NONLINEAR CHARACTERISTICS OF PILE FOUNDATIONS UNDER HARMONIC VIBRATIONS – FIELD TESTING AND ANALYSIS

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by

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in fulfilment of the requirements of the degree of Doctor of Philosophy

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Dedicated to my

adorable nephew Taj

CERTIFICATE

This is to certify that the thesis entitled "**Nonlinear Characteristics of Pile Foundations under Harmonic Vibrations - Field Testing and Analysis**", submitted by **Mr. Sanjit Biswas** to the **Indian Institute of Technology Delhi**, is a record of bonafide research work carried out by him under my supervision and is worthy of consideration for the award of **Doctor of Philosophy** degree. The research reported in this thesis has not been submitted in part or full to any other university or institute for the award of any degree or diploma.

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ABSTRACT

This study includes the determination of soil-pile separation lengths and frequency-amplitude responses of single and group piles under rotating machine induced vertical and coupled i.e. horizontal and rocking vibrations by experimental investigation. Another aspect of the present study is the estimation of boundary zone parameters for single and group piles using the measured responses of the soil-pile systems by numerical analysis. To fulfil these objectives, forced vibration tests were performed in the field on a single pile and a 2 × 2 pile group made of hollow steel piles of length 5.8 m and outer diameter of 0.166 m to determine the frequency-amplitude responses for different eccentric moments under a static load of 15 kN. In addition to that the soil-pile separation lengths of single and group piles are determined by measuring the contact pressure between the pile and soil. The experimental frequency-amplitude responses of the single pile and 2 × 2 pile group are found nonlinear in nature for both vertical and coupled modes of vibration.

The numerical analyses are performed by continuum approach and superposition method to determine the dynamic response of pile foundations using the soil-pile separation lengths obtained from the dynamic pile tests. Comparing the analytical frequency versus amplitude responses with the experimental response curves, the best possible variations of boundary zone soil parameters are determined for different eccentric moments and under vertical and coupled modes of vibration. In this study, the continuum approach is found very efficient for prediction of the nonlinear responses of single pile as well as pile group with precise inclusion of the boundary zone parameters and soil-pile separation lengths. The variations of stiffness and damping of the soil-pile systems with frequency are presented for all the modes of vibration using the numerical analysis. The pile-soil-pile interaction phenomenon of the 2 × 2 pile group is also investigated by calculating the group efficiency ratios (GER) of the pile group for different eccentric moments and vibration modes. The effect of slenderness ratio of pile, the pile head fixity conditions and the spacing between the piles of pile group on the dynamic response of the pile foundation are demonstrated using the continuum approach analysis. A comparative study is also performed for single pile and 2 × 2 pile group under both vertical and coupled modes of vibration using three different analytical methods: 1. Novak (1974), 2. Novak and El Sharnouby (1983), 3. Novak et al. (1999).

Various design charts are proposed based on the finding of the study, to estimate the soil-pile separation lengths and boundary zone parameters for the single pile and 2 × 2 pile group under vertical and coupled vibrations. The applicability of the proposed design charts is validated for full-scale prototype piles using scaling law. It is found that the proposed design curves can be used to determine the nonlinear frequency-amplitude responses of the full-scale pile foundations under both vertical and coupled vibrations for similar soil-pile conditions. The charts are also validated using experimental data of various literature to check the reliability of the design charts. It is found that the proposed design charts can be used to determine the nonlinear frequency versus amplitude responses of the pile foundations under vertical and coupled vibrations for similar type of soil-pile conditions.

सार

इस अध्ययन में घूमने वाली मशीन के अंतर्गत एकल व समूह पाइल की मृदा-पाइल पृथ्थकरण की लंबाई एवं आवृत्ति-आयाम प्रतिक्रियाओं का ऊर्ध्वाधर और युग्मित कंपन के अंतर्गत प्रयोगात्मक अन्वेषण किया गया है। वर्तमान अध्ययन का एक अन्य पहलू, सिंगल और ग्रुप पाइल के लिए सीमा के क्षेत्र मानकों का अनुमान है, जो सांख्यिकीय विश्लेषण द्वारा मृदा-पाइल प्रणालियों के मापा प्रतिक्रियाओं का उपयोग करते हैं। इन उद्देश्यों को पूरा करने के लिए, मैदान में खोखले लौह के एक एकल पाइल एवं 2 × 2 - पाइल समूह, जिनकी लंबाई 5.8 मीटर एवं बाहरी व्यास 0.166 मीटर है, विभिन्न विलक्षण क्षणों और 15 kN के एक स्थिर भार के लिए प्राभावित कंपन द्वारा परीक्षण किया गया है और आवृत्ति-आयाम प्रतिक्रिया का निर्धारण किया गया है। एकल और समूह पाइल के मृदा-पाइल पृथ्थकरण की लंबाई का आंकलन मृदा एवं पाइल के बीच संपर्क दबाव को माप के निर्धारित किया गया है। एकल पाइल और 2 × 2 - पाइल समूह की प्रायोगिक आवृत्ति-आयाम प्रतिक्रिया कंपन के ऊर्ध्वाधर और युग्मित प्रणालियों के लिए प्रकृति में गैर-रेखीय दिखती है।

संख्यात्मक विश्लेषण गतिशील पाइल परीक्षणों से प्राप्त मृदा-पाइल पृथ्थकरण लंबाई का उपयोग कर पाइल नींव की गतिशील प्रतिक्रिया निर्धारित करने के लिए निरंतर दृष्टिकोण और सुपरपोजी पद्धति द्वारा किया जाता है। प्रायोगिक प्रतिक्रिया घटता के साथ आयाम प्रतिक्रियाओं की तुलना में विश्लेषणात्मक आवृत्ति की तुलना, सीमा क्षेत्र के मृदा के मापदंडों

का सर्वोत्तम संभव रूपांतर विभिन्न विलक्षण क्षणों के लिए और कंपन के ऊर्ध्वाधर और युग्मित मोड के तहत निर्धारित होते हैं। इस अध्ययन में, निरंतर दृष्टिकोण को गैर-रेखीय प्रतिक्रियाओं की भविष्यवाणी के लिए बहुत ही कुशल पाया गया है। सीमा के मानकों और मृदा-पाइल पृथ्थकरण लंबाई के सटीक समावेश के साथ एकल पाइल के साथ ही पाइल समूह आवधिकता वाले मृदा-पाइल प्रणालियों की कठोरता और अवमन्दक विविधताएं संख्यात्मक विश्लेषण के उपयोग से कंपन के सभी तरीकों के लिए प्रस्तुत की जाती हैं। 2 × 2- पाइल समूह के पाइल -मृदा- पाइल घटना की प्रक्रिया को विभिन्न विलक्षण क्षणों और कंपन मोडों के लिए पाइल समूह के समूह दक्षता अनुपात (जीईआर) की गणना के द्वारा जांच की जाती है। पाइल के धीमे अनुपात का प्रभाव, पाइल के ढक्कन की स्थिति और पाइल समूह के पाइल के बीच की दूरी को पाइल फाउंडेशन की गतिशील प्रतिक्रिया पर प्रदर्शित किया जाता है, सातत्य दृष्टिकोण विश्लेषण का उपयोग करते हुए दिखाया गया है। तीन अलग-अलग विश्लेषणात्मक विधियों का उपयोग करते हुए एकल पाइल और 2 × 2- पाइल समूह के लिए एक तुलनात्मक अध्ययन भी किया जाता है: 1. नोवाक (1974), 2. नोवाक और एल शर्नबी (1983), 3. DYNA5 (1999)।

एकमात्र पाइल के लिए मृदा-पाइल पृथ्थकरण लंबाई और सीमा क्षेत्र मानकों का अनुमान लगाने के लिए, ऊर्ध्वाधर और युग्मित कंपनों के तहत 2 × 2-पाइल समूह के अध्ययन के आधार पर विभिन्न डिजाइन चार्ट प्रस्तावित किए जाते हैं। प्रस्तावित डिजाइन चार्ट की प्रयोज्यता स्केलिंग सिद्धांत का उपयोग करके पूर्ण-स्केल प्रोटोटाइप पाइल के लिए मान्य है। यह पाया जाता है कि प्रस्तावित डिजाइन वक्र का इस्तेमाल समरूप - मृदा के पाइल परिस्थितियों के लिए दोनों ऊर्ध्वाधर और युग्मित कंपनों के तहत पूर्ण-पैमाने पर पाइल नींव के गैर-रेखीय आवृत्ति-आयाम प्रतिक्रियाओं को निर्धारित करने के लिए किया जा

सकता है। डिजाइन चार्ट की विश्वसनीयता की जांच विभिन्न साहित्यों के प्रयोगात्मक तथ्य का उपयोग करके किया गया है । यह पाया जाता है कि प्रस्तावित डिजाइन चार्ट का उपयोग समान प्रकार की मृदा -पाइल परिस्थितियों के लिए ऊर्ध्वाधर और युग्मित कंपनों के तहत पाइल नींवों के अणुभरण की आवृत्ति के विरुद्ध अमानक आवृत्ति को निर्धारित करने के लिए किया जा सकता है।

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LIST OF SYMBOLS AND ABBREVIATIONS

Most of the symbols are defined as they appear in the thesis. Some of the most common symbols which are used repeatedly are listed below.

Roman symbols

a_o	Dimensionless frequency
a_o^*	Complex dimensionless frequency
A	Cross-sectional area of pile
B	Integration constant
C	Integration constant
c	Cohesion of soil
c_c^1	Equivalent viscous damping of single pile in cross direction
c_c^G	Equivalent viscous damping of pile group in cross direction
c_i	Coefficient of pile internal damping
c_u^1	Equivalent viscous damping of single pile in horizontal direction
c_u^G	Equivalent viscous damping of pile group in horizontal direction
c_v	Equivalent viscous damping
c_v^1	Equivalent viscous damping of single pile in vertical direction
c_v^G	Equivalent viscous damping of pile group in vertical direction

c_{ψ}^{1}	Equivalent viscous damping of single pile in rocking direction
c_{ψ}^{G}	Equivalent viscous damping of pile group in rocking direction
d	Diameter of pile
D	Damping ratio of soil
D_b	Damping ratio of soil below pile tip
D_m	Damping ratio of inner boundary zone soil
e	Eccentricity of rotating masses of oscillator
E	Young’s modulus of pile
E_m	Young’s modulus of model pile
E_p	Young’s modulus of prototype pile
E_s	Young’s modulus of soil
f_i	Dimensionless function
F	A coefficient for frequency variation of dynamic interaction factors
F_i	Amplitude of axial force
g	Acceleration due to gravity
G	Shear modulus of soil
G_b	Shear modulus of soil below pile tip
G_m	Shear modulus of inner boundary zone soil
h_i	Length of pile element
H_i	Amplitude of horizontal force
$\{H\}$	Horizontal forces at the pile heads of a pile group
i	Imaginary unit satisfying $i^2 = -1$
I	Moment of inertia of pile
I_m	Moment of inertia of model pile
I_p	Moment of inertia of prototype pile

k_c^1	Stiffness of single pile in cross direction
k_c^G	Stiffness of pile group in cross direction
k_{inner}	Inner boundary zone complex stiffness of soil in horizontal direction
k_{outer}	Outer boundary zone complex stiffness of soil in horizontal direction
k_u	Equivalent linear complex stiffness of soil in horizontal direction
k_u^1	Stiffness of single pile in horizontal direction
k_u^G	Stiffness of pile group in horizontal direction
k_u^i	Stiffness of an individual pile member for coupled vibration
k_{ub}	Complex stiffness of pile base in horizontal direction
k_{ul}	Linear complex stiffness of soil in horizontal direction
k_v	Equivalent linear complex stiffness of soil in vertical direction
k_v^1	Stiffness of single pile in vertical direction
k_v^G	Stiffness of pile group in vertical direction
k_v^i	Stiffness of an individual pile member for vertical direction
k_{vb}	Complex stiffness of pile base in vertical direction
k_{vl}	Linear complex stiffness of soil in vertical direction
k_ψ	Equivalent linear complex stiffness of soil in rocking direction
k_ψ^1	Stiffness of single pile in rocking direction
k_ψ^G	Stiffness of pile group in rocking direction
$k_{\psi b}$	Complex stiffness of pile base in rocking direction
$k_{\psi l}$	Linear complex stiffness of soil in rocking direction
K_0	Zero order modified Bessel function of second kind
K_1	First order modified Bessel function of second kind

K_c	Dynamic stiffness of single pile in cross direction
K_c^1	Complex stiffness of single pile in cross direction
K_c^G	Complex stiffness of pile group in cross direction
K_c^n	Cross stiffness generated due to the coupling between lateral force and moment (= $K_{u\psi}^n = K_{\psi u}^n$) at pile node n
K_v	Dynamic stiffness of the single pile in vertical direction
K_v^1	Complex stiffness of single pile in vertical direction
K_v^G	Complex stiffness of pile group in vertical direction
K_v^n	Stiffness corresponding to the vertical force at pile node n
K_{vs}	Static stiffness of single pile in vertical direction
K_u	Dynamic stiffness of single pile in horizontal direction
K_u^1	Complex stiffness of single pile in horizontal direction
K_u^G	Complex stiffness of pile group in horizontal vibration
K_u^n	Stiffness corresponding to lateral force at pile node n
K_{us}	Static stiffness of single pile in horizontal direction
K_ψ	Dynamic stiffness of single pile in rocking direction
K_ψ^1	Complex stiffness of single pile in rocking direction
K_ψ^G	Complex stiffness of pile group in rocking direction
K_ψ^n	Stiffness corresponding to moment at pile node n
$\{k_b\}$	Stiffness matrix of the soil/element below pile tip
$\{K_{TV}\}$	Total stiffness matrix of pile for vertical vibration
$\{K_{TC}\}$	Total stiffness matrix of pile for coupled vibration

l	Length of pile
m	Mass of eccentric rotating part in oscillator
M_i	Amplitude of the moment in vertical plane
$\{M\}$	Moments at pile heads of a pile group
n	Scaling factor for full-scale pile length to model pile length
N	SPT value
N_s	Static axial force on pile
p	Soil resistance in lateral direction
P	Dynamic force of oscillator
$\{P\}$	Vertical forces at pile heads of a pile group
R	Radius of pile
R_0	Radius of pile plus thickness of inner boundary zone soil (= $R + t_m$)
R_b	Radius of pile tip
s	Spacing of piles in pile group
S_{u1}	Dimensionless stiffness parameter of equivalent linear soil stiffness in horizontal direction
S_{u2}	Dimensionless damping parameter of equivalent linear soil stiffness in horizontal direction
S_{ub1}	Dimensionless stiffness parameter of the pile base complex stiffness in horizontal direction
S_{ub2}	Dimensionless damping parameter of the pile base complex stiffness in horizontal direction
S_{ul1}	Dimensionless stiffness parameter of linear soil stiffness in horizontal direction

S_{ul2}	Dimensionless damping parameter of linear soil stiffness in horizontal direction
S_{v1}	Dimensionless stiffness parameter of equivalent linear soil stiffness in vertical direction
S_{v2}	Dimensionless damping parameter of equivalent linear soil stiffness in vertical direction
S_{vb1}	Dimensionless stiffness parameter of the pile base complex stiffness in horizontal direction
S_{vb2}	Dimensionless damping parameter of the pile base complex stiffness in vertical direction
S_{vl1}	Dimensionless stiffness parameter of linear soil stiffness in vertical direction
S_{vl2}	Dimensionless damping parameter of linear soil stiffness in vertical direction
$S_{\psi 1}$	Dimensionless stiffness parameter of equivalent linear soil stiffness in rocking direction
$S_{\psi 2}$	Dimensionless damping parameter of equivalent linear soil stiffness in rocking direction
$S_{\psi b1}$	Dimensionless stiffness parameter of the pile base complex stiffness in rocking direction
$S_{\psi b2}$	Dimensionless damping parameter of the pile base complex stiffness in rocking direction
$S_{\psi l1}$	Dimensionless stiffness parameter of linear soil stiffness in rocking direction

$S_{\psi l2}$	Dimensionless damping parameter of linear soil stiffness in rocking direction
t	Time
t_m	Thickness of boundary zone soil
u	Horizontal displacement of pile
$\dot{u}$	Time derivative
u_n	Displacement at pile node n in horizontal direction
v	Vertical displacement of pile
$\dot{v}$	Time derivative
v_n	Displacement at pile node n in vertical direction
$\{v\}$	Vertical displacements at pile heads of a pile group
$U_{1,2,3,4}$	Integration constants
V_s	Shear wave velocity of soil
V_b	Shear wave velocity soil below pile tip
W	Weight of eccentric rotating part in oscillator
W_s	Static Load
y	Pile defection in lateral direction
z	Depth of pile

Greek symbols

α	A constant quantifies the dependency of stress level on the system stiffness
α_1	Real part of complex dynamic interaction factor
α_2	Imaginary part of complex dynamic interaction factor
α_d	Complex dynamic interaction factor

α_{ij}	Complex vertical interaction factors of individual piles in a group between piles i and j
α_{ij}^{c}	Complex cross interaction factors of individual piles in a group between piles i and j.
α_{ij}^{u}	Complex horizontal interaction factors of individual piles in a group between piles i and j.
α_{ij}^{ψ}	Complex rocking interaction factors of individual piles in a group between piles i and j.
α_{st}	Static interaction factor
$[\alpha_H]$	Dynamic group interaction matrix for coupled vibration
$[\alpha_v]$	Dynamic group interaction matrix for vertical vibration
β	frequency independent soil material damping
ω	Circular frequency
ψ	Rocking displacement (rotation) of pile
ψ_n	Rotation at pile node n
$\varepsilon_{ij}{}^{H}$	Complex elements of $inv[\alpha_H]$
$\varepsilon_{ij}{}^{v}$	Complex elements of $inv[\alpha_v]$
μ	Mass of pile per unit length
ν	Poisson’s ratios for outer zone of soil
ν_b	Poisson’s ratio of soil below pile tip
ν_m	Poisson’s ratios for inner zone of soil
ϕ	Complex frequency parameter for vertical vibration
φ	Friction angle of soil
θ	Eccentric angle between rotating masses of oscillator

$\lambda_{1,2}$	Complex frequency parameters for coupled vibration

Abbreviations

AC	Alternating-current
@	At the rate of
BEM	Boundary element method
BH	Borehole
C.G.	Center of gravity
CU	Consolidated undrained
Eq.	Equation
FE	Finite element
FEM	Finite element method
Fig.	Figure
GER	Group efficiency ratio
hp	horsepower
Hz	Hertz
N	Newton
LL	Liquid limit
m	Meter
mm	Millimeter
MPF	Mass participation factor
psi	Pounds per square inch
Pa	Pascal
PL	Plastic limit
Rad	Radian

RPM	Revolutions per minute
s	Second
SPT	Standard penetration test
USCS	Unified soil classification system
°	Degree