

**ANALYSIS AND DESIGN OF PILED RAFT FOUNDATIONS
CONSIDERING SERVICEABILITY LIMIT STATES**

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

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by

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*Dedicated to my family
For their endless love, support and encouragement*

CERTIFICATE

This is to certify that the thesis entitled, “**Analysis and Design of Piled Raft Foundations Considering Serviceability Limit States**” which is being submitted by **Ms. Priyanka Bhartiya (2014CEZ8366)** to the **Indian Institute of Technology (IIT) Delhi** for the award of the degree of **Doctor of Philosophy** is a record of the student’s own work carried out under our supervision and guidance. Her research work has reached the requisite standard as demonstrated by excellent research publications in peer reviewed journals.

Further, the contents of her research work, in full or in parts, have not been submitted to any other institute or university for the award of any degree or diploma to the best of our knowledge and belief.

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ABSTRACT

In the last two decades, advantages of using piled-raft foundations have become apparent to geotechnical and structural engineers and a great deal of attention has been paid to study the different engineering aspects of piled-raft foundations. Because of the three-way raft-pile-soil interaction in a piled raft system, the designer can optimize the location and dimensions of the piles to restrict the maximum and differential settlements, and to improve the load carrying capacity of piled rafts without excessive cost.

The present study aims to understand the behavior of piled raft foundations considering the serviceability limit state condition to get a safe and economical design using simple and quick approaches. To fulfill this purpose a large range of piled raft configurations are considered in different types of sands at various states (loose, medium, dense) and clays with different over-consolidation ratio ($OCR = 1, 2, 5$ and 10) subjected to a wide range of vertical and eccentric loading. All the piled rafts considered for the present study are analyzed using a rigorous continuum based three dimensional elasto-plastic finite element approach in Abaqus software. To model soils, critical state-based soil constitutive models are used such as the “Clay And Sand Model” (CASM) for sand and the “Modified Cam Clay Model” (MCC) for clay. These rigorous finite element analyses are capable of considering complex interactions among raft-piles-soil considering nonlinear elasto-plastic behavior of the soil. Systematic parametric studies are performed using these rigorous finite element analyses to determine the factors affecting different types of settlements (immediate settlements, time dependent consolidation settlements, differential settlements) and load sharing between raft and piles which govern the design of piled rafts under various circumstances. Based on detailed parametric study on load settlement behavior of piled raft foundations, predictive equations are proposed for estimation of piled raft stiffness considering soil-structure

interactions, short-term and long-term settlements, soil subgrade modulus at different interfaces of the piled raft system. Also, effects of load eccentricity on the behavior of piled rafts are studied to understand its importance in design considerations.

The major findings of the present study comprises of (i) a simplified design methodology to predict combined piled raft stiffness, average elasto-plastic settlement and load sharing between raft and piles for piled rafts in sand; (ii) an approximate method of piled raft analysis and design by predicting soil subgrade modulus at various points of piled rafts in sand using the SAP2000 software package; (iii) a simple method to predict long term piled raft settlement, load sharing characteristics and overall time to complete more than 95% consolidation settlement and (iv) effect of load eccentricity with triangularly distributed load on piled raft load-settlement response.

The accuracy of all the proposed methods are cross checked in comparison with rigorous finite element analysis results as well as through validation or verification with existing load settlement data obtained from various literature which indicates the meaningful outcome of the research for use in piled raft design practice.

सार

पिछले दो दशकों में, पाइल्ड-राफ्ट नींव का उपयोग करने के लाभ भू-तकनीकी और संरचनात्मक अभियंताओं के लिए स्पष्ट हो गए हैं और पाइल्ड-राफ्ट नींव के विभिन्न अभियांत्रिक पहलुओं का अध्ययन करने के लिए विशेष ध्यान दिया गया है। एक पाइल्ड-राफ्ट प्रणाली में तीन-तरफ़ा राफ्ट-पाइल-मिट्टी की परस्पर क्रिया के कारण, अभिकल्पक अधिकतम और डिफरेंशियल सेटलमेंट को रोकने के लिए पाइल के स्थान और आयामों का अनुकूलन कर सकते हैं, और कम लागत के साथ पाइल्ड-राफ्ट्स की भार वहन क्षमता में सुधार कर सकते हैं।

वर्तमान अध्ययन का उद्देश्य सर्विसेबिलिटी लिमिट स्टेट की स्थिति को ध्यान में रखते हुए, पाइल्ड-राफ्ट नींव के व्यवहार को समझना एवं सरल और त्वरित दृष्टिकोण वाला एक सुरक्षित और मितव्ययी अभिकल्प प्राप्त करना है। इस उद्देश्य को पूरा करने के लिए विभिन्न प्रकार के पाइल्ड-राफ्ट के विन्यास को, विभिन्न स्थिति की रेत (ढीले, मध्यम, घने) और विभिन्न ओवर-कंसॉलिडेशन अनुपात ($OCR = 1, 2, 5$ और 10) वाले क्ले के साथ विभिन्न प्रकार की उर्ध्वाधर और उत्केन्द्र लोडिंग की स्थिति के लिए लिया गया है। वर्तमान अध्ययन के लिए विचार किए गए सभी पाइल्ड-राफ्ट का विश्लेषण अबैकस सॉफ्टवेयर में एक व्यापक सातत्य आधारित तीन आयामी इलास्टो-प्लास्टिक फाइनाइट एलिमेंट विधि का उपयोग करके किया गया है। मिट्टी को मॉडल करने के लिए, क्रिटिकल स्टेट-आधारित मृदा संवैधानिक मॉडल का उपयोग किया जा गया है जो कि "क्ले एंड सैंड मॉडल" (CASM) है रेत के लिए एवं "संशोधित कैम क्ले मॉडल" (MCC) है क्ले के लिए। यह विस्तृत फाइनाइट एलिमेंट विश्लेषण विधि, मिट्टी के विषम इलास्टो-प्लास्टिक व्यवहार को ध्यान में रखते हुए राफ्ट-पाइल्ड-मिट्टी के बीच जटिल परस्पर क्रिया का विश्लेषण करने में सक्षम हैं। विभिन्न प्रकार की सेटलमेंट (तत्काल सेटलमेंट, समय पर निर्भर कंसोलिडेशन सेटलमेंट, डिफरेंशियल सेटलमेंट) को प्रभावित करने वाले कारकों को निर्धारित करने के लिए एवं विभिन्न परिस्थितियों में पाइल्ड-राफ्ट के लिए पाइल और राफ्ट के बीच लोड शेयरिंग ज्ञात करने के लिए विस्तृत फाइनाइट एलिमेंट विश्लेषण विधि का उपयोग करके व्यवस्थित पैरामीट्रिक अध्ययन किया गया है। पाइल्ड-राफ्ट के लोड सेटलमेंट व्यवहार पर विस्तृत पैरामीट्रिक अध्ययन के आधार पर, मिट्टी- ढांचा परस्पर क्रिया, अल्पकालिक और दीर्घकालिक

सेटलमेंट, पाइल्ड-राफ्ट के विभिन्न इंटरफेस पर मिट्टी के सबग्रेड मॉडुलस को ध्यान में रख कर, पाइल्ड-राफ्ट स्टिफनेस के आकलन के लिए पूर्वानुमान समीकरणों का प्रस्ताव किया गया है। इसके अतिरिक्त, डिज़ाइन किए गए विचारों में इसके महत्व को समझने के लिए पाइल्ड-राफ्ट के व्यवहार पर लोड उत्केन्द्रता के प्रभाव का भी अध्ययन किया गया है।

वर्तमान अध्ययन के प्रमुख निष्कर्षों में शामिल है (i) संयुक्त पाइल्ड-राफ्ट स्टिफनेस, औसत इलास्टो-प्लास्टिक सेटलमेंट और रेत में पाइल्ड-राफ्ट के लिए पाइल और राफ्ट के बीच लोड शेयरिंग की अनुमान करने के लिए एक सरलीकृत अभिकल्प पद्धति; (ii) SAP2000 सॉफ्टवेयर पैकेज का उपयोग करते हुए रेत में पाइल्ड-राफ्ट के विभिन्न बिंदुओं पर मिट्टी के सबग्रेड मॉडुलस का अनुमान लगाकर पाइल्ड-राफ्ट विश्लेषण और अभिकल्प का एक अनुमानित विधि; (iii) लंबी अवधि के लिए पाइल्ड-राफ्ट सेटलमेंट का अनुमान करने की एक सरल विधि, लोड साझा करने की विशेषताएं और 95% से अधिक कंसोलिडेशन सेटलमेंट के लिए समग्र समय (iv) उत्केन्द्र लोडिंग एवं त्रिकोणीय रूप से वितरित लोड का पाइल्ड-राफ्ट सेटलमेंट प्रतिक्रिया पर प्रभाव ।

सभी प्रस्तावित तरीकों की सटीकता को विस्तृत फाइनलिट एलिमेंट विश्लेषण परिणामों के साथ सत्यापित किया गया है एवं विभिन्न साहित्य से उपलब्ध लोड सेटलमेंट डेटा की तुलना में प्रति-परीक्षण किया गया है, जो कि पाइल्ड-राफ्ट अभिकल्प अभ्यास में उपयोग के लिए शोध के सार्थक परिणाम को दर्शाता है।

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