

BEHAVIOUR OF MICROPILES IN GLACIAL DEPOSITS UNDER AXIAL AND LATERAL LOADS: FIELD TESTING AND NUMERICAL SIMULATIONS

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**DEPARTMENT OF CIVIL ENGINEERING
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UNDER AXIAL AND LATERAL LOADS: FIELD TESTING
AND NUMERICAL SIMULATIONS**

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Dedicated To Badrivishal ji

CERTIFICATE

This is to certify that the thesis entitled, “ **BEHAVIOUR OF MICROPILES IN GLACIAL DEPOSITS UNDER AXIAL AND LATERAL LOADS: FIELD TESTING AND NUMERICAL SIMULATIONS**” being submitted by **Mr. Manish Kapil** to the Indian Institute of Technology Delhi for the award of ‘**Doctor of Philosophy**’ is a record of the bonafide research work carried out by him under our supervision of this thesis, which to the best of our knowledge has reached the requisite standard. The material contained in this thesis has not been submitted in part or fully to any other university or institute for the award of any degree or diploma.

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Manish Kapil

ABSTRACT

India, as a rapidly developing nation, is undertaking extensive infrastructure projects across the Himalayan region to improve connectivity between its northern states. These initiatives primarily involve the construction of roads, railway lines, tunnels, and bridges to traverse the rugged mountainous terrain. Due to the presence of numerous rivers, valleys, and depressions, bridge construction is particularly crucial. However, the unique geological conditions in the Himalayas, especially the presence of thick glacial moraine deposits—formed by the movement and retreat of glaciers and often exceeding 100 meters in depth—pose significant challenges for foundation design. Conventional deep foundations like driven or bored piles are often impractical in such deposits due to the inaccessibility of hard strata. In this context, micropiles emerge as a promising alternative due to their small diameter (typically less than 300 mm), ability to be installed with minimal disturbance, and adaptability to a wide range of subsurface conditions.

This study focuses on the glacial deposits of the Ladakh and Uttarakhand regions, where both geomorphological mapping and geotechnical characterization are systematically carried out. Laboratory investigations classified the deposits predominantly as poorly graded gravel (GP), with gravel content varying between 36% to 57%, and high shear strength values reflected in internal friction angles exceeding 40° . Mineralogical analysis through X-ray diffraction (XRD) and scanning electron microscopy (SEM) revealed a dominance of angular particles composed mainly of quartz, feldspar, and traces of clay minerals, contributing to the high frictional resistance of the material.

A comprehensive field testing program was undertaken, comprising 28 full-scale load tests on micropiles installed in glacial deposits. It includes 9 vertical, 9 lateral, 5 group load tests, and 5 load tests on instrumented micropiles. These tests demonstrated that the actual in-situ load

capacity of micropiles exceeded analytically predicted values (based on IS 14593:1998 and IS 2911 Part 1 Sec-2) by more than 2.5 times. Vertical load capacities reached up to 80 tons, with corresponding settlements ranging from 3.12 mm to 8.9 mm, while lateral capacities were significantly affected by scour depth—experiencing up to 160% reduction after 1 m of scouring and complete failure beyond 2 m.

To complement the field investigation, a parametric numerical study was performed using PLAXIS 3D. The effects of various parameters such as type of loading, elastic modulus of the glacial deposits, scouring depth, slenderness ratio (L/D), and grade of grout were evaluated. The results indicated that increasing the stiffness of the surrounding soil and using higher-grade concrete improved the micropile capacity. Conversely, increased scouring depth and L/D ratios led to reduced performance. The numerical analysis corroborated field findings and emphasized the critical role of lateral loads and scour in micropile design. Inclined micropiles and improved concrete grades were identified as viable solutions to enhance lateral resistance.

In summary, this study provides a robust understanding of the behavior of micropiles in glacial deposits through integrated geomorphological, geotechnical, in-situ, and numerical approaches. The findings not only demonstrate the viability of micropiles as a foundation solution in complex Himalayan terrain but also provide essential insights and a comprehensive field test data to develop design guidelines for micropiles in glacial deposits.

सार

भारत, एक तेज़ी से विकासशील राष्ट्र के रूप में, अपने उत्तरी राज्यों के बीच संपर्क में सुधार के लिए हिमालयी क्षेत्र में व्यापक बुनियादी ढाँचा परियोजनाएँ चला रहा है। इन पहलों में मुख्य रूप से ऊबड़-खाबड़ पहाड़ी इलाकों को पार करने के लिए सड़कों, रेलवे लाइनों, सुरंगों और पुलों का निर्माण शामिल है। कई नदियों, घाटियों और अवसादों की उपस्थिति के कारण, पुल निर्माण विशेष रूप से महत्वपूर्ण है। हालाँकि, हिमालय की अनूठी भूवैज्ञानिक परिस्थितियाँ, विशेष रूप से ग्लेशियरों के

आवागमन और पीछे हटने से बने मोटे हिमोढ़ जमावों की उपस्थिति और अक्सर 100 मीटर से अधिक गहराई वाले, नींव के डिज़ाइन के लिए महत्वपूर्ण चुनौतियाँ पेश करते हैं। कठोर परतों की दुर्गमता के कारण, ऐसे जमावों में पारंपरिक गहरी नींव जैसे कि संचालित या बोर किए गए ढेर अक्सर अव्यावहारिक होते हैं। इस संदर्भ में, माइक्रोपाइल अपने छोटे व्यास (आमतौर पर 300 मिमी से कम), न्यूनतम व्यवधान के साथ स्थापित होने की क्षमता और विभिन्न प्रकार की भूमिगत स्थितियों के अनुकूल होने के कारण एक आशाजनक विकल्प के रूप में उभर रहे हैं। यह अध्ययन लद्दाख और उत्तराखंड क्षेत्रों के हिमनद निक्षेपों पर केंद्रित है, जहाँ

भू-आकृति विज्ञान मानचित्रण और भू-तकनीकी लक्षण-वर्णन दोनों व्यवस्थित रूप से किए जाते हैं। प्रयोगशाला जाँचों ने निक्षेपों को मुख्यतः निम्न-श्रेणीबद्ध बजरी (GP) के रूप में वर्गीकृत किया, जिसमें बजरी की मात्रा 36% से 57% के बीच थी, और उच्च अपरूपण शक्ति मान 40° से अधिक आंतरिक घर्षण कोणों में परिलक्षित होते थे। एक्स-रे विवर्तन (XRD)

और स्कैनिंग इलेक्ट्रॉन माइक्रोस्कोपी (SEM) के माध्यम से खनिज विश्लेषण से कोणीय कणों की प्रधानता का पता चला, जो मुख्य रूप से क्वार्ट्ज, फेल्डस्पार और मिट्टी के खनिजों के अंशों से बने थे, जो सामग्री के उच्च घर्षण

प्रतिरोध में योगदान करते हैं एक व्यापक क्षेत्र परीक्षण कार्यक्रम शुरू किया गया, जिसमें हिमनद निक्षेपों में स्थापित माइक्रोपाइल्स पर 28 पूर्ण-स्तरीय भार परीक्षण शामिल थे। इसमें 9 ऊर्ध्वाधर, 9 पार्श्व, 5 समूह भार परीक्षण और यंत्रयुक्त माइक्रोपाइल्स पर 5 भार परीक्षण शामिल हैं। इन परीक्षणों से पता चला कि माइक्रोपाइल्स की वास्तविक इन-सीटू भार क्षमता विश्लेषणात्मक रूप से अनुमानित मानों (IS 14593:1998 और IS 2911 भाग 1 खंड-2 पर आधारित) से 2.5 गुना से भी अधिक थी। ऊर्ध्वाधर भार क्षमता 80 टन तक पहुँच गई, तदनुसूची जमाव 3.12 मिमी से 8.9 मिमी तक था, जबकि पार्श्व क्षमताएँ घिसाव की गहराई से काफी प्रभावित थीं मीटर घिसाव के बाद 160% तक की कमी का अनुभव और 2 मीटर से आगे पूर्ण विफलता।

क्षेत्रीय जाँच को पूरक बनाने के लिए, PLAXIS 3D का उपयोग करके एक पैरामीट्रिक संख्यात्मक अध्ययन किया गया। विभिन्न मापदंडों जैसे भार के प्रकार, हिमनद जमाव का प्रत्यास्थ मापांक, घिसाव की गहराई, क्षीणता अनुपात (L/D), और ग्राउट के ग्रेड के प्रभावों का मूल्यांकन किया गया।

परिणामों से संकेत मिलता है कि आसपास की मिट्टी की कठोरता बढ़ाने और उच्च-श्रेणी के कंक्रीट के उपयोग से माइक्रोपाइल क्षमता में सुधार हुआ। इसके विपरीत, बढ़ी हुई घर्षण गहराई और L/D अनुपात के कारण प्रदर्शन में कमी आई। संख्यात्मक विश्लेषण ने क्षेत्र के निष्कर्षों की पुष्टि की और माइक्रोपाइल डिज़ाइन में पार्श्व भार और घर्षण की महत्वपूर्ण भूमिका पर बल दिया। पार्श्व प्रतिरोध को बढ़ाने के लिए झुके हुए माइक्रोपाइल और बेहतर कंक्रीट ग्रेड को व्यवहार्य समाधान के रूप में पहचाना गया। संक्षेप में, यह अध्ययन एकीकृत भू-आकृति विज्ञान, भू-तकनीकी, इन-सीटू और संख्यात्मक दृष्टिकोणों के माध्यम से हिमनदों के निक्षेपों में माइक्रोपाइल के व्यवहार की एक मजबूत समझ प्रदान करता है। ये निष्कर्ष न केवल जटिल हिमालयी भूभाग में एक आधार समाधान के रूप में माइक्रोपाइल की व्यवहार्यता को प्रदर्शित करते हैं, बल्कि हिमनदों के निक्षेपों में माइक्रोपाइल के लिए डिज़ाइन दिशानिर्देश विकसित करने हेतु आवश्यक अंतर्दृष्टि और व्यापक क्षेत्र परीक्षण डेटा भी प्रदान करते हैं।

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LIST OF NOTATIONS

A_g = Area of the grout (inside casing only)

A_s = Area of the steel bar

$P_{c\text{-allowable}}$ = Allowable structural axial compression load

$P_{t\text{-allowable}}$ = Allowable structural axial tension load

f'_c = Unconfined compression strength of the grout

f_y = Specific yield point of steel

f_a = Axial applied stress

f_b = Bending stress

S = Elastic section modulus of the steel casing

F_a = Allowable axial stress

F_b = Allowable bending stress

F_e = Euler buckling stress

E = Young's modulus of the steel casing

FS = Factor of safety

K = Effective length factor

L = Unsupported length of the micropile

r = Radius of gyration of the steel casing

P_{\max} = Maximum axial compression load

$P_{c\text{-allowable}}$ = Allowable structural axial compression load

M_{\max} = Maximum bending moment

$M_{\text{allowable}}$ = Allowable bending moment

I_{casing} = Moment of inertia of the pile casing

OD = Outer diameter of the pile

α_{bond} = Unit value for the grout/ground bond

f_s = Unit side friction resistance

α = Adhesion factor

C_u = Undrained shear strength of the soil adjacent to the foundation

L_e = Effective pile length

N_c^* = Bearing capacity factor

C_u = Undrained shear strength of the soil under the toe

A_t = Pile toe area

Q_{shaft} = Shaft resistance obtained from the enlargement geometry

V_{inc} = Percentage increase in the pile volume

A_{inc} = Percentage increase in the pile area

V_{grout} = Volume of grout used in the micropile construction

V_{hole} = Volume of the hole based on the diameter of the drill bit

A_{hole} = Area of the hole based on the diameter of the drill bit

Q_s = Resistance of the shaft based on the diameter of the drill bit