EXPERIMENTAL AND NUMERICAL STUDIES ON RESPONSE OF TAPERED PILES UNDER COMBINED VERTICAL COMPRESSION AND LATERAL LOADING

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FEBUARY 2024

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by

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submitted

in fulfillment of requirements of degree of Doctor of Philosophy

to the

INDIAN INSTITUTE OF TECHNOLOGY, DELHI

FEBUARY 2024

Dedicated to My Beloved Mother and Father

For their endless love, support, and encouragement

CERTIFICATE

This is to certify that the thesis entitled **"EXPERIMENTAL AND NUMERICAL STUDIES ON RESPONSE OF TAPERED PILES UNDER COMBINED VERTICAL COMPRESSION AND LATERAL LOADING"** submitted by **MS. CHINJU VIJAYAN** to the Indian Institute of Technology Delhi, is a record of the bonafide research work carried out by her under my supervision and guidance. This thesis work, in my opinion, has reached the standard, fulfilling the requirements for **DOCTOR OF PHILOSOPHY** degree. The research report and the results presented in this thesis have 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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ACKNOWLEDGEMENTS

The completion of this doctoral dissertation would not have been possible without the invaluable support of numerous individuals. I would like to extend my sincere gratitude to each one of them. First of all, I am deeply indebted to my supervisor, **Prof. R. Ayothiraman,** Professor, Department of Civil Engineering, for his fundamental role in my doctoral work. His guidance and matchless exuberant inspiration helped me complete this dissertation. I am extremely grateful to my supervisor for his valuable guidance, scholarly input, and consistent encouragement I have been receiving throughout this research work. This feat was possible only because of the unconditional support provided by him. My supervisor is amicable and positive, always making him available in every aspect of work despite his busy schedule. I consider it a great opportunity to do my doctoral programme under his guidance and learn from his research expertise. I would like to sincerely thank my supervisor for all kinds of help and support.

The author expresses his gratitude to SRC: **Prof. Geetam Tiwari (Chairman), Prof. G. V. Ramana (Member),** and **Prof. M. K. Singha (Member)** for their valuable input at different stages of this thesis work for improving the quality of the work.

I am thankful to **Prof. A. K. Nema**, Head of the Civil Engineering Department, **Prof. N. K. Garg**, and **Prof. G. V. Ramana,** Former Heads of the Civil Engineering Department and **Laboratory In-charge(s)** of Geotechnical Engineering Lab(s), for providing the necessary space, fund, equipment, etc. for conducting this research work.

I would like to thank the faculty members of Geotechnical Engineering Section: **Emeritus Prof. Manoj Datta, Emeritus Prof. K. S. Rao, Prof. J. T. Shahu, Prof. B. Manna, Prof. Tanusree Chakraborty**, **Prof. Banerjee Arnab, Prof. Prashanth Vangla, Prof. Debayan Bhattacharya, Prof. Deepanshu Shirole** and **Prof. S. K. Sinha** for providing encouragement and suggestions. I'm grateful to **Prof. Manoj M.** for encouraging me to join and providing me the confidence to proceed on this Ph.D. journey. Additionally, I wish to thank **Prof. N. M. Anoop Krishnan**, the Laboratory in charge of the Concrete Structures Laboratory (CSTL), for permitting me to utilize the laboratory facilities.

I thank all geotechnical lab staff: **Mr. Manoj Kumar Neelam**, **Mr. D. Biswas, Mr. Alok Kumar,** and **Mr. Lokendra Singh Dangi** for their kind help and support during the experimental work. I also acknowledge the extensive help from **Mr. Biri Singh**, Staff in-charge Concrete Structures Laboratory (CSTL). I thank **Mr. Amit Bundela,** for facilitating my uninterrupted use of the computational lab facilities.

I am sincerely grateful to my friends, Mr. Ashwinth Raj, Mr. Upendra M., Mr. Befkadu Otoma, and Amit Jain Sir for their invaluable understanding during the challenging phases of my research.

I must thank **Mr. Dinesh, Mr. Ramjanm, Mr. Rahul, Mr. Siraj, Mr. Raju, Mr. Ashok, Mr. Sirajuddin, and Mr. Kailash** for their hard work in tasks such as material testing, welding and fabrication, and preparation of the sand bed for model experiments has been invaluable to the progress of this study.

I am profoundly grateful to **Mr. Vinay Kumar Singh** for his consistent availability and unwavering support, which extended not only to academic challenges but also encompassed crucial moments like my medical emergency during this journey. My heartfelt gratitude goes to **Mrs. Gayathri V. L.** and **Mrs. Radhika T. P**. for their steadfast emotional support during this challenging period. I am also deeply thankful to **Mrs. Ishitha Bhatnagar** for her continuous encouragement throughout this journey. As my best friends, your collective support has been indispensable for the successful completion of this thesis.

No words are adequate to express my gratitude towards my parents for all their pains and suffering to bring me up to this stage of life. The consistent encouragement and inspiration helped me at every stage of my personal and academic life, and I longed to see this achievement come true. I am deeply indebted to my parents for their unwavering support. I also want to extend my heartfelt thanks to my aunts, uncles, and cousins. Their encouragement and pride, even in every small milestone of mine, instead of pressuring me about marriage, mean a lot to me.

Above all, I owe it all to Almighty God for granting me the wisdom, health, and strength to undertake this research task and enabling me to its completion.

Date: **Chinju Vijayan**

ABSTRACT

When shallow foundations fail to meet design criteria for bearing capacity and settlement, pile foundations are used to transfer building loads to stronger layers at greater depths. Tapered piles offer better load-carrying capacity than uniform-diameter piles, but their limited usage may be due to a lack of understanding and design guidelines. This study investigates the behaviour of tapered piles and their ultimate resistance in different soil conditions and taper angles. While there have been various studies on tapered piles under various static loading situations, such as vertical, lateral, and uplift loads, there is a lack of research on their behaviour under combined loading. Most existing studies assume simultaneous application of loads, but sequential loading is more realistic. Therefore, further research is needed to simulate combined loads applied sequentially on pile foundations. Thus, this study analysed tapered pile foundation response under sequentially applied combined loading.

In the present study, 1-*g* model experiments were carried out using model-reinforced concrete piles embedded in sandy soil with different relative densities. Two sets of sequential combined loading tests were performed to analyse the interaction of lateral and axial loading. A constant load of 0.4 and 0.6 times the corresponding ultimate axial or lateral load values is used respectively during the sequential-combined load testing. Results show that the axial capacity increases with the pile taper angle; however, there seems to be a critical taper angle (about 1.0º) beyond which the axial capacity of the pile does not increase with the taper angle. The ultimate lateral load increases even beyond the critical taper angle (1º) observed in the ultimate axial load value, which indicates that the critical taper angle is different for axial and lateral loading. In the 1-*g* model test, it was not possible to understand the zone of deformation; hence the whole problem is numerically analysed using PLAXIS 3D.

The bending moment profiles predicted by the numerical analysis are in close agreement with the model test data, however, the elastic analysis overestimated the bending moment value. The maximum bending moment variation with taper angle under the respective ultimate load shows a significant variation than that under constant load. The ultimate load values obtained from the predicted load-deformation curve are also compared with 1-*g* model test results, which show very close agreement. The normalized depth of fixity tends to reduce with taper angle in both numerical analysis and IS (2911 (P1/S2) 2010) code method.

A comprehensive numerical analysis was carried out using prototype dimensions of the pile under different combinations of loading (independent-vertical, independent-lateral, and sequential-combined (40, 60, and 80% of ultimate load value) loading). The ultimate axial load values under independent loading are significantly influenced by the pile length, relative density, and taper angle. The study observes that longer piles, higher relative density values, and lower taper angles exhibit a gradual increase in axial capacity, while higher taper angles, especially in combination with longer piles, result in notable percentage enhancements of axial capacity. This study also presents semi-empirical equations developed via linear regression analysis to predict ultimate axial and lateral load values of tapered piles subjected to combined loading. The proposed equations accommodate various lateral load conditions, providing a comprehensive framework for estimating axial and lateral capacities in such scenarios.

सार

जब शैलो फाउंडेशन डिज़ाइन मानकों की भार क्षमता और सेटलमेंट के लिए पूरा नहीं कर पाते हैं, तो पाइल फाउंडेशन का उपयोग किया जाता है ताकि इमारत के भूमिगत भरों को मजबूत स्तरों तक पहुँचाया जा सके, जो गहराई में और अधिक हैं। टेपर्ड पाइल्स, सामान्य पाइल्स से अधिक भार उठाने की क्षमता प्रदान करती हैं, लेकिन उनका सीमित उपयोग उनकी डिज़ाइन मार्गदर्शिकाओं की कमी के कारण हो सकता है। यह अध्ययन टेपर्ड पाइल्स के व्यवहार और विभिन्न मृदा स्थितियों और टेपर कोणों में उनके अंतिम प्रतिरोध की अनुसंधान करता है। विभिन्न स्थितियों में टेपर्ड पाइल्स के बारे में विभिन्न स्थिर लोडिंग परिस्थितियों की तुलना में, जैसे कि ऊपरी, पारंपरिक, और ऊपरी लोड, इसपर कई अध्ययन हो चुके हैं, लेकिन उनके संयुक्त लोडिंग के तहत व्यवहार पर अध्ययन की कमी है। अधिकांश मौजूदा अध्ययन स्थिति को समान समय पर लगाए जाने की मानते हैं, लेकिन क्रमशः लोडिंग करना और अधिक वास्तविक है। इसलिए, पाइल फाउंडेशन पर क्रमशः लागू होने वाले संयुक्त लोडिंग के तहत टेपर्ड पाइल फाउंडेशन की प्रतिक्रिया का अध्ययन करने की आवश्यकता है। इस प्रकार, इस अध्ययन ने संयुक्त लोडिंग को क्रमशः लागू करने पर टेपर्ड पाइल फाउंडेशन की प्रतिक्रिया का विश्लेषण किया। वर्तमान अध्ययन में, मॉडल कंक्रीट पाइल्स का अध्ययन किया गया, जो विभिन्न आपेक्षिक घनत्व में दबे हुए हैं। विभिन्न घनत्व के साथ लोडिंग परीक्षणों के लिए दो सेट के सीक्वेंशियल संयुक्त लोडिंग परीक्षणों का आयोजन किया गया था, जिसका उद्दीपन करने के लिए लटरल और एक्सियल लोडिंग के संवाद का विश्लेषण किया गया। इस सीक्वेंशियल-संयुक्त लोड परीक्षण के दौरान समान रूप से 0.4 और 0.6 बारीकी अंतिम एक्सियल या लैटरल लोड मूल्यों का प्रयोग किया गया है। परिणाम दिखाते हैं कि एक्सियल क्षमता पाइल टेपर कोण के साथ बढ़ती है; हालांकि, एक सीमित टेपर कोण (लगभग 1.0°) जिसके पार एक्सियल क्षमता बढ़ती नहीं है, इसे दिखाई देता है। अंतिम लैटरल लोड उस सीमांत टेपर कोण (1°) से

आगे बढ़ता है जो अंतिम एक्सियल लोड मूल्य में देखा गया है, जिससे यह सिद्ध होता है कि सीमित टेपर कोण एक्सियल और लैटरल लोडिंग के लिए अलग होता है। 1-जी मॉडल परीक्षण में, यह संज्ञान नहीं किया जा सका कि बिकृति क्षेत्र क्या है; इसलिए पूरी समस्या को प्लाक्सिस 3डी का उपयोग करके संख्यात्मक रूप से विश्लेषण किया गया है।

आंकिक विश्लेषण द्वारा पूर्वानुमानित की गई मोडल टेस्ट डेटा के बेंडिंग मोमेंट प्रोफाइल निकट सहमति में हैं, हालांकि, इलास्टिक विश्लेषण ने बेंडिंग मोमेंट मूल्य को अधिधारित किया था। पूर्वानुमानित लोड-डिफॉर्मेशन कर्व से प्राप्त अंतिम लोड मूल्यों को 1-g मॉडल टेस्ट के परिणामों के साथ तुलना की गई, जो बहुत ही निकट सहमति दिखाती है। नॉर्मलाइज्ड डेप्थ ऑफ फिक्सिटी की वृद्धि को टेपर कोण के साथ भी न्यूमेरिकल विश्लेषण और आईएस (2911 (P1/S2) 2010) कोड विधि में कम होने की प्रवृत्ति है।

विभिन्न लोडिंग के संयोजनों के तहत पाइल के प्रोटोटाइप आयामों का व्यापक आंकिक विश्लेषण किया गया था (स्वतंत्र-ऊर्ध्व, स्वतंत्र-पार्श्व, और क्रमबद्ध-संयुक्त (अंतिम लोड मूल्य के 40, 60, और 80%))। स्वतंत्र लोडिंग के तहत अंतिम धारीदार लोड मूल्य भी पाइल लंबाई, सांघीय घनत्व, और टेपर कोण से प्रभावित होते हैं। अध्ययन यह सुरक्षित करता है कि लंबी पाइल, उच्च सांघीय घनत्व मूल्य, और कम टेपर कोण वाले पाइल्स में धारीदार की सीढ़ी वृद्धि होती है, जबकि उच्च टेपर कोण, विशेषकर लंबी पाइल्स के साथ, धारीदार की प्रतिशत वृद्धि के प्रमुख कारण हैं। यह अध्ययन यह भी सुझाव देता है कि संयुक्त लोडिंग के अधीन रहने वाली टेपर्ड पाइल्स के अंतिम ऊर्ध्व और पार्श्व लोड मूल्यों को पूर्वानुमान करने के लिए लीनियर परिप्रेक्ष्य विश्लेषण द्वारा विकसित की गई अर्ध-प्रायोगिक समीकरणों को प्रस्तुत करता है। प्रस्तुत समीकरण विभिन्न पार्श्व लोड स्थितियों को समाहित करते हैं, जो ऐसी परिस्थितियों में ऊर्ध्व और पार्श्व क्षमताओं का अनुमान लगाने के लिए एक व्यापक ढाँचा प्रदान करते हैं।

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LIST OF NOTATIONS

ϕ	Angle of shearing resistance, °
ψ	Dilation angle, °
ν_s	Poisson's ratio of soil
η_h	Horizontal subgrade modulus
c	Cohesion intercept, kPa
C_c	Coefficient of curvature
C_u	Coefficient of uniformity
CP	Cylindrical Pile
D	Pile diameter, mm
L	Length of pile, m
α	Taper angle of pile, (°)
E_{50}	Triaxial loading stiffness, kN/m^2
E_{oed}	Oedometer loading stiffness, kN/m^2
E_p	Pile elastic modulus, kPa
E_s	Soil elastic modulus, kPa
E_{ur}	Triaxial unloading stiffness, kN/m^2

$(EI)_M$ Flexural rigidity of model, kN-m^2

$(EI)_P$ Flexural rigidity of prototype, kN-m^2

G_s Soil shear modulus

H Lateral load, N

H_u Ultimate lateral load of pile, N

Q Axial load, N

Q_u Ultimate axial load of pile, N

I_p Pile moment of inertia, m^4

k_h Coefficient of horizontal subgrade reaction

K_0 Coefficient of Earth pressure at rest

K_p Coefficient of Passive earth pressure

n Scale factor

N Standard Penetration Test Value

R_{int} Interface strength reduction factor

RD Relative density, %

T Stiffness factor

$TP\ 1$ Tapered Pile (0.5° taper angle)

TP 2 Tapered Pile (1.0° taper angle)

TP 2 Tapered Pile (1.5° taper angle)