Soil Dynamics and Earthquake Engineering 30 (2010) 456–469

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

Dynamic nonlinear response of pile foundations under vertical vibration—Theory versus experiment

B. Manna [a,*], D.K. Baidya [b]

[a] Department of Civil Engineering, National Institute of Technology, Rourkela 769008, Orissa, India
[b] Department of Civil Engineering, Indian Institute of Technology, Kharagpur 721302, West Bengal, India

ARTICLE INFO

Article history:
Received 17 September 2008
Received in revised form
5 January 2010
Accepted 7 January 2010

Keywords:
Pile foundation
Stiffness
Damping
Vertical vibration
Dynamic interaction factor
Nonlinear response

ABSTRACT

The influence of nonlinearity on the dynamic response of cast-in-situ reinforced concrete piles subjected to strong vertical excitation was studied. Forced vibration test of single piles (L/d=10, 15, 20) and 2×2 pile groups (s/d=2, 3, 4 for each L/d) were conducted in the field for two different embedded conditions of pile cap. From the measured nonlinear response curves, the effective pile–soil system mass, stiffness and damping were determined and the nonlinear response curves were back-calculated using the theory of nonlinear vibration. The test results were compared with the continuum approach of Novak with dynamic interaction factor approach using both linear and linear-equivalent numerical methods. Reasonable match between the measured and predicted response was found for linear-equivalent methods by introducing a weak boundary-zone around the pile to approximately account for the nonlinear behaviour of pile–soil system. The test data were used to establish the empirical relationship in order to estimate the extent of soil separation around the pile with soil under vertical vibration.

1. Introduction

Dynamic pile–soil interaction is a very complex problem and it has been a subject of broad interest. A number of solutions have been developed for the dynamic linear analysis of piles such as (i) using the concept of elastic subgrade reaction [1] for obtaining soil springs, (ii) treating the pile problem as a case of one dimensional wave propagation in a rod [2], (iii) elastic half space approach [3,4]; (iv) continuum methods using finite element or other numerical techniques [5]. These approximate solutions are very useful in providing insights into the mechanism of dynamic pile–soil interaction. However, in reality both separation and slippage can appear due to the formation of weak bond at the contact between the soil and the pile. In addition, the soil region immediately adjacent to the pile may experience high strain level under dynamic loading and consequently, the pile–soil system behaves in a nonlinear manner.

A perfect theoretical solution to dynamic pile–soil interaction due to slippage and nonlinearity is very difficult and therefore approximate methods need to be used. Matlock et al. [6] introduced lumped mass models with nonlinear discrete springs, dashpot, and friction elements. The combination of these elements makes it possible to generate a variety of nonlinear force–displacement relationship. Another approximate approach, which includes a weak cylindrical zone or inner boundary zone around the pile, was proposed by Novak and Sheta [7]. One of the simplifications involved in the original boundary-zone concept was that the inner zone was neglected to avoid the wave reflections from the interface between the inner boundary zone and the outer zone. To overcome this problem Veletsos and Dotson [8] proposed a scheme that can account for the mass of the boundary zone. Mitwally and Novak [9] accounted approximately for the nonlinear behaviour of the soil adjacent to the pile by incorporating an annular weak zone with reduced soil shear modulus and a slippage element. El Naggar and Novak [10] further extended this model by accounting for loading rate effects. Some of the effects of the boundary-zone mass were investigated by Novak and Han [11] and it was found that a homogeneous boundary zone with a non-zero mass yields undulated impedances due to wave reflections from the fictitious interface between the near field and the far field. To solve this problem Han and Sabin [12] proposed a model of ideal boundary zone with nonreflective interface. El Naggar and Novak [13,14] presented a model for the analysis of pile axial response allowing for nonlinear soil behaviour, energy dissipation through radiation damping, soil hysteresis, and the loading rate dependency of the soil resistance. An analytical solution to the plane strain axisymmetric problem of a vertically vibrating pile slice was presented by some researchers [15,16] for different variation of soil shear modulus.

Although there have been a large number of analytical studies on the dynamic response of piles, relatively a few dynamic load

* Corresponding author. Tel.: +91 9438136166.
E-mail addresses: bd_manna@yahoo.com (B. Manna), baidya@civil.iitkgp.ernet.in (D.K. Baidya).

0267-7261/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.soildyn.2010.01.002

Nomenclature

A	steady state amplitude
A_p	cross-sectional area of pile
A_V	vertical amplitude of pile
$A_{V\text{-}res}$	resonant vertical amplitude of pile
b	radius of the interface between the soil and the soft medium
c	damping value vary with frequency
D_s	dimensionless damping constant of outer soil medium
D_{sm}	dimensionless damping constant of inner weak soil medium
d	diameter of the pile
e	eccentricity of rotating part of the oscillator
E_p	Young's modulus of the pile
$F(A)$	restoring force
f_n	resonant frequency of pile
f_{w1c}	dimensionless stiffness constants of the composite medium
f_{w2c}	dimensionless damping constants of the composite medium
g	acceleration due to gravity
G	shear modulus of outer soil medium
G_m	shear modulus of inner weak soil medium
h	embedded depth of pile cap
K_{ww}	complex vertical stiffness of one pile
$K_e(A)$	equivalent linear stiffness
k_{wc}	axial stiffness of the composite medium
k_i	constants
L	length of the pile
l_s	separation length between the pile and soil
m	mass of eccentric rotating part in oscillator
m_s	mass of total static load including machine on pile
m_{eff}	effective mass of the pile–soil system
N	SPT value
P	dynamic force
R	radius of pile
s	centre-to-centre distance of the piles in a pile group
S_{w1c}	stiffness parameters of composite medium
S_{w2c}	damping parameters of composite medium
t_m	thickness of inner weak soil medium
V_s	shear wave velocity of soil
W	weight of eccentric rotating part in oscillator
W_s	weight of total static load including machine on pile
ω	circular frequency
ω_1, ω_2	frequencies of the points of interaction between response curve and a line
β	material damping
θ	angle of the eccentric mass
Ω	backbone curve
ξ	mass coefficient
Δ_v	maximum vibration amplitudes of pile

tests on piles have been reported in the literature. Novak and Grigg [17] conducted the dynamic experiments on small-scale single piles and pile groups in the field. A series of dynamic experiments were conducted with a group of 102 closely spaced piles for all modes of vibration by El Sharnouby and Novak [18] and these experimental results were evaluated by Novak and El Sharnouby [19]. Similar field dynamic tests on small-scale piles were conducted by Burr et al. [20]. The full scale dynamic field tests on pile were conducted by a few researchers [21,22]. Both theoretical and experimental studies have shown [23–25] that the dynamic response of the piles is very sensitive to the properties of the soil in the vicinity of the pile shaft.

The main objective of the present investigation is to study the nonlinear dynamic behaviour of piles under strong vertical vibrations. A broad study involving both model dynamic testing of pile foundation and theoretical analysis is described. In the first part of the paper, the methodology and the results of vertical vibration field tests are presented. The dynamic tests were carried out on model reinforced concrete single pile and 2×2 pile groups ($s=2d$, $3d$, and $4d$, where d is the diameter of the pile and s is the centre-to-centre distance of the piles in a pile group). In this study, three different pile lengths ($L/d=10$, 15, 20 and $d=0.10$ m, where L is the length of the pile) were used. Soil properties at this site were determined by conducting in-situ tests and laboratory tests. Frequency versus amplitude curves of piles were experimentally established in the field for different intensities of excitation, different static loads on pile, and different contact conditions of the pile cap with the soil.

In the second part, the observed response is compared with theoretical solutions. First the effective pile–soil system mass, stiffness and damping are determined using the methodology proposed by Novak [26] from the measured nonlinear frequency amplitude response curves. The nonlinear response curves are back-calculated using the theory of nonlinear vibration. Secondly, the test results are compared with Novak's continuum approach using both linear and linear-equivalent numerical methods. The stiffness and damping of a single pile are computed on the basis of a method given by Novak et al. [27] and Novak and Aboul-Ella [28,29]. To account for the pile–soil–pile interaction problem or group effects on the dynamic response of piles, the dynamic interaction factors [30,31] are used. For linear-equivalent numerical solution, an approximate approach which includes a weak cylindrical zone around the pile proposed by Novak and Sheta [7] is used to account for the nonlinear characteristics of piles. Two different linear-equivalent models are used: (1) using no separation of pile with constant boundary zone parameters with depth; (2) using separation of pile with varying boundary zone parameters with depth. The methodology involved in this study is incorporated in the computer program DYNA 5 which is formulated by Novak et al. [32]. This program is used to present the dynamic behaviour of piles as frequency response curves for vertical displacement, stiffness, and damping constants.

2. Site conditions and test piles

The field tests were conducted at the site which was located adjacent to Hangar, at Indian Institute of Technology, Kharagpur Campus, India. First soil samples were collected from three bore holes (BH) located at different places of the site. The subsurface investigation indicated that the test site was underlain by three different soil layers up to a depth of 2.80 m. Both laboratory and in-situ tests were performed to characterize the static and dynamic properties of the soil. The laboratory experiments included natural moisture content, bulk density, triaxial test, Atterberg limits test and particle size distribution analysis of soil. In the in-situ test consisted of standard penetration tests (SPT) to determine N value and seismic crosshole tests for determining the shear wave velocity (V_s) of soil layer. Typical S-wave arrival with time at two bore holes of seismic crosshole tests at the depth of