

**MODEL TESTS AND NUMERICAL STUDIES ON SINGLE
AND GROUP OF SOIL-CEMENT COLUMN FOUNDATIONS
IN SOFT CLAY**

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**DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
SEPTEMBER 2020**

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AND GROUP OF SOIL-CEMENT COLUMN FOUNDATIONS
IN SOFT CLAY**

by

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Submitted

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

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

SEPTEMBER 2020

To
My family

CERTIFICATE

This is to certify that the thesis entitled “**MODEL TESTS AND NUMERICAL STUDIES ON SINGLE AND GROUP OF SOIL-CEMENT COLUMN FOUNDATIONS IN SOFT CLAY**” being submitted by **Mrs. Mamata Mohanty** to the Indian Institute of Technology Delhi is a record of bonafide research work carried out by him under our supervision and guidance. The thesis work, in our opinion, has reached the standard, fulfilling the requirements for **DOCTOR OF PHILOSOPHY** degree. The research report and results presented in this thesis have not been submitted, in part or full, to any university or Institute for the award of any degree or diploma.

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ACKNOWLEDGEMENTS

My thesis represents the combined effort of many people and it is my pleasure to acknowledge those involved; who guided, supported and stood by me all the long years of my study.

First and foremost, I offer my deep sense of gratitude to my academic supervisor, Prof. J. T Shahu, Department of Civil Engineering, IIT Delhi for his invaluable guidance, cooperation, support and for providing all assistance required for the completion of this work. His painstaking efforts in going through the manuscript and giving suggestions for its improvement are gratefully acknowledged.

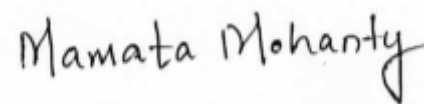
I express my sincere thanks and deepest gratitude to my Student Research Committee members, namely, Prof. A. K. Gupta, Prof. K.S Rao and Prof. B. P. Patel for their suggestions and expert advice during the entire period of my research work.

It is a pleasure to acknowledge the support extended by Dr. Suresh Kumar, Miss Riya Bhowmik, Mr. Mayuresh Bakre and Mr. Pranjal Mandhaniya for providing their valuable time and cooperation during this research. I am greatly benefited from their keen scientific knowledge. I would like to thanks Miss Madhulika Mohanty and Miss Snigdha Behera for their extensive help and support during my research work.

It is a pleasure to thank all the Technical staff members Soil and Rock Mechanics Laboratory namely, Mr. Manoj Kumar Neelam and Mr. Alok Kumar for providing much needed help and assistance in experimental work. I am also thankful to the contract workers, Mr. Ram Janam, and Mr. Sandeep for helping me during the preparation of the huge quantity of soft soil for model testing.

I would like to thank the various members of Geotechnical section, IIT Delhi with whom I had the opportunity to work and those who have contributed directly or indirectly in the course of my research work.

Last, but certainly not the least, I would like to specially acknowledge and record my deep sense of love and gratitude to my father Priya Kanta Mohanty, husband Sudhanshu Sekhar Sahu, and my sister Sujata Mohanty for their affection, continuous encouragement, and invaluable moral and emotional support during my entire research programme.

A handwritten signature in black ink that reads "Mamata Mohanty". The script is cursive and fluid, with the first name "Mamata" and last name "Mohanty" clearly distinguishable.

(MAMATA MOHANTY)

ABSTRACT

The inclusion of soil-cement columns in soft soil is a ground improvement technique that is used to reduce the settlement and improve the bearing capacity of the soft soil ground. In recent years, soil-cement columns have been largely used to support embankments over soft foundations as it provides a better alternative to the existing method of improving soft clay ground and is suitable for use on any type of soil. Other common applications of soil-cement columns include supporting flexible structures, such as bridge approach, roadway widening, subgrade improvement, and support of storage tanks

Although several studies have been done on the composite ground improved by soil-cement columns, most of the works were conducted on end-bearing columns. Very few experimental studies are available on the behavior of soft soil improved with floating soil-cement columns. Previous studies are still inconclusive on the behavior and failure mechanism of floating soil-cement columns under different group foundation parameters, such as area ratio, amount of binder content, water-cement ratio, and length and diameter of columns. These studies are only confined to few chosen group foundation parameters over a narrow range and evaluation of relative effect of different parameters over a large range of values is missing. The failure pattern of the columns after the ground is subjected to vertical loading has been studied by very few researchers. Also, no study is presently available regarding comparison of end-bearing and floating columns behavior over a range of group parameters.

Model tests are performed on the remoulded ground improved with groups of end-bearing and floating soil-cement columns under plane strain and axisymmetric conditions. The soil-cement columns were installed and cured inside the model soil bed using a continuous replacement method. The effect of various group foundation parameters, such

as area ratio, length and diameter of columns and binder content, is investigated. Deformation behavior and ultimate failure load of groups of end-bearing and floating soil-cement columns under plane strain and axisymmetric configuration vis-à-vis the unimproved ground are evaluated. The failure pattern of the group of soil-cement columns after the test is established by exhumation technique.

Model tests are also performed on slurry deposited soft soil beds improved with single soil-cement column subjected to undrained loading and the load-settlement response of the improved ground is investigated. Pore pressure response of the composite ground when subjected to undrained monotonic loading is studied using miniature pore pressure transducers.

Three dimensional elasto-plastic finite element analyses of groups of soil-cement columns are performed using a commercially available finite element code. The results of the model tests performed in this study have been validated using the finite element analyses and the data available in the literature.

The study reveals that the stiffness and ultimate failure stress of the ground increase in the following order - soft soil bed, floating column foundation and end-bearing column foundation. Higher stiffness and failure stress of the floating columns vis-à-vis soft ground appear to be the result of a better stress distribution in the former owing to the transfer of footing stresses to deeper depths of the soft soil having higher confinement by the floating columns. On the other hand, higher stiffness and failure stress of the end-bearing columns vis-à-vis floating columns appears to be the result of contribution of high end-bearing stresses in the former.

The effect of area ratio on the stiffness and bearing capacity of the composite ground is much higher in the case of end-bearing columns compared to that in the case of floating columns. For the same area ratio, as the diameter of soil-cement columns

decreases, the stiffness and failure stress increase in the case of both floating and end-bearing columns. As the diameter of column decreases, the number of columns below the footing increases for the same area ratio. Thus, a higher number of smaller diameter soil-cement columns are more efficient in load transfer compared to a fewer number of large diameter columns. A higher number of columns helps in more uniform and hence, more efficient distribution of applied stresses in the composite ground.

In case of end-bearing columns, area ratio has a significant effect on failure pattern. At an area ratio of 25 %, the columns failed by outward displacement and bending. On the other hand, at an area ratio of 32 %, the columns failed due to bending at a distance of approximately one-half to two-third of the column length from the top. In case of floating columns, the relative strength of columns to soft clay (c_{uc}/c_{us}) appears to be the major governing factor. For the high value of (c_{uc}/c_{us}) used in the present study, punching shear failure was observed with slight outward displacement and some horizontal cracks for area ratios of 25 % and 32 %.

For a cement content of ≤ 16 %, a higher value of BCF is observed in case of axisymmetric condition. However, for cement content ≥ 16 %, the above sharp increase results in higher values of BCF in case of plane-strain condition compared to those for axisymmetric condition.

As the applied stresses increase, some part of load is shared by the clay and hence pore water pressures begin to rise with time. When the applied load approaches the failure load, the column begins to crumble and a higher proportion of the applied load begins to transfer to clay, thereby giving rise to sharp increase in pore water pressures in clay near failure. After failure, the applied load decreases and consequently, clay stresses as well as pore water pressures in clay decrease.

नरम मिट्टी में मिट्टी-सीमेंट स्तंभों को शामिल करना एक जमीनी सुधार तकनीक है जिसका उपयोग निपटान को कम करने और नरम मिट्टी के मैदान की असर क्षमता में सुधार के लिए किया जाता है। हाल के वर्षों में, मृदा-सीमेंट स्तंभों का उपयोग नरम नींव पर तटबंधों का समर्थन करने के लिए किया गया है क्योंकि यह नरम मिट्टी के मैदान को बेहतर बनाने के मौजूदा तरीके का एक बेहतर विकल्प प्रदान करता है और किसी भी प्रकार की मिट्टी पर उपयोग के लिए उपयुक्त है। मिट्टी-सीमेंट स्तंभों के अन्य सामान्य अनुप्रयोगों में लचीली संरचनाओं का समर्थन करना शामिल है, जैसे कि पुल का दृष्टिकोण, सड़क का चौड़ीकरण, भूमिगत सुधार और भंडारण टैंकों का समर्थन

यद्यपि मिट्टी-सीमेंट स्तंभों द्वारा सुधार किए गए समग्र जमीन पर कई अध्ययन किए गए हैं, लेकिन अधिकांश कार्य अंत-असर वाले स्तंभों पर किए गए थे। फ्लोटिंग मिट्टी-सीमेंट स्तंभों के साथ नरम मिट्टी के व्यवहार पर बहुत कम प्रयोगात्मक अध्ययन उपलब्ध हैं। पिछले अध्ययन अभी भी विभिन्न समूह नींव मापदंडों के तहत फ्लोटिंग मिट्टी-सीमेंट कॉलम के व्यवहार और विफलता तंत्र पर अनिर्णायक हैं, जैसे कि क्षेत्र अनुपात, बांधने की सामग्री की मात्रा, पानी-सीमेंट अनुपात, और स्तंभों की लंबाई और व्यास। ये अध्ययन केवल कुछ चुने हुए समूह नींव मापदंडों पर सीमित सीमा तक सीमित हैं और मानों की एक बड़ी सीमा पर विभिन्न मापदंडों के सापेक्ष प्रभाव का मूल्यांकन गायब है। जमीन पर ऊर्ध्वाधर लोडिंग के बाद स्तंभों की विफलता पैटर्न का

अध्ययन बहुत कम शोधकर्ताओं द्वारा किया गया है। इसके अलावा, कोई अध्ययन वर्तमान में समूह के मापदंडों की एक श्रृंखला के अंत-असर और अस्थायी कॉलम व्यवहार की तुलना में उपलब्ध नहीं है।

मॉडल परीक्षणों को विमान के तनाव और अक्षांकीय स्थितियों के तहत अंत-असर और फ्लोटिंग मिट्टी-सीमेंट कॉलम के समूहों के साथ सुधरे हुए जमीन पर प्रदर्शन किया जाता है। निरंतर प्रतिस्थापन विधि का उपयोग करके मॉडल मिट्टी के बिस्तर के अंदर मिट्टी-सीमेंट कॉलम स्थापित और ठीक किए गए थे। विभिन्न समूह नींव मापदंडों के प्रभाव, जैसे कि क्षेत्र अनुपात, स्तंभों की लंबाई और व्यास और बांधने की सामग्री की जांच की जाती है। प्लेन स्ट्रेन के तहत अंत-असर और फ्लोटिंग मिट्टी-सीमेंट स्तंभों के समूहों के विरूपण व्यवहार और अंतिम विफलता भार का आकलन किया गया है, जो कि असिंचित जमीन के विज़िबल-एक्सिसमेट्रिक कॉन्फ़िगरेशन का मूल्यांकन करते हैं। परीक्षण तकनीक के बाद मिट्टी-सीमेंट स्तंभों के समूह की विफलता पैटर्न उद्गम तकनीक द्वारा स्थापित की जाती है।

मॉडल परीक्षण भी गंदे जमा किए गए नरम मिट्टी के बेड पर किए गए हैं, जो कि बिना मिट्टी लोड किए हुए एकल मिट्टी-सीमेंट कॉलम में सुधार किए गए हैं और बेहतर जमीन की लोड-सेटलमेंट प्रतिक्रिया की जांच की गई है। समग्र जमीन के दबाव की प्रतिक्रिया जब अप्रशिक्षित मोनोटोनिक लोडिंग के अधीन होती है, तो लघु ताकना दबाव ट्रांसड्यूसर्स का उपयोग करके अध्ययन किया जाता है।

मिट्टी-सीमेंट स्तंभों के समूहों के तीन आयामी इलास्टो-प्लास्टिक परिमित तत्व विश्लेषण व्यावसायिक रूप से उपलब्ध परिमित तत्व कोड का उपयोग करके किए जाते हैं। इस अध्ययन में किए गए मॉडल परीक्षणों के परिणामों को परिमित तत्व विश्लेषण और साहित्य में उपलब्ध आंकड़ों का उपयोग करके मान्य किया गया है।

अध्ययन से पता चलता है कि निम्न क्रम में जमीन की कठोरता और अंतिम विफलता तनाव बढ़ जाता है - नरम मिट्टी का बिस्तर, अस्थायी स्तंभ नींव और अंत-असर स्तंभ नींव। फ्लोटिंग कॉलमों की उच्च कठोरता और असफलता के कारण नरम-नरम जमीन दिखाई देती है, जो कि पूर्व की ओर बेहतर तनाव वितरण के कारण होती है, जिससे फ्लोटिंग स्ट्रेस के स्थानांतरण के लिए नरम मिट्टी की गहरी गहराई तक तैरते हुए स्तंभों द्वारा उच्च सीमा होती है। । दूसरी ओर, अंत-असर वाले स्तंभों की उच्च कठोरता और विफलता तनाव, दृश्यमान स्तंभों के पूर्व में उच्च अंत-असर वाले तनावों के योगदान का परिणाम प्रतीत होता है।

फ्लोटिंग कॉलम के मामले में एंड-बेयरिंग कॉलम के मामले में कम्पोजिट ग्राउंड की कठोरता और असर क्षमता पर क्षेत्र अनुपात का प्रभाव बहुत अधिक है। उसी क्षेत्र अनुपात के लिए, जैसा कि मिट्टी-सीमेंट स्तंभों का व्यास घटता है, अस्थायी और अंत-असर वाले दोनों स्तंभों के मामले में कठोरता और विफलता तनाव बढ़ता है। जैसे ही स्तंभ का व्यास घटता है, उसी क्षेत्र अनुपात के लिए फ्लोटिंग के नीचे स्तंभों की संख्या बढ़ जाती है। इस प्रकार, छोटे व्यास वाले मिट्टी के सीमेंट स्तंभों की संख्या अधिक होती है, जो कि बड़े व्यास स्तंभों की संख्या की तुलना में लोड ट्रांसफर में अधिक कुशल होते हैं।

स्तंभों की एक उच्च संख्या अधिक वर्दी में मदद करती है और इसलिए, समग्र जमीन में लागू तनावों का अधिक कुशल वितरण होता है।

अंत-असर स्तंभों के मामले में, क्षेत्र अनुपात विफलता पैटर्न पर एक महत्वपूर्ण प्रभाव पड़ता है। 25% के क्षेत्र अनुपात में, स्तंभ बाहरी बहिष्कार और झुकने से विफल रहे। दूसरी ओर, 32% के क्षेत्र अनुपात में, स्तंभ ऊपर से स्तंभ की लंबाई के लगभग डेढ़ से दो-तिहाई की दूरी पर झुकने के कारण विफल हो गया। प्लोटिंग कॉलम के मामले में, सॉफ्ट क्ले (c_{uc}/c_{us}) को कॉलम की सापेक्ष ताकत प्रमुख शासी कारक प्रतीत होती है। वर्तमान अध्ययन में उपयोग किए जाने वाले (c_{uc}/c_{us}) के उच्च मूल्य के लिए, मामूली बाहरी छिद्र के साथ छिद्रण कतरनी विफलता देखी गई थी

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LISTS OF NOTATIONS

2D	=	two-dimensional
3D	=	three-dimensional
DMM	=	deep mixing method;
DCM	=	deep cement mixing method;
A_r	=	area ratio;
B	=	width of the footing;
BCF	=	bearing capacity factor;
C	=	cement content;
c_{uc}	=	undarined shear strength of soil-cement column;
c_{us}	=	undrained shear strength of clay bed;
d	=	diameter of soil-cement column;
E	=	Young's modulus
h	=	height of clay bed;
L	=	length of footing;
l	=	length of soil-cement column;
N_c	=	bearing capacity factor;
q_u	=	ultimate bearing capacity of the composite ground;
q_{uc}	=	unconfined compression strength of the soil-cement column;
q_{ult}	=	ultimate bearing capacity of the composite ground;
w_c	=	water content of clay bed;
δ	=	settlement of footing;
σ	=	applied vertical stress on footing;

n = stress concentration ratio;

σ_{soil} = stress on the soil;

σ_{soil} = stress on column;

σ'_v = consolidation pressure;

δ = Settlement of footing;

ϕ = Friction angle;

ν = Poisson's ratio;