

**PILE RESPONSE IN JOINTED ROCKS UNDER
COMBINED VERTICAL AND LATERAL LOADING**

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

FEBRUARY 2026

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COMBINED VERTICAL AND LATERAL LOADING**

by

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DEPARTMENT OF CIVIL & ENVIRONMENTAL ENGINEERING

Submitted

In fulfilment of the requirement of Doctor of philosophy

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

FEBRUARY 2026

DEDICATED TO MY BELOVED PARENTS AND MY GURUS

CERTIFICATE

This is to certify that the thesis entitled "**PILE RESPONSE IN JOINTED ROCKS UNDER COMBINED VERTICAL AND LATERAL LOADING**" submitted by **Mr. R. ASHWINTH RAJ** to the Indian Institute of Technology Delhi, is a record of the bonafide research work carried out by him under my supervision and guidance. This thesis work, in our 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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Place: IIT Delhi

Date: 27. 02. 2026

ACKNOWLEDGEMENTS

I am deeply grateful to **Prof. R. Ayothiraman** for his exceptional guidance throughout my doctoral journey, from shaping the research plan to carrying out experimental work and data analysis. His support has been truly invaluable.

I extend my heartfelt gratitude to the esteemed members of my SRC, **Prof. A. K. Nema, Prof. G. V. Ramana, and Prof. M. K. Singha**, for their insightful feedback and unwavering support. Their guidance during my initial comprehensive seminar and periodic progress reviews significantly shaped the direction and depth of my research. I am deeply thankful for the wisdom they generously shared whenever I sought their counsel.

I am sincerely thankful to all faculty members of the Department of Civil Engineering, IIT Delhi, for enriching my knowledge in various ways. My special thanks to Prof. K. G. Sharma, Prof. K. S. Rao, Prof. Manoj Datta, Prof. J. T. Shahu, Prof. Bappaditya Manna, Prof. Deepanshu Shirole, Prof. Prasanth Vangla, Prof. Debayan Bhattacharya, and Prof. S. K. Sinha for the valuable ideas and lessons gained during my coursework.

I am also grateful to the staff of the Geotechnical Engineering Laboratory and Rock Mechanics Laboratory, especially Mr. Manoj Kumar Neelam, Mr. Alok, Mr. Lokendra, Mr. Dinesh Kumar, Mr. Lal Singh, Mr. Ramjanam, and Mr. Suraj, for their constant help and assistance throughout my experimental work. For their assistance during experiments, I sincerely thank Mr. Vinay Singh, Dr. Upendra, Dr. A. P. Singh, Dr. Amit Jain, Dr. Raghavendra Saghu, Dr. Sumeet Mahajan, Dr. Adithaya, Dr. Rajkumar, Dr. Chinju Vijayan, Dr. Bruick, Mr. Venkateswarlu, Mr. Koushik, Mr. Befkadu, Mr. Nirbhay, Dr. Deepesh Bansal, Dr. Dev Prakash,

Mr. Siva Raj, Mr. Girish, Mrs. Sarangai, Dr. Vasudha, Mr. Anikesh Paul, Ms. Rose Paul, Ms. Abitha Banu, and Ms. Nanditha. I also thank all the workers involved in conducting the model and field tests. I am indebted to my friends, both within and outside IIT Delhi Dr. Lalit, Dr. Mayuresh, Dr. Sujatha, Dr. Nekitha, Dr. Angel, Dr. Priyadarshini, Dr. Tulja, Ms. Akila, Mr. Jegan, Dr. Durai Vadivel, Dr. Jeeva Raj, Mr. Surender, Dr. Sayanthi, Dr. Debatanu, Dr. Ravi, Dr. Susmitha, Dr. Somya, Mr. Arpan, Ms. Sriparna Roy, Mr. Rajvee, Dr. Sasi Kumar, Dr. Shahid Mohammed, Mr. Haneef, Ms. Shakshi and Ms. Neithala for their moral and emotional support throughout this journey. My special thanks go to Mr. Ilaiyaraaja, IIT Tirupati and friends from IIT-T who made my stay there joyful, as well as my master's mentors Prof. Arumairaj, Dr. Kumar, Dr. Jeya Priya, and Dr. Sateesh Kumar from the Government College of Technology. I also sincerely thank Dr. Daniel (Scientist, SERC), Mr. Palani Kumar (Scientist, CSMRS) and Mr. Kannan. I am especially grateful to all my teachers from my early school days to my doctoral studies, each of whom has played a vital role in shaping me into the person and scholar I am today. Above all, I am forever indebted to my parents, sister, and brother (Mr. Senthil Kumar) for their unwavering love, care, encouragement, and sacrifices. I cherish the memory of my late father, **Mr. Raju**, and my late grandfather, **Mr. P. Natarajan**, whose blessings, love, and values have been a constant source of strength throughout my doctoral journey. They have been my closest constants and strongest supporters, enduring hardships so I could pursue my dreams. Finally, I express my deepest gratitude to Almighty God for blessing me with the strength, health, and wisdom to embark on this research journey and see it through to completion.

Date: 27.02.2026

R Ashwinth Raj

ABSTRACT

Rock-socketed piles are widely adopted as deep foundation elements in geotechnical engineering due to their ability to transfer heavy structural loads through weak overburden soils into competent rock. Their performance is influenced by rock mass conditions/joint characteristics, socket geometry, and construction-induced effects such as sediment deposition at the pile-rock interface. A comprehensive understanding of these factors is essential for safe and economical foundation design, particularly under combined axial and lateral loading.

This study investigates the behaviour of rock-socketed piles through an integrated approach combining laboratory model tests and numerical simulations using Plaxis 3D. Experimental work was conducted on model piles installed in synthetic rock blocks representing weak rock conditions. The intact synthetic rock material had uniaxial compressive strengths of 5 MPa and 8 MPa, while jointed rock conditions were simulated by introducing predefined discontinuities. The study considered two socket length-to-diameter ratios ($L/D = 3$ and 5) to investigate pile behaviour under different rock conditions. Additional tests examined the influence of drilling-induced sediments of varying thickness at the pile toe/base. The results demonstrate that pile performance is governed by a complex interplay of rock strength, pile length-to-diameter ratio, joint roughness, and sediment conditions. Stronger rock and longer sockets generally enhance axial and lateral resistance, though the efficiency of increased length is limited in weaker rocks due to incomplete mobilisation of shaft resistance. Jointed rock conditions influence pile behaviour by altering load transfer mechanisms, in which shear mobilisation along joint planes contributes to load resistance while simultaneously reducing overall stiffness and altering moment distribution under combined loading. Sediment at the pile toe/base

was found to affect the pile response. Interestingly, thin sediment layers showed reduced settlement due to micro-concrete penetration and hardening.

Numerical simulations complemented the experimental findings, validating observed load-displacement trends and enabling parametric studies beyond the scope of physical testing. The simulations revealed that axial capacity is highly sensitive to sediment at shorter socket lengths, where end bearing dominates, but becomes governed by side friction at greater depths, with marginal gains beyond this length. Lateral response under combined loading showed notable improvement for shorter sockets, but the axial contribution diminished with depth, and for deeper sockets, lateral capacity was largely governed by pile-rock interaction alone.

Overall, the study establishes that rock-socketed pile behaviour is strongly influenced by the interaction between socket length, rock conditions, joint properties, and loading type. Independent loading tests tend to overestimate field performance, while combined loading provides a more realistic and conservative estimate. The findings have direct implications for the design of pile foundations in jointed and sediment-influenced rock masses, highlighting the need to account for socket length, joint orientation, and sediment effects in practice. This work provides a systematic framework for understanding pile-rock interaction and offers guidance for optimising deep foundation design in complex geological conditions.

Keywords: Rock-socketed pile, Socket length, Axial loading, Lateral loading, Combined loading, Joint roughness, Sediment effects, Numerical simulation, Plaxis 3D.

सार

रॉक-सॉकेटेड पाइल्स को जियोटेक्निकल इंजीनियरिंग में डीप फाउंडेशन एलिमेंट के तौर पर बड़े पैमाने पर अपनाया जाता है, क्योंकि वे कमज़ोर ओवरबर्डन मिट्टी से भारी स्ट्रक्चरल लोड को अच्छी चट्टान में ट्रांसफर करने की अपनी क्षमता रखते हैं। उनकी परफॉर्मेंस रॉक मास कंडीशन/जॉइंट विशेषताएँ, सॉकेट ज्यामेट्री, और कंस्ट्रक्शन से होने वाले असर जैसे पाइल-रॉक इंटरफेस पर सेडिमेंट डिपोजिशन से प्रभावित होती है। इन फैक्टर्स की पूरी समझ सुरक्षित और किफायती फाउंडेशन डिजाइन के लिए ज़रूरी है, खासकर कंबाइंड एक्सियल और लैटरल लोडिंग के तहत।

यह स्टडी प्लैक्सिस ३-डी का इस्तेमाल करके लैबोरेटरी मॉडल टेस्ट और न्यूमेरिकल सिमुलेशन को मिलाकर एक इंटीग्रेटेड अप्रोच के ज़रिए रॉक-सॉकेटेड पाइल्स के बिहेवियर की जांच करती है। कमज़ोर चट्टान की कंडीशन को दिखाने वाले सिंथेटिक रॉक ब्लॉक में लगाए गए मॉडल पाइल्स पर एक्सपेरिमेंटल काम किया गया था। बरकरार सिंथेटिक रॉक मटीरियल में ५ एमपीए और ८ एमपीए की यूनिएक्सियल कम्प्रेसिव स्ट्रेंथ थी, जबकि जॉइंटेड रॉक कंडीशन को पहले से तय डिसकंटीन्यूटी लाकर सिमुलेट किया गया था। स्टडी में अलग-अलग चट्टान की कंडीशन में पाइल बिहेवियर की जांच करने के लिए दो सॉकेट लेंथ-टू-डायमीटर रेश्यो (एल/डी = ३ और ५) पर विचार किया गया। और टेस्ट में पाइल टो/बेस पर ड्रिलिंग से बनने वाले अलग-अलग मोटाई के सेडिमेंट के असर की जांच की गई। नतीजों से पता चलता है कि पाइल का परफॉर्मेंस चट्टान की मजबूती, पाइल की लंबाई-से-डायमीटर का अनुपात, जॉइंट की खुरदरापन और सेडिमेंट की स्थितियों के बीच के मुश्किल तालमेल से तय होता है। मजबूत चट्टान और लंबे सॉकेट आम तौर पर एक्सियल और लैटरल रेजिस्टेंस को बढ़ाते हैं, हालांकि शाफ्ट रेजिस्टेंस के अधूरे मोबिलाइजेशन के कारण कमजोर चट्टानों में बढ़ी हुई लंबाई की एफिशिएंसी सीमित होती है। जॉइंटेड चट्टान की स्थितियां लोड ट्रांसफर मैकेनिज्म को बदलकर पाइल के व्यवहार पर असर डालती हैं, जिसमें जॉइंट प्लेन के साथ शियर मोबिलाइजेशन

लोड रेजिस्टेंस में योगदान देता है, साथ ही कंबाइंड लोडिंग के तहत ओवरऑल स्टिफनेस को कम करता है और मोमेंट डिस्ट्रीब्यूशन को बदलता है। पाइल टो/बेस पर सेडिमेंट पाइल रिस्पॉन्स को प्रभावित करता पाया गया। दिलचस्प बात यह है कि पतली सेडिमेंट परतों में माइक्रो-कंक्रीट पेनिट्रेशन और हार्डनिंग के कारण सेटलमेंट कम हुआ।

संख्यात्मक सिमुलेशन ने प्रयोगात्मक नतीजों को पूरा किया, देखे गए लोड विस्थापन ट्रेंड को मान्य किया और फिजिकल परीक्षण के दायरे से बाहर पैरामीट्रिक अध्ययन को मुमकिन बनाया। सिमुलेशन से पता चला कि छोटी सॉकेट लंबाई पर एक्सियल कैपेसिटी सेडिमेंट के प्रति बहुत सेंसिटिव होती है, जहाँ एंड बेयरिंग हावी होती है, लेकिन ज़्यादा गहराई पर यह साइड फ्रिक्शन से कंट्रोल हो जाती है, इस लंबाई से आगे मामूली फ़ायदे के साथ। कंबाइंड लोडिंग के तहत लैटरल रिस्पॉन्स ने छोटी सॉकेट के लिए काफ़ी सुधार दिखाया, लेकिन गहराई के साथ एक्सियल कंट्रीब्यूशन कम हो गया, और गहरी सॉकेट के लिए, लैटरल कैपेसिटी ज़्यादातर सिर्फ़ पाइल-रॉक इंटरैक्शन से कंट्रोल होती थी।

कुल मिलाकर, स्टडी यह बताती है कि रॉक-सॉकेटेड पाइल का व्यवहार सॉकेट की लंबाई, रॉक की स्थिति, जॉइंट प्रॉपर्टी और लोडिंग टाइप के बीच इंटरैक्शन से बहुत ज़्यादा प्रभावित होता है। इंडिपेंडेंट लोडिंग टेस्ट फ़ील्ड परफ़ॉर्मेंस को ज़्यादा आंकते हैं, जबकि कंबाइंड लोडिंग ज़्यादा रियलिस्टिक और कंज़र्वेटिव अनुमान देती है। इन नतीजों का जॉइंटेड और सेडिमेंट-इंफ्लुएंस्ड रॉक मास में पाइल फ़ाउंडेशन के डिज़ाइन पर सीधा असर पड़ता है, जो असल में सॉकेट की लंबाई, जॉइंट ओरिएंटेशन और सेडिमेंट के असर को ध्यान में रखने की ज़रूरत पर ज़ोर देता है। यह काम पाइल-रॉक इंटरैक्शन को समझने के लिए एक सिस्टमैटिक फ्रेमवर्क देता है और मुश्किल जियोलॉजिकल कंडीशन में डीप फ़ाउंडेशन डिज़ाइन को ऑप्टिमाइज़ करने के लिए गाइडेंस देता है।

मुख्य शब्द: रॉक-सॉकेटेड पाइल, सॉकेट लेंथ, एक्सियल लोडिंग, लैटरल लोडिंग, कंबाइंड लोडिंग, जॉइंट रफनेस, सेडिमेंट इफेक्ट्स, न्यूमेरिकल सिमुलेशन, प्लैक्सिस ३-डी ।

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LIST OF NOTATIONS

c	Cohesion
ϕ	angle of internal friction
ν	Poisson's ratio
τ	shear stress
σ_3 and σ_c	Confining pressure
σ_n	Normal stress
σ_1	Triaxial compressive strength
ε_a	Axial strain
ε_d	Diametrical strain
p	Mean principle stress
q	Mean shear stress
$\Delta \sigma_f$	Failure deviatoric stress
D	Diameter of the pile
d_s	size of aggregates
E	Modulus of elasticity
h	Height of the pile
L or L_s	Pile socketing length
IS	Indian Standard
MP	Mix Proportions

