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Principle of superposition for assessing horizontal dynamic response of pile groups encompassing soil nonlinearity

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ABSTRACT

Model tests on fixed-head floating piles embedded in dry cohesionless soil (Gifu sand) are carried out under 1-g conditions on a shaking table, to investigate the effects of local soil nonlinearity on the dynamic response of pile groups. Results obtained from these tests are employed to assess the applicability of Poulos' superposition method in determining the pile group response under different levels of material nonlinearity. A wide range of head loading amplitudes inducing low-to-high levels of soil strain are employed for a broad range of frequencies. Utilizing the aforementioned superposition method, horizontal impedance functions of a closely spaced 3×3-pile group are computed based on: (1) experimentally-measured values of horizontal impedance functions for a single pile, and (2) experimentally-measured pile-to-pile interaction factors. Comparisons between computed and measured impedance functions show good agreement for low to intermediate loading amplitudes, suggesting that the superposition method is valid even under moderately nonlinear conditions.

1. Introduction

A considerable amount of work in recent years has been carried out in developing rational methods for predicting the response of piles and pile groups subjected to static and dynamic loads [1–6]. This is important as piles are often employed to support a wide range of massive structures on soft ground. For such structures, neither the structural nor the foundation displacements are independent of each other. Under earthquake loading, the response of soil influences the motion of the structure due to soil-pile-structure interaction. A detailed review of the subject has been presented by Gazetas and Mylonakis [7]. In most applications, it is desirable that the dynamic response of pile supported structures is obtained accounting for such interaction effects.

Computation of response of structures with full consideration of soil-pile-structure interaction under dynamic loading is a complex problem. One of the most widely employed analysis methods relies on the concept of sub-structuring [8]. In the realm of this approach, three distinct impedance functions are formulated for planar analysis of a laterally-loaded pile group connected to a rigid cap [9], describing resistance to swaying, rocking and cross-swaying rocking. For large pile groups and squat structures, the rotational component of the foundation motion is typically negligible and the horizontal component governs the response.

The impedance functions (IFs) are complex-valued frequency-dependent quantities; for the horizontal component we get

$$K^*_{hh} = k_{hh} + iC_{hh} \tag{1}$$

where k_{hh} and C_{hh} are the real and imaginary parts of the impedance functions, respectively. Of these, the real part reflects stiffness, while the imaginary part reflects the combined action of the (frequency dependent) wave radiation and the (frequency independent) material damping of the pile and the soil. Alternatively, Eq. (1) can be presented in the following form

$$K^*_{hh} = k_{hh} + i\omega c_{hh} \tag{2}$$

in which $c_{hh} = C_{hh}/\omega$ is the coefficient of equivalent viscous damping and ω is the cyclic excitation frequency.

It is important to note that the dynamic behavior of a pile group is fundamentally different from that of a single pile, and the overall impedance of the pile group cannot be simply predicted by superimposing the impedances of the individual piles. This is because, piles in a group are not only affected by their individual head loads, but also by additional loads transferred through the

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soil from the neighboring piles. Pile-to-pile interaction is a frequency-dependent dynamic phenomenon described by pertinent complex quantities called ‘interaction factors’, first introduced by Poulos [10].

Approximate solutions based on the theory of elasticity for pile-to-pile interaction factors are widely used in practice [11–14]. Poulos' superposition method [10], which assumes that the interaction effects between individual pile pairs can be superimposed considering only two piles at a time, has been extensively employed for computing pile group response, once the IFs of a single pile and the interaction factors have been determined. Though originally developed for static conditions, the superposition method has been shown to be applicable to the dynamic regime [2,11,12].

It is also well known that the response of soil is strain-dependent. Soils can be considered nearly elastic under low strain levels, yet under higher strains, soil near a oscillating pile behaves nonlinearly (a phenomenon to be referred hereafter to as ‘local nonlinearity’) and may have a strong influence on the response. This cannot be captured by purely elastic or visco elastic solutions. Experimental investigations on the effects of such local nonlinearity on horizontal pile-to-pile interaction factors are available [15]. The effects of local nonlinearity on the IFs of individual piles, however, are largely unknown, although the effects of local nonlinearity on the force–displacement (p–y) relations of piles have been studied [16]. The current work aims at investigating the effects of local soil nonlinearity on the horizontal IFs of both single and grouped piles. To this end, experimentally measured horizontal IFs of a single pile and horizontal pile-to-pile interaction factors [15] are employed to assess the IFs of a pile group by means of the superposition method, encompassing local soil nonlinearity. By comparing against experimental measurements, the accuracy of the method is assessed.

Separate sets of dynamic experimental data on model soil-pile systems involving a single pile and a 3 × 3-pile group embedded in cohesionless dry sand and encased in a laminated shear box under natural gravity (1-g) conditions are reported. A closely spaced fixed-head floating pile group with spacing to diameter ratio (s/d) of 2.5 is selected. A wide range of loading amplitudes is employed to induce low-to-high strain levels in the soil for a broad range of frequencies.

2. Model tests

Physical model testing requires scaling equations for relating the response of a model to that of a prototype. In the context of similitude theory, loading rate in the model is always faster than in the prototype, to balance the difference in scale and stiffness mismatch between the two systems. Scaling relations for soils considering such issues were first derived by Rocha [17] and Roscoe [18]. Further work was carried out by Kagawa [19], Iai [20] and Kokusho and Iwatate [21], who extended the theory to more general conditions.

2.1. Model-prototype relations

For the purposes of the present experimental investigation, the scaling laws derived by Kokusho and Iwatate [21] pertaining to 1-g conditions, are employed. Table 1 summarizes the scaling relationship used in the present work, where λ is the geometric scaling ratio of the model to the prototype and η is the corresponding density scaling ratio.

Table 1
Model-prototype scaling relations for model tests.

Items	Similitude		Physical properties			Units
	Law	Factor	Prototype	Target	Attained	
Length of pile (L)	λ	0.05	18.0	0.90	0.90	m
Diameter of pile (d)	λ	0.05	0.80	0.04	0.04	m
Density of pile (ρ_p)	η	0.81	2.40	1.95	1.21	Mg/m^3
Young's modulus of pile (E_p)	$\eta^{1/2}\,\lambda^{1/2}$	0.20	25.0	5.04	3.20	GPa
Depth of soil (H)	λ	0.05	20.0	1.00	1.00	m
Density of soil (ρ_s)	η	0.81	1.80	1.46	1.46	Mg/m^3
Shear wave velocity (V_s)	$\eta^{-1/4}\,\lambda^{1/4}$	0.50	171.5	85.44	96.0	m/s
Natural frequency of soil (f_n)	$\eta^{-1/4}\,\lambda^{-3/4}$	9.96	2.14	21.36	24.0	Hz

Table 2
Standard properties of Gifu sand (adopted from [22]).

Items	Values	Units
Specific gravity (G_s)	2.64	–
Maximum diameter (D_{max})	0.84	mm
60% diameter (D_{60})	0.35	mm
30% diameter (D_{30})	0.31	mm
10% diameter (D_{10})	0.22	mm
Coefficient of uniformity (C_u)	1.59	–
Maximum voids ratio (e_{max})	1.13	–
Minimum voids ratio (e_{min})	0.72	–
Friction angle (ϕ)	27.5	deg

2.2. Experimental setup

The experimental model consists of soil-pile systems cased in a laminar shear box of dimensions 1200 mm × 800 mm × 1000 mm bolted on a uniaxial shaking table. The shear box comprises of a set of rectangular aluminum frames stacked on top of each other with ball bearings between each frame to minimize the shear resistance of the housing, i.e., allowing the shear box to move freely in horizontal shear.

2.2.1. Soil

Cohesionless dry Gifu sand, found in Japan, was employed. The standard properties of Gifu sand are presented in Table 2 based on experimental results by Ishida et al. [22]. To obtain the desired compaction, soil in the shear box was compacted by shaking the box using the shaking table at a frequency of 40 Hz and an amplitude of 5 m/s^2, to a density of 1.46 Mg/m^3, as listed in Table 1. Corresponding voids ratio was 0.81 with an estimated relative density of 78%.

2.2.2. Single pile

A solid acrylic pile having diameter d=40 mm and length L=900 mm with a 125 mm × 125 mm × 125 mm solid acrylic head was used. The pile head was connected to a horizontal actuator that provided restraints, so that only horizontal translation (i.e., no rotation and vertical movement) was allowed. No contact between the base of the pile head and soil was allowed, to eliminate possible resistance provided by horizontal traction at the soil surface. Fig. 1(a) shows the layout of the single pile in the shear box.