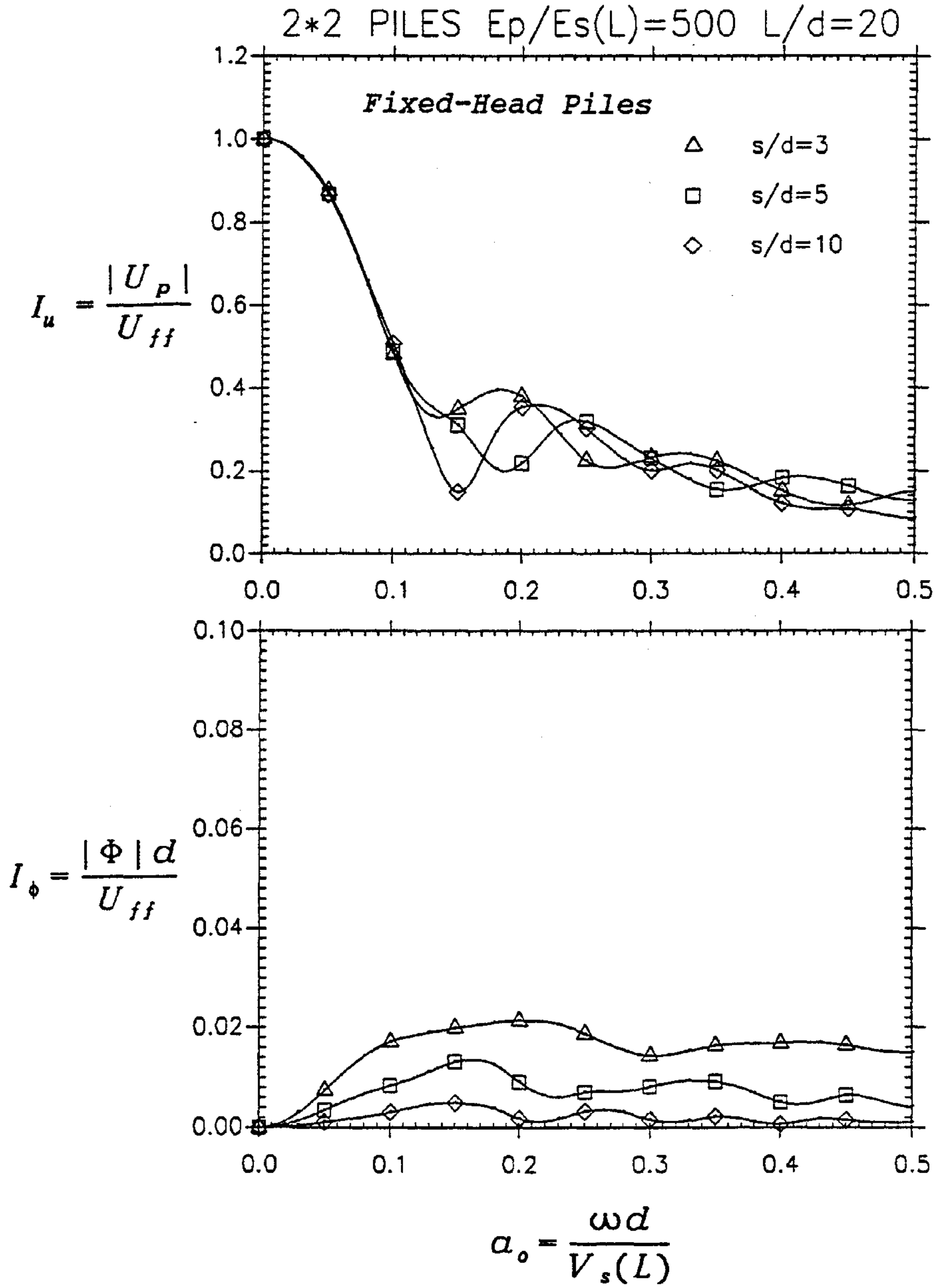

Fig.3-22 Kinematic Seismic Response of 2×2 Relatively-Compressible Fixed-head Pile Groups in Nonhomogeneous Soil ($E_p/E_s(L) = 500$, $L/d = 20$, $\rho_s/\rho_p = 0.7, \beta = 0.05$ and $\nu_s = 0.4$)

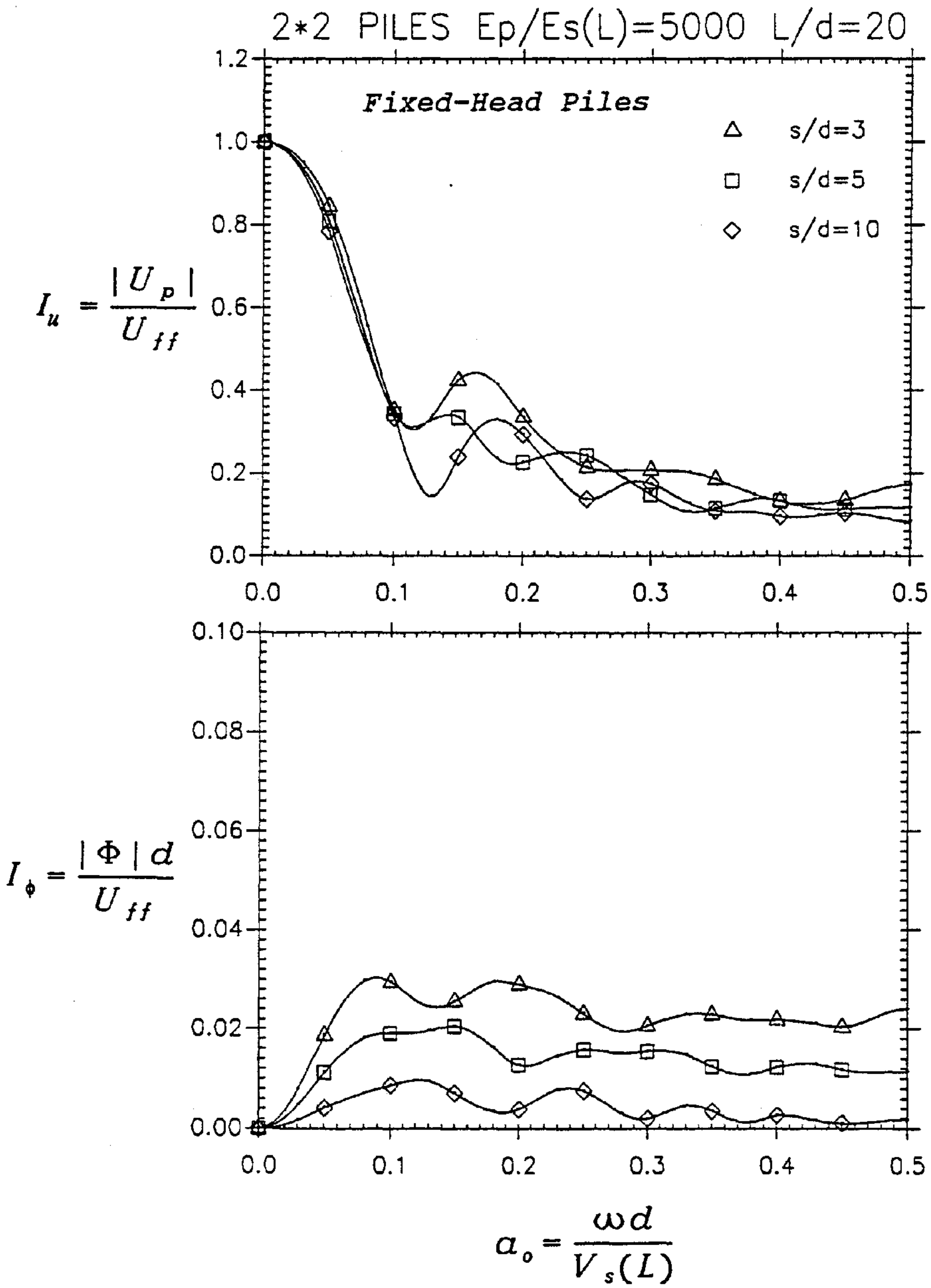

Fig.3-23 Kinematic Seismic Response of 2×2 Relatively-Rigid Fixed-head Pile Groups in Nonhomogeneous Soil ($E_p/E_s(L) = 5,000$, $L/d = 20$, $\rho_s/\rho_p = 0.7, \beta = 0.05$ and $\nu_s = 0.4$)

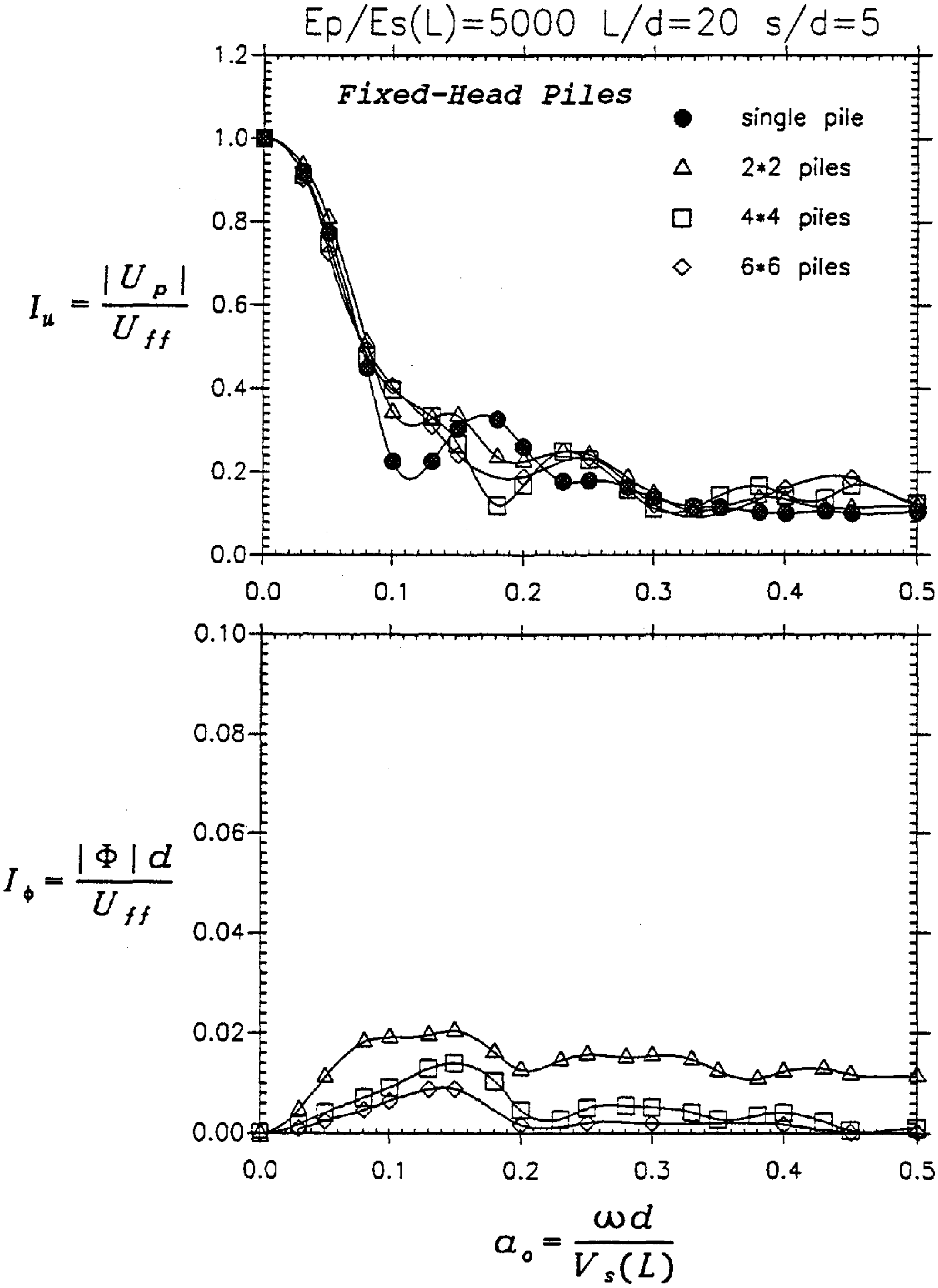

Fig.3-24 Kinematic Seismic Response of $N \times N$ Relatively-Rigid Fixed-head Pile Groups in Nonhomogeneous Soil ($E_p/E_s(L) = 5,000$, $L/d = 20$, $\rho_s/\rho_p = 0.7, \beta = 0.05$ and $\nu_s = 0.4$; $N = 2, 4,$ and 6)

SECTION 4
CONCLUSION

Dimensionless graphs have been presented for the dynamic horizontal displacement and rotation developing at the cap level of single piles and pile groups embedded in several idealized soil profiles and subjected to vertically propagating harmonic waves. These graphs have potential to be of practical value in determining the "effective" seismic input motion at the base of structures, if the free-field motion is known (e.g., in the form of a "design" response spectrum of the seismic code). A discussion of the presented results has focused on elucidating the role of the key problem parameters and has aimed at developing engineering insight into kinematic soil-pile and pile-pile interaction during earthquakes.

SECTION 5
REFERENCES

1. Ahmad, S. (1986). "Linear and nonlinear dynamic analysis by boundary element method", Ph.D. thesis, Dept. of Civil Engrg., State University of New York at Buffalo.

2. Barghouthi, (1984). "Pile response to seismic waves", Ph.D. thesis, Univ. of Wisconsin, Madison.

3. Blaney, G.W., Kausel, E. and Roesset, J.M. (1976). "Dynamic stiffness of piles", Proc. Second Int. Conf. Num. Meth. in Geomech., ASCE Blacksburg, Virginia, pp. 1001-1012.

4. Flores-Berrones, R. and Whitman, R.V. (1982). "Seismic responses of end-bearing piles", J. Geotech. Engng., ASCE 108 (GT4).

5. Gazetas, G. (1984). "Seismic response of end-bearing piles," Int. J. Soil Dynam. Earth. Eng., 3(2), 82-93.

6. Kausel, E. (1981). An explicit solution for the Green Functions for dynamic loads in layered media. Research Report, Dept. of Civil Engrg., MIT, Cambridge, Mass.

7. Kaynia, A.M. & Kausel, E. (1982). "Dynamic stiffnesses and seismic response of pile groups". Research Report, Dept. of Civil Engineering, MIT, Cambridge, Mass.

8. Luco, J.E. and Wong, H.L. (1986). "Response of a Rigid Foundation to a Spatially Random Ground Motion, " Journal of Earthquake Engineering and Structural Dynamics, 14, 891-908.

9. Makris, N. & Gazetas G. (1990). "Dynamic pile-soil-pile interaction II: Lateral and seismic response". Submitted for publication.

10. Pais, A. and Kausel, E. (1985). "Stochastic response of foundations", Research Report R85-6, Massachusetts Inst. Technol.

11. Roesset, J.M. (1977). "Soil amplification of earthquakes", Numerical Methods in Geotech. Engng., Desai, C.S. and Christian, J.T., eds., McGraw-Hill.

12. Scanlan, R.H. (1976). "Seismic wave effects on soil-structure interaction," Int. J. Earthq. Eng. Struct. Dynam., 4, 379-388.

13. Tazoh, T., (1988). "Effective motion of group pile foundation", Proceedings of 9th World Conference on Earthquake Engng, Tokyo, Vol. III.

14. Takemiya, H. and Yamada, Y. (1981). "Layered soil-pile-structure interaction", Int. J. Earthq. Engng. Struct. Dyn., 9, 437.

15 Veletsos, A.S. & Prasad A.M. (1988). "Seismic interaction of structures and soils: Stochastic approach", Technical Report NCEER-88-0021, State Univ. of New York at Buffalo.

16. Wolf, J.P. & Von Arx, G.A. (1982). "Horizontally traveling waves in a group of piles", Earthq. Eng. Struct. Dyn., 10, 225-237.

17. Wolf, J.P. & Von Arx, G.A. (1978). "Impedance function of a group of vertical piles." Soil dynamics & Earthquake Engng., ASCE, 2, 1024-1041.

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