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CONCEPTUALISATION AND EXPERIMENTAL INVESTIGATION OF AN INNOVATIVE FOUNDATION SYSTEM FOR LIGHTLY LOADED BUILDINGS ON EXPANSIVE SOILS

ABITHA BABU

INDIAN INSTITUTE OF TECHNOLOGY DELHI
&
THE UNIVERSITY OF QUEENSLAND
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Conceptualisation and Experimental Investigation of an Innovative Foundation System for Lightly Loaded Buildings on Expansive Soils

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Abitha Babu

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I dedicate this thesis to my family and loved ones: ***Baburaj, Christal, Abin,***

Reshma, Anvi, Ayaan & Rameez *for their unwavering love and support.*

Supervisor Certification

This is to certify that the thesis entitled "**Conceptualisation and Experimental Investigation of an Innovative Foundation System for Lightly Loaded Buildings on Expansive Soils**" being submitted by **Ms. Abitha Babu** to the Indian Institute of Technology Delhi and The University of Queensland for the award of degree of **Doctor of Philosophy** is a record of *bonafide* research work carried out by her. **Ms. Abitha Babu** has worked under our guidance and supervision and has fulfilled the requirements for the submission of this thesis, which to our knowledge has reached the requisite standard. The results contained in this thesis are original and have not been submitted, in part or full, to any other University or Institute for the award of any other degree or diploma.



Ramanathan Ayothiraman

Professor (On-lien)

Department of Civil and Environmental Engineering

Indian Institute of Technology Delhi

Hauz Khas New Delhi - 110016



Alexander Scheuermann

Professor

School of Civil Engineering

University of Queensland

St. Lucia, Australia - 4076



Prashanth Vangla

Associate Professor

Department of Civil and Environmental Engineering

Indian Institute of Technology Delhi

Hauz Khas New Delhi - 110016

Abstract

Expansive soils pose significant challenges to lightly loaded structures due to their swelling and shrinkage behaviour under moisture variations. Existing foundation systems often experience substantial uplift under such conditions, leading to structural distress and serviceability issues. To address this problem, the present research proposed and evaluated a novel foundation concept termed the Composite Annular Sand-Pile (CASP) system, developed to mitigate the adverse effects of expansive soils by introducing an annular sand layer.

The research aimed to conceptualise, experimentally validate, and theoretically substantiate the CASP foundation system, focusing on its performance under water infiltration-induced swelling in comparison with a conventional pile foundation. The study involved the conceptual formulation of the CASP system, including identification of its key components, construction sequence, and hypothesised working mechanism. The proposed concept was initially confirmed through preliminary simplified laboratory experiments. The next stage of the research comprised a comprehensive laboratory scale 1-g model testing program, in which conventional pile and CASP foundation models of different annular sand layer thicknesses were subjected to controlled infiltration tests to assess their comparative performance. Through these experiments, the optimum annular sand layer thickness was determined to achieve maximum performance with material efficiency.

In the subsequent stage, an image-based study was conducted using the Particle Image Velocimetry (PIV) technique to examine interactions at the expansive soil-annular sand-pile interface under two-dimensional plane-strain conditions, providing detailed insights into the deformation mechanisms and thereby validating the proposed working mechanism of the CASP system. Finally, a simplified analytical framework was developed to theoretically substantiate the experimentally observed behaviour. Using elastic stress-strain relationships, expressions were derived for swelling-induced uplift friction and frictional resistance, incorporating the deformability and compaction characteristics of the annular sand layer.

The experimental findings confirmed that the annular sand layer in the CASP foundation effectively accommodated part of the lateral swelling of the expansive soil, redistributed soil swelling, and reduced both soil heave and pile uplift compared to conventional piles. The image-based analysis revealed lower shear strain magnitudes around the pile in the CASP system, demonstrating the cushioning effect of the annular sand layer and its

effectiveness in mitigating swelling effects. The analytical formulation further provided a theoretical explanation for the behaviour observed in the experimental investigations.

Overall, this research establishes the Composite Annular Sand-Pile as a technically viable, mechanistically validated, and experimentally supported foundation solution for mitigating swelling-induced uplift in expansive soils. The findings provide a strong basis for further refinement, including field-scale validation and integration into practical design guidelines.

Abstract in Hindi

विस्फारशील मिट्टियाँ नमी में परिवर्तन के कारण होने वाले उनके फुलाव और सिकुड़न व्यवहार के चलते हल्के भार वाली संरचनाओं के लिए गंभीर चुनौतियाँ प्रस्तुत करती हैं। मौजूदा नींव प्रणालियाँ ऐसे परिस्थितियों में प्रायः पर्याप्त उर्ध्व बल (uplift) का अनुभव करती हैं, जिससे संरचनात्मक क्षति और सेवा-क्षमता संबंधी समस्याएँ उत्पन्न होती हैं। इस समस्या के समाधान हेतु, प्रस्तुत शोध में एक नवीन नींव अवधारणा-कॉम्पोज़िट ऐनुलर सैंड-पाइल (CASP) प्रणाली-का प्रस्ताव और मूल्यांकन किया गया है, जिसे विस्फारशील मिट्टी के प्रतिकूल प्रभावों को कम करने के लिए एक ऐनुलर रेत परत सम्मिलित करके विकसित किया गया है।

यह शोध CASP नींव प्रणाली की संकल्पना, प्रायोगिक सत्यापन, और सैद्धांतिक पुष्टिकरण पर केंद्रित था, विशेषकर पारंपरिक पाइल नींव की तुलना में जल-प्रवेशन-जनित फुलाव स्थितियों में इसके प्रदर्शन को समझने हेतु। अध्ययन में CASP प्रणाली का वैचारिक विकास, इसके प्रमुख घटकों की पहचान, निर्माण क्रम, और अनुमानित कार्य-विधि का विवरण शामिल था। प्रस्तावित अवधारणा का प्रारंभिक रूप से सरल प्रयोगशाला परीक्षणों द्वारा सत्यापन किया गया। शोध के अगले चरण में व्यापक 1-g मॉडल परीक्षण कार्यक्रम सम्मिलित था, जिसमें विभिन्न ऐनुलर रेत परत मोटाई वाले पारंपरिक तथा CASP नींव मॉडलों को नियंत्रित जल-प्रवेशन परीक्षणों के अधीन कर उनके तुलनात्मक प्रदर्शन का मूल्यांकन किया गया। इन प्रयोगों के माध्यम से अधिकतम दक्षता प्राप्त करने हेतु उपयुक्त रेत परत मोटाई निर्धारित की गई।

अगले चरण में, पार्टिकल इमेज वेलोसिमेट्री (PIV) तकनीक का उपयोग करके विस्फारशील मिट्टी–ऐनुलर रेत–पाइल के द्वि-आयामी प्लेन-स्ट्रेन अंतःक्रियाओं का अध्ययन किया गया, जिससे विरूपण तंत्रों की विस्तृत समझ प्राप्त हुई और CASP प्रणाली की प्रस्तावित कार्य-विधि का सत्यापन हुआ। अंततः, एक सरल सैद्धांतिक रूपरेखा विकसित की गई, जो प्रायोगिक रूप से देखे गए व्यवहार का सैद्धांतिक समर्थन प्रदान करती है। प्रत्यास्थ तनाव–विकृति संबंधों का उपयोग करके फुलाव-जनित उर्ध्व घर्षण तथा घर्षणीय प्रतिरोध के लिए अभिव्यक्तियाँ विकसित की गईं, जिनमें रेत परत की विकृतिशीलता और संघनन गुण सम्मिलित थे।

प्रायोगिक परिणामों से पुष्टि हुई कि CASP नींव में ऐनुलर रेत परत विस्फारशील मिट्टी के पार्श्वीय फुलाव का एक हिस्सा प्रभावी रूप से अवशोषित करती है, मिट्टी के फुलाव का पुनर्वितरण करती है, और पारंपरिक पाइलों की तुलना में मिट्टी के उभार (heave) तथा पाइल उर्ध्व बल को उल्लेखनीय रूप से कम करती है। इमेज-आधारित विश्लेषण से पाइल के आसपास कम शीयर स्ट्रेन का पता चला, जो रेत परत के कुशनिंग प्रभाव और फुलाव को कम करने में इसकी प्रभावशीलता को दर्शाता

है। सैद्धांतिक मॉडल ने प्रयोगों में देखे गए व्यवहार की व्याख्या के लिए आवश्यक आधार प्रदान किया।

समग्र रूप से, यह शोध कॉम्पोज़िट ऐनुलर सैंड-पाइल (CASP) प्रणाली को विस्फारशील मिट्टियों में फुलाव-जनित उर्ध्व बल कम करने के लिए एक तकनीकी रूप से उपयुक्त, यांत्रिक रूप से सत्यापित, और प्रायोगिक रूप से समर्थित नींव समाधान के रूप में स्थापित करता है। शोध निष्कर्ष आगे के परिशोधन, क्षेत्र-स्तरीय सत्यापन, और व्यावहारिक डिज़ाइन दिशानिर्देशों में इसके एकीकरण के लिए एक ठोस आधार प्रदान करते हैं।

Declaration by author

This thesis is composed of my original work, and contains no material previously published or written by another person except where due reference has been made in the text. I have clearly stated the contribution by others to jointly authored works that I have included in my thesis.

I have clearly stated the contribution of others to my thesis as a whole, including statistical assistance, survey design, data analysis, significant technical procedures, professional editorial advice, financial support and any other original research work used or reported in my thesis. The content of my thesis is the result of work I have carried out since the commencement of my higher degree by research candidature and does not include a substantial part of work that has been submitted to qualify for the award of any other degree or diploma in any university or other tertiary institution. I have clearly stated which parts of my thesis, if any, have been submitted to qualify for another award.

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Publications included in this thesis

1. Ayothiraman, R., Scheuermann, A., and **Babu, A**. (2026). Composite Annular Sand-Pile (CASP) Foundation System (Indian Patent No. 591368). Indian Patent Office.
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List of Abbreviations and Symbols

CASP	Composite Annular Sand-Pile
CNS	Cohesive non-swelling
C_c	Coefficient of Curvature
C_u	Coefficient of Uniformity
D_{50}	Mean particle size
D_p	Diameter of pile
D_t	Diameter of test tank
DAQ	Data acquisition
DFS	Differential free swell
DG	Dial gauge
DIC	Digital Image Correlation
F	Factor of safety
f_u	Unit uplift friction
f_r	Unit frictional resistance
GSD	Gradin size distribution
La	Length of active zone
Ls	Length of stable zone
LL	Liquid limit
LSP	Lateral swelling pressure
OMC	Optimum moisture content
PI	Plasticity index
PIV	Particle image velocimetry
PL	Plastic limit
Q_u	Uplift force
Q_r	Resisting force

SEM	Scanning Electron Microscopy
SWRC	Soil Water Retention Curve
t_{as}	Annular sand layer thickness
t_{oas}	Optimum annular sand layer thickness
t_s	Shear band thickness
VSP	Vertical swelling pressure
w	Water content
XRD	X-ray diffraction
c_a	Sand-pile interface cohesion
σ_v	Vertical stress due to overburden
σ_r	Horizontal stress due to overburden
δ	Soil-pile interface frictional angle
ε_h	Horizontal strain
ε_v	Vertical strain
μ	Poisson's ratio
φ	Angle of internal friction
K	Coefficient of earth pressure
p_l	Lateral swelling pressure
γ_d	Dry density
γ_{dmin}	Minimum dry density
γ_{dmax}	Maximum dry density
S_h	Swelling strain in horizontal direction
S_v	Swelling strain in vertical direction
z	Depth