DYNAMIC RESPONSE OF BLOCK FOUNDATIONS SUBJECTED TO VIBRATIONS INDUCED BY SINGLE AND TWO ROTATING MACHINES

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SEPTEMBER 2021

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by

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Submitted

in fulfillment of the requirements of the degree of Doctor of Philosophy

to the

INDIAN INSTITUTE OF TECHNOLOGY DELHI

SEPTEMBER 2021

Dedicated to my parents
and brothers

DECLARATION

I certify that

a. the work contained in this thesis is original and has been done by me under the guidance of my supervisor.
b. the work has not been submitted to any other Institute for any degree or diploma.
c. I have followed the guidelines provided by the Institute in preparing the thesis.
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This is to certify that the thesis entitled "**DYNAMIC RESPONSE OF BLOCK FOUNDATIONS SUBJECTED TO VIBRATIONS INDUCED BY SINGLE AND TWO ROTATING MACHINES**," submitted by **Ms. Kavita Tandon** to the Indian Institute of Technology Delhi, is a record of bonafide research work carried out by her under our supervision and guidance. The thesis work, in our opinion, has reached the standard fulfilling the requirements for a **DOCTOR OF PHILOSOPHY** degree. The research report and results presented in this thesis have not been submitted, in part or whole, to any university or institute to award any degree or diploma.

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ACKNOWLEDGEMENTS

I express my sincere gratitude and indebtedness towards my respected supervisor Dr. B. Manna, Professor, Department of Civil Engineering, Indian Institute of Technology Delhi, and Dr. G. V. Ramana, Professor, Department of Civil Engineering Indian Institute of Technology Delhi, for their invaluable guidance, cooperation, encouragement, and all the assistance required for the completion of this work. Their painstaking efforts in going through the manuscript and suggestions for its improvement are gratefully acknowledged.

I express my sincere thanks to Student Research Committee members Prof. B. Bhattacharjee, Prof. S. Pradyumna, and Prof. R. Ayothiraman for their suggestions and support during the entire period of my research work.

I express my gratitude and thankfully acknowledge the encouragement and support of the Department of Civil Engineering faculty members throughout my research tenure.

I am grateful to the laboratory staff members of the Geotechnical and Geoenvironmental section for their help in bringing this project into reality. I am thankful to Mr. Manoj Kumar Nilam, Mr. Alok Kumar, Mr. Nitin Chaurasia, Mr. Naik for their valuable assistance at various stages of the experimental work. I would also like to thank Mr. Ram Janam, Mr. Aakash, Mr. Dinesh, Mr. Anand for their help during the field tests.

I am thankful for the support extended by my friends Dr. Sanjit Biswas, Dr. Shiva Shankar Choudhary, Dr. Aali Pant, Dr. Riya Bhowmik, Dr. Heena Dhawan, Ms. Sweta Aggarwal, Ms. Vandana, Mr. Rohit Ralli, Mr. Prasun Halder, Ms. Sujata Fulambarkar, Mr. Anil Yadav, Mr. Atul Singh and Mr. Sandeep Patil for their selfless help and cooperation during this research. I would also like to express my gratitude to all those who have contributed directly or indirectly to my research work.

I am very much grateful to my parents Mr. Ram Naresh Tandon and Ms. Chandrakanti Tandon, my brothers Mr. Ashwin Tandon and Mr. Praveen Tandon, for their incredible sacrifices, patience, and understanding during my entire research period. Their continuous encouragement, love, blessings, endless moral and emotional supports provided me strength throughout the journey, without which I could not have accomplished this task.

Place: New Delhi

Date: Kavita Tandon

ABSTRACT

The dynamic response of the block foundation soil-oscillator system largely depends on the geotechnical characteristics of the surrounding soil, half-space parameters, and foundation geometry (shape, size, and depth of embedment). These parameters influence the stiffness of the soil-foundation system and damping characteristics. The analysis of machine foundations is carried out assuming that the foundation rests on the surface of the ground. However, in reality, foundations are usually embedded. The soil resistance is mobilized below the base and on the sides for an embedded foundation and significantly influences the dynamic response. Calculating the dynamic response of an embedded foundation supporting a machine is of great importance and has been the subject of several theoretical and experimental studies over the past eight decades or so. However, there are only guidelines available in the literature to analyze and design block foundations subjected to a single dynamic load. Experimental investigations are still carried out to date for evaluating/refining/modifying the existing theoretical solutions and improve design practices. The literature also observed relatively little field confirmation of the accuracy of commonly used design methods for the combined block foundation subjected to two dynamic loads. Thus, there is a great need to monitor the performance of prototype machine foundations.

The present study determines dynamic responses of block foundation soil-oscillator systems subjected to single and two dynamic loads. The behavior of block foundations subjected to a single dynamic load is identified under machine-induced vertical and coupled sliding and rocking vibrations in the field. Another aspect of the present study is analyzing the measured

responses under different vibration modes for the combined block foundations subjected to two dynamic loads under different machine orientations. To fulfill these objectives, dynamic vibration tests were carried out in the field on three different surface and embedded block foundations of various aspect ratios (L/B = 1.0, 1.25, and 1.5) under vertical and coupled vibrations to determine the frequency-amplitude responses for various excitation forces and two static loads (W_s = 6.6 kN and 8.6 kN). Another combined block foundation of aspect ratio L/B = 2.5 was constructed to determine the influence of machine orientations on the overall dynamic response of the block foundation subjected to two unbalanced forces and resultant moments. The six possible machine orientations for combined block foundations in the present study are V_Z-V_Z, V_Z-H_X, V_Z-H_Y, H_X-H_X, H_X-H_Y, H_Y-H_Y. The effect of dynamic force ratio, static weight ratio, and embedment depth on the frequency amplitude response is also determined for the combined block foundations.

The numerical analyses are performed by the theories proposed by various researchers and approximate methods to determine the dynamic response of block foundations under vertical and coupled modes of vibration. The geotechnical properties obtained from the in-situ and laboratory tests are used as input parameters to determine the dynamic stiffness and damping parameters and the frequency amplitude responses for vertical and coupled vibration modes. The experimental response curves of the block foundations subjected to a single dynamic load for the vertical and coupled vibration modes are nonlinear. The response also indicates nonlinear behavior with the increasing embedment depth, resulting in increased resonant frequency and a decrease in the resonant amplitude of the block foundation system. Comparing the theoretical and experimental response curves, a variation of about 5 to 10 % in the resonant frequency is observed, whereas an overestimation of damping value is observed from the different theories for vertical and coupled modes of vibration.

The influence of machine orientation on the dynamic response curves is attributed to the vibration amplitudes obtained in the various vibration modes for a specific machine orientation. Due to the nature of the applied dynamic forces, the maximum resonant amplitudes along the translational *X*-axis, *Y*-axis, and *Z*-axis are obtained for the machine orientations H_X-H_X, H_Y-H_Y, and V_Z-V_Z. The applied dynamic forces in these orientations are additive, and due to the beating effect, the responses are canceled after some time, whereas the applied dynamic forces for the machine orientations V_Z-H_X, V_Z-H_Y, H_X-H_Y are always out of phase and are independent of each other. The dynamic responses for the different orientations are studied and compared with the theoretical results obtained using the theories incorporated in DYNA 6 (El. Naggar et al., 2011). Finally, a comparative study is presented for the effect of machine orientation and other parameters on the dynamic response of the combined block foundation resting on the surface and embedded in the ground.

Keywords: Block foundation, Vertical vibration, Coupled vibration, Combined block foundation, Dynamic force ratio, Embedment depth, Excitation force, Static loads

सार

ब्लॉक नींव मिट्टी-थरथरानवाला प्रणाली की गतिशील प्रतिक्रिया काफी हद तक आसपास की मिट्टी की भू-तकनीकी विशेषताओं, अर्ध-स्थान मापदंडों और नींव ज्यामिति (आकार, आकार और एम्बेड की गहराई) पर निर्भर करती है। ये पैरामीटर मिट्टी-नींव प्रणाली की कठोरता और नमी विशेषताओं को प्रभावित करते हैं। मशीन नींव का विश्लेषण यह मानकर किया जाता है कि नींव जमीन की सतह पर टिकी हुई है। हालांकि, वास्तव में, नींव आमतौर पर अंतर्निहित होती है। मिट्टी के प्रतिरोध को आधार के नीचे और किनारों पर एक एम्बेडेड नींव के लिए जुटाया जाता है और गतिशील प्रतिक्रिया को महत्वपूर्ण रूप से प्रभावित करता है। एक मशीन का समर्थन करने वाली एक एम्बेडेड नींव की गतिशील प्रतिक्रिया की गणना करना बहुत महत्वपूर्ण है और पिछले आठ दशकों में कई सैद्धांतिक और प्रयोगात्मक अध्ययनों का विषय रहा है। हालांकि, एकल गतिशील भार के अधीन ब्लॉक नींव का विश्लेषण और डिजाइन करने के लिए साहित्य में केवल दिशानिर्देश उपलब्ध हैं। मौजूदा सैद्धांतिक समाधानों के मूल्यांकन/परिष्करण/संशोधन और डिजाइन प्रथाओं में सुधार के लिए अभी भी प्रायोगिक जांच की जाती है। साहित्य ने दो गतिशील भारों के अधीन संयुक्त ब्लॉक नींव के लिए आमतौर पर उपयोग की जाने वाली डिजाइन विधियों की सटीकता की अपेक्षाकृत कम क्षेत्र की पुष्टि भी देखी। इस प्रकार, प्रोटोटाइप मशीन नींव के प्रदर्शन की निगरानी करने की बहुत आवश्यकता है।

वर्तमान अध्ययन एकल और दो गतिशील भार के अधीन ब्लॉक नींव मिट्टी-थरथरानवाला प्रणालियों की गतिशील प्रतिक्रियाओं को निर्धारित करता है। एकल गतिशील भार के अधीन ब्लॉक नींव के व्यवहार की पहचान क्षेत्र में मशीन-प्रेरित ऊर्ध्वाधर और युग्मित स्लाइडिंग और रॉकिंग कंपन के तहत की जाती है। वर्तमान अध्ययन का एक अन्य पहलू विभिन्न मशीन अभिविन्यास के तहत दो गतिशील भार के अधीन संयुक्त ब्लॉक नींव के लिए विभिन्न कंपन मोड के तहत मापा प्रतिक्रियाओं का विश्लेषण कर रहा है। इन उद्देश्यों को पूरा करने के लिए, आवृत्ति-आयाम प्रतिक्रियाओं को निर्धारित करने के लिए ऊर्ध्वाधर और युग्मित कंपन के तहत विभिन्न पहलू अनुपात (L/B = 1.0, 1.25, और 1.5) के तीन अलग-अलग सतह और एम्बेडेड ब्लॉक नींव पर क्षेत्र में गतिशील कंपन परीक्षण किए गए थे। विभिन्न उत्तेजना बलों और दो स्थिर भार (W_S = 6.6 kN और 8.6 kN) के लिए। पहलू अनुपात L/B = 2.5 की एक और संयुक्त ब्लॉक नींव का निर्माण दो असंतुलित बलों और परिणामी क्षणों के अधीन ब्लॉक नींव की समग्र गतिशील प्रतिक्रिया पर मशीन अभिविन्यास के प्रभाव को निर्धारित करने के लिए किया गया था। वर्तमान अध्ययन में संयुक्त ब्लॉक नींव के लिए छह संभावित मशीन अभिविन्यास हैं V_Z-V_Z, V_Z-H_X, V_Z-H_Y, H_X-H_X, H_X-H_Y, H_Y-H_Y.। संयुक्त ब्लॉक नींव के लिए आवृत्ति आयाम प्रतिक्रिया पर गतिशील बल अनुपात, स्थिर वजन अनुपात और एम्बेडिंग गहराई का प्रभाव भी निर्धारित किया जाता है।

विभिन्न शोधकर्ताओं द्वारा प्रस्तावित सिद्धांतों और कंपन के ऊर्ध्वाधर और युग्मित मोड के तहत ब्लॉक नींव की गतिशील प्रतिक्रिया को निर्धारित करने के लिए अनुमानित तरीकों द्वारा संख्यात्मक विश्लेषण

किया जाता है। इन-सीटू और प्रयोगशाला परीक्षणों से प्राप्त भू-तकनीकी गुणों को गतिशील कठोरता और भिगोना मापदंडों और ऊर्ध्वाधर और युग्मित कंपन मोड के लिए आवृत्ति आयाम प्रतिक्रियाओं को निर्धारित करने के लिए इनपुट मापदंडों के रूप में उपयोग किया जाता है। ऊर्ध्वाधर और युग्मित कंपन मोड के लिए एकल गतिशील भार के अधीन ब्लॉक नींव के प्रयोगात्मक प्रतिक्रिया वक्र गैर-रेखीय हैं। प्रतिक्रिया बढ़ती हुई गहराई के साथ गैर-रेखीय व्यवहार को भी इंगित करती है, जिसके परिणामस्वरूप गुंजयमान आवृत्ति में वृद्धि होती है और ब्लॉक नींव प्रणाली के गुंजयमान आयाम में कमी होती है। सैद्धांतिक और प्रायोगिक प्रतिक्रिया वक्रों की तुलना में, गुंजयमान आवृत्ति में लगभग ५ से १०% की भिन्नता देखी जाती है, जबकि कंपन के ऊर्ध्वाधर और युग्मित मोड के लिए विभिन्न सिद्धांतों से भिगोना मूल्य का एक overestimation देखा जाता है।

गतिशील प्रतिक्रिया वक्रों पर मशीन अभिविन्यास के प्रभाव को एक विशिष्ट मशीन अभिविन्यास के लिए विभिन्न कंपन मोड में प्राप्त कंपन आयामों के माध्यम से जिम्मेदार ठहराया जाता है। लागू गतिशील बलों की प्रकृति के कारण, ट्रांसलेशनल एक्स-अक्ष, वाई-अक्ष और जेड-अक्ष के साथ अधिकतम गुंजयमान आयाम मशीन ओरिएंटेशन एचएक्स-एचएक्स, एचवाई-एचवाई, और वीजेड-वीजेड के लिए प्राप्त किए जाते हैं। इन अभिविन्यासों में लागू गतिशील बल योगात्मक हैं, और धड़कन प्रभाव के कारण, प्रतिक्रियाएँ कुछ समय बाद रद्द कर दी जाती हैं, जबकि मशीन ओरिएंटेशन V_Z-H_X, V_Z-H_Y, H_X-H_Y के लिए लागू गतिशील बल हमेशा चरण से बाहर होते हैं। और एक दूसरे से स्वतंत्र हैं। विभिन्न अभिविन्यासों के लिए

गतिशील प्रतिक्रियाओं का अध्ययन किया जाता है और DYNA 6 (El. Naggar et al., 2011) में शामिल सिद्धांतों का उपयोग करके प्राप्त सैद्धांतिक परिणामों के साथ तुलना की जाती है। अंत में, सतह पर आराम करने और जमीन में एम्बेडेड संयुक्त ब्लॉक नींव की गतिशील प्रतिक्रिया पर मशीन अभिविन्यास और अन्य मानकों के प्रभाव के लिए एक तुलनात्मक अध्ययन प्रस्तुत किया गया है।

कीवर्ड: ब्लॉक फाउंडेशन, लंबवत कंपन, युग्मित कंपन, संयुक्त ब्लॉक नींव, गतिशील बल अनुपात, एम्बेड गहराई, उत्तेजना बल, स्थिर भार

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LIST OF SYMBOLS

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.

a_o	Dimensionless frequency
A_x	Translational amplitude of vibration in X-direction
A_y	Translational amplitude of vibration in Y-direction
A_z	Translational amplitude of vibration in Z-direction
$A_{\phi z}$	Rotational amplitude of vibration in Z-direction
A_{x1}	First Resonant Amplitude of Vibration along the translational X-direction
A_{x2}	Second Resonant Amplitude of Vibration along the translational X-direction
A_{y1}	First Resonant Amplitude of Vibration along the translational *Y*-direction
A_{y2}	Second Resonant Amplitude of Vibration along the translational *Y*-direction
$A_{\phi x1}$	First Resonant Amplitude of Vibration along the rotational *X*-direction
$A_{\phi x2}$	Second Resonant Amplitude of Vibration along the rotational *X*-direction
$A_{\phi y1}$	First Resonant Amplitude of Vibration along the rotational *Y*-direction
$A_{\phi y2}$	Second Resonant Amplitude of Vibration along the rotational *Y*-direction
$A_{\phi z}$	Rotational amplitude of vibration in Z-direction
b_o	Mass ratio
B	Width of the block foundation

B_v	Modified mass ratio
c	Viscous damping coefficient of the foundation system
C_{xs}	Translational static damping of surface foundation along *X*-axis
C_{ys}	Translational static damping of surface foundation along *Y*-axis
C_{zs}	Translational static damping of surface foundation along *Z*-axis
$C_{\phi x}$	Rotational static damping of surface foundation along *X*-axis
$C_{\phi y}$	Rotational static damping of surface foundation along *Y*-axis
$C_{\phi z}$	Rotational static damping of surface foundation along *Z*-axis
C_{xe}	Translational Damping of embedded foundation along *X*-axis
C_{ye}	Translational Damping of embedded foundation along *Y*-axis
C_{ze}	Translational Damping of embedded foundation along *Z*-axis
$C_{\phi xe}$	Rotational Damping of embedded foundation about *X*-axis
$C_{\phi ye}$	Rotational Damping of embedded foundation about *Y*-axis
$C_{\phi ze}$	Rotational Damping of embedded foundation about *Z*-axis
$C_{x\phi ye}$	Coupled damping of embedded foundation about *XY* plane
$C_{y\phi xe}$	Coupled damping of embedded foundation about *YX* plane
D	Damping ratio of the soil
D_z	Dashpot coefficient
H	Height of the block foundation
h	Embedded depth of footing,
	(h/H = 1 fully embedded footing and h/H = 0 surface footing)
θ	Eccentric angle of the oscillator
f_1, f_2	Frequency-dependent displacement functions

f_{n1}	Resonant frequency for vertical vibration
f_{n2}	Resonant frequency for torsional vibration
f_{n3}	First resonant frequency for coupled vibration in translational X-direction and rotational Y-direction
f_{n4}	Second resonant frequency for coupled vibration in translational X-direction and rotational Y-direction
f_{n5}	First resonant frequency for coupled vibration in translational Y-direction and rotational X-direction
f_{n6}	Second resonant frequency for coupled vibration in translational Y-direction and rotational X-direction
F_{X1}	Amplitude of dynamic force applied by mechanical oscillator 1 along X -direction
F_{X2}	Amplitude of dynamic force applied by mechanical oscillator 2 along X -direction
F_{Y1}	Amplitude of dynamic force applied by mechanical oscillator 1 along Y -direction
F_{Y2}	Amplitude of dynamic force applied by mechanical oscillator 2 along Y -direction
F_{Z1}	Amplitude of dynamic force applied by mechanical oscillator 1 along Z -direction
F_{Z2}	Amplitude of dynamic force applied by mechanical oscillator 2 along Z –direction
F_1	Dynamic force produced by mechanical oscillator 1

F_2	Dynamic force produced by mechanical oscillator 2
$F(A)$	Restoring force
g	Acceleration due to gravity
G_{max}	Shear modulus of soil (ρV_s^2)
I_ψ	Mass moment of inertia about a horizontal axis passing through the center of gravity
I	Moment of inertia of the block foundation assembly
ρ	Mass density
υ	Poisson's ratio of the soil
k_z	Spring coefficient
K_{xs}	Translational static stiffness of surface foundation along *X*-axis
K_{ys}	Translational static stiffness of surface foundation along *Y*-axis
K_{zs}	Translational static stiffness of surface foundation along *Z*-axis
$K_{\phi x}$	Rotational static stiffness of surface foundation along *X*-axis
$K_{\phi y}$	Rotational static stiffness of surface foundation along *Y*-axis
$K_{\phi z}$	Rotational static stiffness of surface foundation along *Z*-axis
K_{xe}	Translational stiffness of embedded foundation along *X*-axis
K_{ye}	Translational stiffness of embedded foundation along *Y*-axis
K_{ze}	Translational stiffness of embedded foundation along *Z*-axis
$K_{\phi xe}$	Rotational stiffness of embedded foundation about *X*-axis
$K_{\phi ye}$	Rotational stiffness of embedded foundation about *Y*-axis
$K_{\phi ze}$	Rotational stiffness of embedded foundation about *Z*-axis
$K_{x\phi ye}$	Coupled stiffness of embedded foundation about *XY* plane

$K_{y\phi xe}$	Coupled stiffness of embedded foundation about *YX* plane
ξ_z	Dashpot coefficient
L	Length of the block foundation
m	Mass of eccentric rotating part in oscillator
m_{eff}	Effective mass of the system
m_s	Total mass of the block foundation system
M_x	Unbalanced moment about *X*-axis
M_y	Unbalanced moment about *Y*-axis
M_z	Unbalanced moment about *Z*-axis
N	SPT value
O_1	Mechanical Oscillator 1
O_2	Mechanical Oscillator 2
Q_o	Dynamic force amplitude acting on the surface of the foundation
R_o	Average equivalent radius
R_h	Equivalent radius for horizontal translation
R_v	Equivalent radius for vertical translation
R_{rx}	Equivalent radius for horizontal rotation about *X*-axis
R_{ry}	Equivalent radius for horizontal rotation about *Y*-axis
R_{rz}	Equivalent radius for horizontal rotation about *Z*-axis
V_s	Shear wave velocity of the soil
ω	Circular frequency
W_s	Static weight of the foundation and steel plates along with the weight of the oscillator

W_c	Static weight of the block foundation
W_1	Static weight of the machine assembly 1 along with the weight of oscillator
W_2	Static weight of the machine assembly 2 along with the weight of oscillator
W_{m1}	Static weight of the mechanical oscillator 1
W_{m2}	Static weight of the mechanical oscillator 2
Z_{e1}	Height of the dynamic excitation force from oscillator 1 above the center of gravity of the system
Z_{e2}	Height of the dynamic excitation force from oscillator 2 above the center of gravity of the system
Z_c	Height of the center of gravity above the base of the foundation

LIST OF ABBREVIATIONS

ASTM	American society for testing and materials
BEM	Boundary Element Method
BH	Bore Hole
C.G.	Center of gravity
CVS	Coupled Vibration Surface theory
CVE	Coupled Vibration Embedded theory
DC	Direct current
Deg	Degree
DOF	Degree of Freedom
Eq.	Equation
FE	Finite element
FEM	Finite element method
G.L.	Ground-level
Hz	Hertz
IS	Indian Standard
kN	Kilo Newton
L.L.	Liquid Limit
m	Meter
mm	Millimeter
M.P.F	Mass participation factor

P.L.	Plastic limit
Rad	Radian
RPM	Revolutions per minute
SDOF	Single degree of freedom
S-wave	Shear wave
USCS	Unified soil classification system
U.U.	Unconsolidated Undrained
VVS	Vertical Vibration Surface theory
VVE	Vertical Vibration Embedded theory
2-D	Two dimensional
3-D	Three dimensional