Nonlinear vertical dynamic response of pile groups

Réponse dynamique verticale non linéaire de groupes de tas

B. Manna
Research Scholar, Indian Institute of Technology, Kharagpur, India, Email: bd_manna@yahoo.com

D. K. Baidya
Professor, Indian Institute of Technology, Kharagpur, India, Email: baidya@civil.iitkgp.ernet.in

ABSTRACT

Results of vertical vibration tests on reinforced concrete 2 × 2 pile groups in the field under varying levels of harmonic excitation are presented in the paper. Response curve obtained from the tests display marked nonlinearity as the natural frequencies decreases with increasing intensity of excitation and the vibration amplitudes are not proportional to exciting intensity. The test results were compared with the results obtained using Novak's plane strain model with dynamic interaction factor approach using both linear elastic solutions and nonlinear solutions. To account for the nonlinearity in the response of the piles, the concept of boundary zone was introduced for yielding of soil around the piles. In this nonlinear model, the natural frequency of pile was decreased with increasing exciting moment due to the nonlinear behavior of the surrounding soil. A considerable increase in resonant amplitudes was found in nonlinear model as the damping of pile was reduced due to the lack of bond between the pile and the surrounding soil. A reasonable match was obtained by introducing a weak boundary zone to approximately account for the nonlinear soil behavior adjacent to the pile and for pile-soil separation. The influence of boundary zone parameters and the depth of separation between the pile and the soil on the nonlinear dynamic response of piles are also investigated in this study.

RÉSUMÉ

Les résultats d'épreuves de vibration verticales sur le béton armé 2 × 2 groupes de tas dans le champ sous les niveaux variables d'excitation harmonique sont présentés dans le papier. La courbe de réponse obtenue de l'étalage d'épreuves la nonlinéarité marquée comme les diminutions de fréquences naturelles avec l'intensité augmentante d'excitation et des ampleurs de vibration n'est pas proportionnelle à l'intensité excitante. Les résultats d'essai étaient par rapport aux résultats obtenus en utilisant le modèle d'effort d'avion de Novak avec l'approche de facteur d'action réciproque dynamique en utilisant tant des solutions élastiques linéaires que des solutions non linéaires. Pour représenter la nonlinéarité en réponse des tas, le concept de zone qui marque la limite a été présenté pour céder du sol autour des tas. Dans ce modèle non linéaire, la fréquence naturelle de tas a été diminuée avec l'augmentation du moment excitant en raison de la conduite non linéaire du sol environnant. Une augmentation considérable dans les ampleurs résonnantes a été trouvée dans le modèle non linéaire comme le fait d'humecter de tas a été réduit en raison du manque d'obligation entre le tas et le sol environnant. Un match raisonnable a été obtenu en présentant une faible zone qui marque la limite pour environ représenter la conduite de sol non linéaire adjacente au tas et pour la séparation de sol de tas. L'influence de paramètres zonaux qui marque la limite et de la profondeur de séparation entre le tas et le sol sur la réponse dynamique non linéaire de tas est aussi enquêtée dans cette étude.

Keywords: pile foundation, nonlinear response, stiffness, damping, separation

1 INTRODUCTION

The interaction between the pile foundation and the surrounding soil represents one of the least understood topics of foundation dynamics. A further complication in this dynamic response comes from the interaction between each of the piles in a pile group. If the spacing between the piles is very wide, the group stiffness can be evaluated simply by summing the contributions from the single piles. Piles that are closely spaced will have a significant effect on one another during dynamic loading due to wave propagating through the soil from each pile under load. As a result, the group efficiency under dynamic excitation exhibits a strong oscillatory behaviour.

An accurate theoretical solution to dynamic pile-soil interaction due to slippage and nonlinearity is difficult and therefore approximate methods need to be used. Matlock et al. (1978) introduced lumped mass models with nonlinear discrete springs, dashpot, and friction elements. Another approximate approach, which includes a weak cylindrical zone or inner boundary zone around the pile, was proposed by Novak & Sheta (1980). 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 & Dotson (1988) proposed a scheme that can account for the mass of the boundary zone. El Naggar & Novak (1994) presented a model for the analysis of axial pile response allowing for nonlinear soil behaviour, energy dissipation through radiation damping, and soil hysteresis.

Full scale dynamic tests on pile were conducted in the field by Vaziri & Han (1991). Novak & Grigg (1976) conducted the dynamic experiments on small-scale single piles and pile groups in the field. Similar field dynamic tests on small scale piles were conducted by El Sharnouby & Novak (1984), Han & Vaziri (1992) and Burr et al. (1997).

A comprehensive study involving both model dynamic testing of pile foundation and theoretical analysis is presented in this paper. The dynamic tests were carried out on model reinforced concrete 2 × 2 pile groups of different length (L) and spacing (s). Frequency versus amplitude curves of piles were experimentally established in the field for different excitation intensities. The test results are compared with the results obtained by Novak's plane strain model using both linear elastic solutions and nonlinear solutions. The stiffness and damping of a single pile are computed on the basis of a method given by Novak et al. (1978) and Novak & Aboul-Ella (1978). To

Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering
M. Hamza et al. (Eds.)

doi:10.3233/978-1-60750-031-5-1128

account for the pile-soil-pile interaction problem on the dynamic response of piles, the dynamic interaction factors proposed by Kaynia & Kausel (1982) and Novak & Mitwally (1990) are used in this analysis. For nonlinear solution an approximate approach which includes a weak cylindrical zone around the pile proposed by Novak & Sheta (1980) is used to account for the nonlinear characteristics of piles. The influences of various boundary zone parameters and pile-soil separation on the dynamic response of piles are also studied.

2 THEORETICAL ANALYSIS

In this study Novak's plane strain method is used to analyze the dynamic behavior of pile foundation with dynamic interaction factor. Both linear and nonlinear analysis, are used to analyze the dynamic behavior of pile foundation under vertical vibrations.

Novak et al. (1978) proposed the soil stiffness of homogeneous medium (k_w) for vertical vibration as

$$k_w = G_s\left[S_{w1}\left(a_o, D_s\right) + iS_{w2}\left(a_o, D_s\right)\right] \quad (1)$$

in which G_s is the shear modulus of homogeneous soil, a_o is dimensionless frequency, D_s is dimensionless damping constant, S_{w1} and S_{w2} are the real and imaginary parts of the dimensionless complex stiffness of homogeneous medium, respectively. Substituting the stiffness of soil layer into the governing equation of the pile, the stiffness and damping constants of the single pile (Novak & Aboul-Ella 1978) were obtained as

$$k_w^1 = \frac{E_p A_p}{R} f_{w1} \quad (2)$$

$$c_w^1 = \frac{E_p A_p}{V_s} f_{w2} \quad (3)$$

where V_s is the shear wave velocity in the lowest layer of soil at the pile tip; E_p is the Young's modulus of the pile material, R is the radius of the pile, A_p is the cross sectional area of pile, and f_{w1} and f_{w2} are the dimensionless stiffness and damping parameters, respectively.

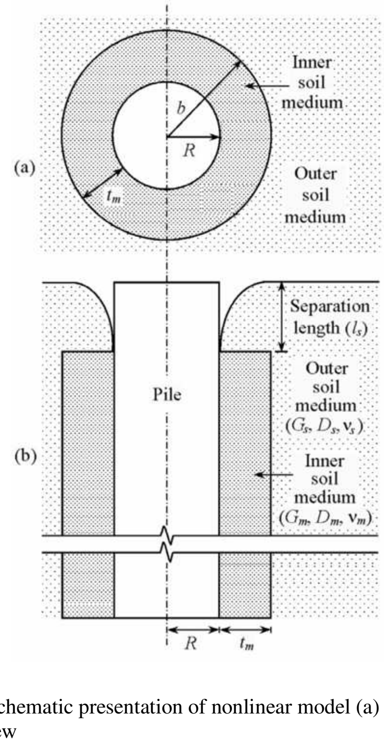

Figure 1. Schematic presentation of nonlinear model (a) Section view (b) Plan view

To account approximately for the effects of nonlinearity and slippage, it is assumed that an embedded cylindrical body is surrounded by a linear viscoelastic medium composed of two parts (Novak & Sheta 1980): an outer infinite region and an inner weak layer surrounding the cylindrical body as shown in Figure 1. The complex dynamic stiffness (k_{wc}) of the composite medium is given by

$$k_{wc} = G_s(S_{w1c} + iS_{w2c}) \quad (4)$$

in which the dimensionless stiffness (S_{w1c}) and damping (S_{w2c}) parameters of composite medium are real and depend on dimensionless frequency a_o, t_m/R, G_m/G_s, D_s, and D_m. Here, t_m is the thickness of the inner soil medium and D_m is the dimensionless damping constant of inner weak soil medium. Using the ratio $G_m/G_s = 0$ in the topmost layer, the separation between the pile and the soil is accounted for.

In this study, the dynamic interaction factor method is used to perform the relevant theoretical analysis. For two identical and equally loaded piles i and j, the dynamic interaction factor α_{ij} is defined as:

$$\alpha_{ij} = \frac{\delta_{dij}}{\delta_{sjj}} \quad (5)$$

where δ_{dij} is dynamic displacement of pile i due to load on pile j, and δ_{sij} is static displacement of pile j due to its own load.
The vertical stiffness of pile group is calculated by:

$$K_V = \bar{K}_V \sum_{i=1}^{n} \sum_{j=1}^{n} \varepsilon_{ij}^V \quad (6)$$

where $\bar{K}_V$ is the vertical static stiffness of single pile, ε_{ij}^V is the elements of $[\alpha]_V^{-1}$; $[\alpha]_V$ is the interaction matrix of vertical displacements. The theoretical calculations of piles under vertical vibration were performed using the computer program DYNA5, which employs the previous assumptions and procedure.

3 TEST DESCRIPTION AND RESULTS

The site was located adjacent to Hangar, at Indian Institute of Technology, Kharagpur Campus, India. Both disturbed and undisturbed soil samples were collected from three bore holes located at different places of the site. The soil properties were determined by in-situ and laboratory tests. Two different in situ tests were conducted, namely, standard penetration tests (SPT) to determine N value and cross hole seismic tests for determining the shear wave velocity of soil layer. The piles were constructed in the field by bored cast-in-situ method. The diameter (d) of the pile was 0.1 m. In this study, two different pile length (L/d = 15, 20) and three different spacing (s/d = 2, 3, 4) were used for the investigation. The dimension of pile cap was 0.57 m × 0.57 m × 0.25 m. Tests were carried out for two different embedded depths (h) of pile cap: Case 1 - Pile cap embedded into soil (h = 0.175 m); Case 2 - No contact of pile cap with soil (h = 0).

Forced vibration tests were conducted on model 2 × 2 group piles subjected to vertical vibration. In order to connect the pile cap to the oscillator, a rigid mild steel plate was attached on the pile cap with nut and bolt system. Lazan type mechanical oscillator was mounted over the steel plate. To ensure that the resonance peaks were well pronounced and within the frequency range of the exciting mechanism, mild steel ingots or test bodies were rigidly bolted on the top of the oscillator. The test body was comprised of steel ingots each weighing 650 N (8 nos) and 450 N (10 nos). Whole set up was then connected so that it acts as a single unit. Proper care was taken to keep the center of gravity of loading system and that of the pile cap in the same vertical line. A flexible shaft was used to connect the mechanical oscillator to a DC motor. The motor was connected to a speed control unit to control the speed of the DC motor. The vibration measuring equipment consisted of a two piezoelectric acceleration pickup and vibration meter. For vertical excitation, displacements were measured using two acceleration pickup mounted symmetrically one on each side of the centroid of the foundation. The schematic diagram of the experimental setup is shown in Figure 2.

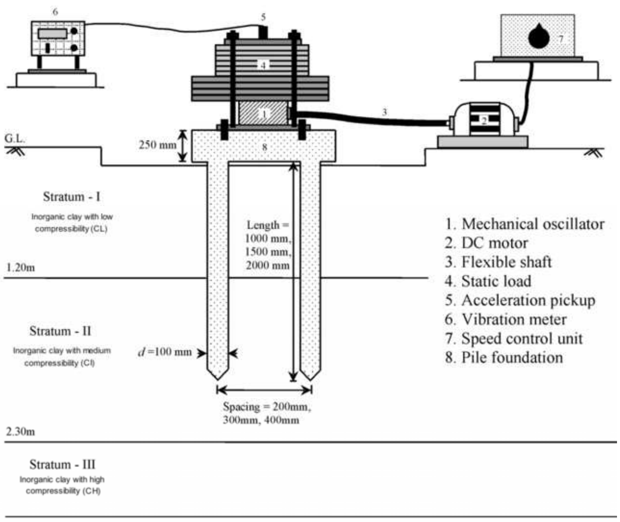

Figure 2. Schematic diagram of test setup for vertical vibration

The oscillator was run slowly through a motor using speed control unit. Thus the pile was subjected to vibration in the vertical direction. The vibration amplitudes were measured at different frequencies for each eccentric moment ($W{\cdot}e$). A typical frequency amplitude response curve of pile under vertical excitation is presented in Figure 3.

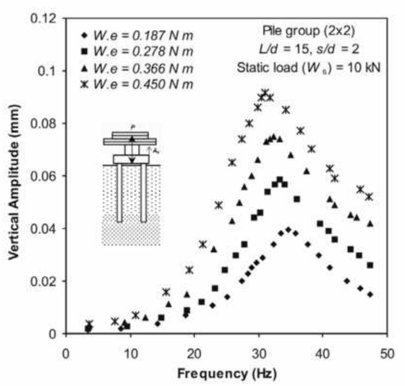

Figure 3. Experimental frequency-amplitude response curves for vertical vibration (L/d = 15, s/d = 2, W_s = 10 kN, Case 2)

It can be seen that the observed response curves display nonlinearity as the resonant frequencies decreases with increasing excitation intensity and also the amplitudes are not proportional to the excitation intensity. Tests were conducted for two different static loads (W_s = 10 kN and 12 kN) and it is observed that both the natural frequency and resonant amplitude decreases as the static load increases. The variations of natural frequency and resonant amplitude are observed for different *s/d* ratio of pile groups and it is found that the natural frequency increases and the resonant amplitude decreases with increasing pile spacing. It is also found that embedded pile cap (Case 1) produced higher stiffness and damping of pile than the no contact condition of pile cap (Case 2).

4 COMPARISON OF THEORETICAL AND TEST RESULTS

For clear understanding of the significance and influence of nonlinearity, this section is divided in two parts: 1. comparison with linear theory; 2. comparison with nonlinear theory.

For linear theory, the stiffness and damping characteristics do not vary with the excitation level. Theoretical calculations were performed using the properties of pile material and measured soil parameters. In this analysis, no weak zone around the pile was considered and the value of damping ratio of soil was assumed constant (D_s = 0.15) with depth. The soil below the pile tip is assumed to be homogeneous. A typical comparison of experimental response curves and the linear theoretical predictions under vertical vibration is presented in Figure 4.

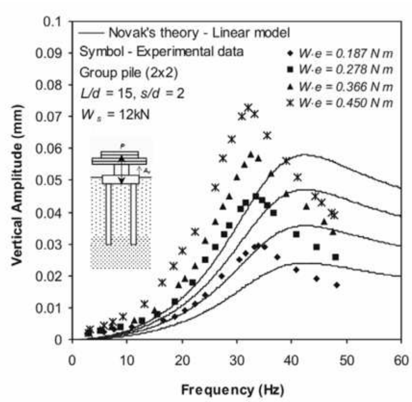

Figure 4. Comparison of experimental and theoretical (Linear model) response curves (L/d = 15, s/d = 2, W_s = 12 kN, Case 1)

It can be observed that the linear theory highly overestimates both the stiffness and damping due to the perfect bonding between pile and soil which is assumed in laws of linear elasticity. Hence the linear theory is not that useful to predict the dynamic behaviour of pile under vertical vibration because in practice the pile and the soil bonding rarely perfect and slippage or even separation often occur at the contact surface between the soil and pile.

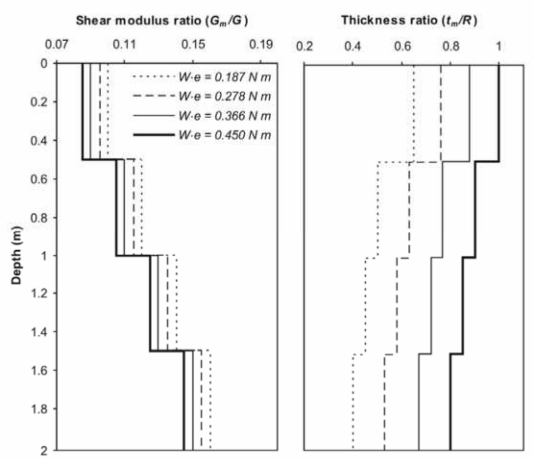

Figure 5. Variations of boundary zone parameters with depth

In case of nonlinear analysis, the boundary-zone concept, which accounts for yielding of soil around the piles, was incorporated into the linear-elastic based mathematical model. This model provides for the gradual expansion of the yielded zone around the pile and also the separation of pile and top layer of soil as the excitation level increases. For different excitation intensities, the soil parameter in the weakened zone are adjusted so that the nonlinear theoretical response curves approach the observed results. The variations of boundary zone parameters with depth for different excitation levels are shown in Figure 5.

The depth of anticipated separation (l_s) ranges from 1.8*d* for $W \cdot e$ = 0.187 N m to 2.4*d* for $W \cdot e$ = 0.450 N m. Comparison between the observed results and theoretical solutions using boundary zone and pile separation is shown in Figure 6.

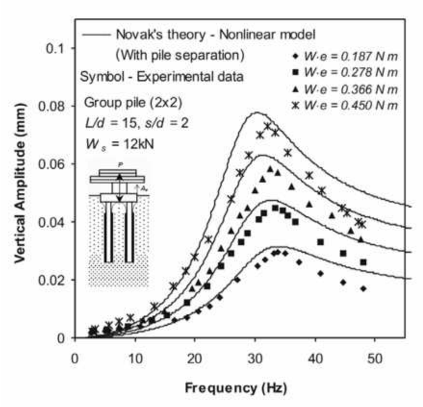

Figure 6. Comparison of experimental and theoretical (Nonlinear model) response curves (L/d = 15, s/d = 2, W_s = 12 kN, Case 1)

It can be seen that both the predicted natural frequencies are decreased and resonant amplitudes are increased by introducing the weak cylindrical zone around the pile and by providing sufficient pile separation with soil and a very close agreement with observed results are achieved.

5 PILE STIFFNESS AND DAMPING

A typical nonlinear theoretical stiffness and damping of pile for vertical mode is shown in Figure 7.

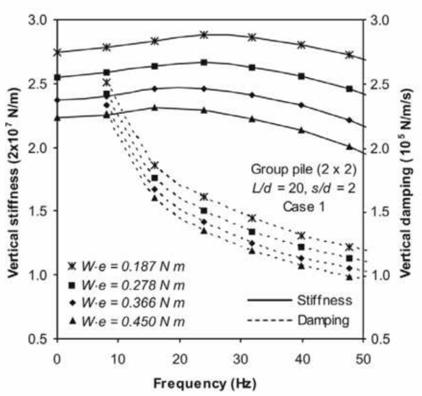

Figure 7. Vertical stiffness and damping of pile group (L/d = 20, s/d = 2, Case 1) for different exciting moment

It can be seen that the pile stiffness is almost frequency independent at lower frequencies. This is because at low frequencies, the dynamic stiffness of pile is quite close to static stiffness. The pile damping, on the other hand, rapidly decreases as frequency increases. This is primarily due to the conversion of frequency-independent soil material damping (β) and frequency (ω) to the equivalent viscous damping coefficient (c) as $c = 2\beta/\omega$. It can also be observed that both the pile stiffness and damping decreases with increasing excitation intensity.

6 CONCLUSIONS

This paper describes vertical vibration test of piles in the field subjected to harmonic loading. The observed pile response exhibit typical nonlinear behavior. Many parameters, namely, exciting intensities, static load and embedment of pile cap have influence on the nonlinear dynamic response of pile foundation under vertical vibration.

Test results are compared with Novak's plane strain analysis with both linear and nonlinear model. The theoretical analysis based on linear theory highly overestimates both the stiffness and damping of piles. The discrepancies are due to the perfect bonding between pile and soil which is assumed in linear analysis. The nonlinear model with pile separation sufficiently decreases the stiffness values and the predicted natural frequencies agree with the observed values. The predicted values of damping are found close to the experimental results, particularly at higher excitation intensity.

The accuracy of the nonlinear theory in predicting the nonlinear response depends on the choice of boundary zone parameters and the length of pile separation. It has been found in the present study that the separation length of pile varies with excitation intensity. The depth of separation varies between 1.8*d* to 2.4*d*. Further research is needed to develop criteria for pile separation prediction and nonlinear pile dynamic analysis.

REFERENCES

Burr, J. P. Pender, M. J. & Larkin, T. J. 1997. Dynamic response of laterally excited pile groups. *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, 123(1): 1-8.

El Naggar, M. H. & Novak, M. 1994. Non-linear model for dynamic axial pile response. *Journal of Geotechnical Engineering,* ASCE 120(2): 308-329.

El Sharnouby, B. & Novak, M. 1984. Dynamic experiments with group of piles. *Journal of Geotechnical Engineering,* ASCE, 110(6): 719-737.

Han, Y. & Vaziri, H. 1992. Dynamic response of pile groups under lateral loading. *Soil Dynamics and Earthquake Engineering*, 11: 87-99.

Matlock, H. Foo, H. C. & Bryant, L. M. 1978. Simulation of lateral pile behaviour under earthquake motion. *In: Proceedings ASCE. Specialty Conference on Earthquake Engineering and Soil Dynamics*, XI: 600-619. Pasadna, CA.

Novak, M. & Aboul-Ella, F. 1978. Impedance functions of piles in layered media. *Journal of Engineering Mechanics*, ASCE, 104(3): 643-661.

Novak, M. & Grigg, R. F. 1976. Dynamic experiments with small pile foundations. *Canadian Geotechnical Journal,* 13: 372-385.

Novak, M. & Mitwally, H. 1990. Random response of offshore towers with pile-soil-pile interaction. *Journal Offshore Mechanics and Arctic Engineering*, 112: 35-41.

Novak, M. Nogami, T. & Aboul-Ella, F. 1978. Dynamic soil reactions for plane strain case. *Journal Engineering Mechanics*, ASCE, 104(EM4): 953-959.

Novak, M. & Sheta, M. 1980. Approximate approach to contact problems of piles. *Proceedings: Dynamic Response of Pile Foundations: Analytical Aspects,* M. O'Neill et al., eds., ASCE: 53–79. New York.

Kaynia, A. M. & Kausel, E. 1982. Dynamic behavior of pile groups. *In: Proceedings of 2nd Int Conf Num Meth Offshore Piling*: 509-532. Austin, Texas.

Veletsos, A.S. & Dotson, K. W. 1988. Vertical and torsional vibration of foundations in inhomogeneous media. *Journal of Geotechnical Engineering*, ASCE, 114(9): 1002-1021.

Vaziri, H. & Han, Y. 1991. Full-scale field studies of the dynamic response of piles embedded in partially frozen soils. *Canadian Geotechnical Journal*, 28: 708-718.