EXPERIMENTAL AND NUMERICAL INVESTIGATIONS INTO BASAL REINFORCED EMBANKMENT RESTING ON SOFT SOIL IMPROVED WITH SOIL CEMENT COLUMNS

SUJATA JITENDRA FULAMBARKAR

INDIAN INSTITUTE OF TECHNOLOGY DELHI

NEW DELHI-110016, INDIA

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by

SUJATA JITENDRA FULAMBARKAR

Department of Civil Engineering

submitted

in fulfillment of requirements of the degree of

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to the

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Dedicated to

my

Parents and Husband

CERTIFICATE

This is to certify that the thesis titled "**Experimental and Numerical Investigations into Basal Reinforced Embankment Resting on Soft Soil Improved with Soil Cement Columns**", submitted by **Ms. Sujata Jitendra Fulambarkar** to the Indian Institute of Technology Delhi is a record of bonafide research work carried out by her under our supervision and guidance. This thesis work, in our opinion, has reached the standard of fulfilling the requirements for a **Doctor of Philosophy** degree. The research report and results presented in this thesis have not been submitted, in part or full, to any University or Institute for the award of the degree or diploma.

Dr. J. T. Shahu
Professor,
Department of Civil Engineering,
IIT Delhi
New Delhi - 110016

Dr. Bappaditya Manna
Professor,
Department of Civil Engineering,
IIT Delhi
New Delhi - 110016

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Date: Sujata Jitendra Fulambarkar

ABSTRACT

Embankments, which are essential for transportation infrastructure, can face challenges such as settlements and instability when built on weak, compressible soils. Traditional consolidation methods may be economically uncertain and time-consuming, leading to potential damage from significant settlements. In response, Soil cement columns (SCC), with or without basal reinforcement, offer a rapid and cost-effective solution for ground stabilization. The Deep Mixing Method (DMM) involves blending binders with weak geomaterials to create a composite ground with enhanced strength and stiffness, resulting in improved bearing capacity. This enables the rapid construction of embankments while minimizing total and differential settlements, addressing the limitations of conventional consolidation techniques.

The current study involves model testing for various embankment cases, namely, unreinforced (UR), basal geotextile reinforced (BGR), column-supported (CS), and basal-reinforced column-supported (BRCS). These embankments rest on soft clay with different shear strengths and various column installation patterns like Square Group Columns (SGC), Longitudinal Tangent Wall (LTW), Transverse Tangent Wall (TTW), and Tangent Grid (TG) beneath the embankment. Parameters such as settlement at the crest, lateral deformation of the embankment slope, and heaving of the soft soil foundation are thoroughly examined. The Particle Image Velocimetry (PIV) technique is employed to capture soil deformation under the embankment. The findings of the study, presented as displacement contours and deformation profiles, explore the impact of reinforcement, length, number, and installation patterns of the SCC columns. Additionally, a finite element model delves into the effects of various parameters on the performance of BRCS embankments, including soft soil strength parameters, geotextile tensile strength, SCC column characteristics, and geometric parameters. The research provides

valuable insights and predictions for the performance of prototype BRCS embankments under vertical loads.

सार

तटबंध, जो परिवहन अवसंरचना के लिए आवश्यक होते हैं, कमजोर, संपीडनीय मिट्टी पर बनाए जाने पर धंसाव और अस्थिरता जैसी चुनौतियों का सामना कर सकते हैं। पारंपरिक संपीड़न विधियाँ आर्थिक रूप से अनिश्चित और समय लेने वाली हो सकती हैं, जिससे महत्वपूर्ण धंसाव से संभावित नुकसान हो सकता है। इसके प्रत्युत्तर में, सोईल सीमेंट कॉलम (SCC), बेसल सुदृढीकरण के साथ या बिना, भूमि स्थिरीकरण के लिए एक त्वरित और किफायती समाधान प्रदान करते हैं। डीप मिक्सिंग मेथड (DMM) कमजोर भू-सामग्री के साथ बाइंडर को मिलाकर एक मिश्रित भूमि बनाता है जिसमें बढ़ी हुई शक्ति (strength) और कठोरता (stiffness) होती है, जिससे भार वहन क्षमता में सुधार होता है। यह कुल और अंतर धंसाव को कम करते हुए तटबंध का त्वरित निर्माण सक्षम बनाता है, पारंपरिक संपीड़न तकनीकों की सीमाओं को संबोधित करता है।

वर्तमान अध्ययन विभिन्न तटबंध मामलों के लिए मॉडल परीक्षण शामिल किया गया है, अर्थात्, असंवर्धित (UR), बेसल जियोटेक्सटाइल संवर्धित (BGR), कॉलम-समर्थित (CS), और बेसल-संवर्धित कॉलम-समर्थित (BRCS)। ये तटबंध विभिन्न प्रकार की कटाई शक्ति वाली नरम मिट्टी पर और विभिन्न कॉलम स्थापना पैटर्न जैसे कि स्क्वायर ग्रुप कॉलम (SGC), लांगिट्यूडिनल टैन्जेंट वॉल (LTW), ट्रांसवर्स टैन्जेंट वॉल (TTW), और टैन्जेंट ग्रिड (TG) के नीचे स्थित हैं। शिखर पर जमावट, तटबंध ढलान का पार्श्व विकृति, और नरम मिट्टी की नींव का हिविंग जैसे मापदंडों की पूरी तरह से जाँच की गई है। पार्टिकल इमेज वेलोसिमेट्री (PIV) तकनीक का उपयोग तटबंध के नीचे मिट्टी के विकृति को पकड़ने के लिए किया गया है। अध्ययन के निष्कर्ष, विस्थापन कोंटूर और विकृति प्रोफाइल के रूप में प्रस्तुत किए गए हैं, जो सुदृढीकरण, लंबाई, संख्या, और SCC कॉलम के स्थापना पैटर्न के प्रभावों का पता लगाते हैं। इसके अतिरिक्त, एक सीमित तत्व मॉडल BRCS तटबंध के प्रदर्शन पर विभिन्न मापदंडों के प्रभावों की जाँच की

गई है, जिसमें नरम मिट्टी की ताकत के मापदंड, जियोटेक्सटाइल तन्य शक्ति, SCC कॉलम की विशेषताएँ, और ज्यामितीय मापदंड शामिल हैं। शोध ऊर्ध्वाधर भारों के तहत प्रोटोटाइप BRCS तटबंध के प्रदर्शन के लिए मूल्यवान अंतर्दृष्टि और भविष्यवाणियाँ प्रदान की गई हैं।

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LIST OF ABBREVIATIONS

ASTM	American Society for Testing and Materials
BGR	Basal Geotextile Reinforced
BRCS	Basal Reinforced Column Supported
BS EN	British Standard European Norm
CBR	California Bearing Ratio
CDIT	Coastal Development Institute of Technology
CDM	Cement Deep Mixing
CMOS	Complementary Metal-Oxide Semiconductor
CS	Column Supported
DAQ	Data Acquisition
DCM	Deep Cement Mixing
DJM	Deep Jet Mixing
DM	Deep Mixed
DMM	Deep Mixing Method
DSLR	Digital Single-Lens Reflex
DSM	Deep Soil Mixing
FEM	Finite Element Method
FGC	Fly Ash Gypsum Cement
FHWA	Federal Highway Administration
FS	Factor of safety
GRCS	Geosynthetic Reinforced Column Supported
IRC	Indian Road Congress
IS	Indian Standard
LTW	Longitudinal Tangent Wall
LVDT	Linear Variable Differential Transformer
MC	Mohr Coulomb
MCC	Modified Cam Clay
MEPS	Miniature Earth Pressure Sensor
PHRI	Port and Harbour Research Institute
PIV	Particle Image Velocimetry

PVD	Pre-fabricated Vertical Drain
RoI	Region of Interest
SCC	Soil Cement Column
SCR	Stress Concentration Ratio
SCSE	SDCM Column-Supported Embankments
SDCM	Stiffened Deep Cement Mixing
SGC	Square Group Columns
TG	Tangent Grid
TTW	Transverse Tangent Wall
UBC	Ultimate Bearing Capacity
UPVC	Unplasticized Polyvinyl Chloride
UR	Unreinforced

LIST OF NOTATIONS

A	Sectional area of footing
A	Cross-sectional area of the column
Al_2O_3	Aluminate
A_r	Area improvement ratio
AV_{max}	Maximum value of the assessed variable
AV_{min}	Minimum value of the assessed variable
b	Load-sharing factor
c’	Cohesion
C_2S	Dicalcium silicate
C_2SHx, C_3S_2Hx	Hydrated Calcium silicates
C_3A	Tricalcium aluminate
C_3A	Tricalcium aluminate
C_3AHx, C_4AHx	Hydrated Calcium aluminates
C_3S	Tricalcium silicate
C_4AF	Tricalcium alumino-ferrite
$Ca(OH)_2$	Hydrated lime
CaO	Calcium
C_c	Compression index
C_s	Swelling index
c_u	Undrained Shear Strength
c_{uc}	Undrained shear strength of clay layer
c_{ut}	Undrained shear strength of SCC column (= $q_u/2$)
d	Diameter of the column
δ	Settlement
d_{50}	Mean particle size
ε	Axial strain measured from strain gauges
E	Elastic modulus of SCC
e_0	Initial void ratio
E_{50}	Secant modulus of elasticity
EA	Elastic stiffness

E_{col}	Design modulus of elasticity of the soil cement column
F	Axial load
ϕ'	Angle of internal friction
γ	Unit weight
h	Heaving of the foundation soft soil
H_2O	Water
I_p	Plasticity index
IR	Influence ratio
l	Length of the column
L	Lateral deformation of the embankment slope
L/D	Embedment ratio
M	Slope of the critical state line
n	Scaling factor
N	Number of columns
N_1	Tension developed in geotextile
N_c	Bearing capacity factor
ν_{col}	Poisson's ratio of soil cement column
P	Vertical load
p'_i	Initial geostatic stress
q_u	Unconfined compressive strength
q_{uc}	Unconfined compressive strength of the soil-cement columns
SiO_2	Silicate
T	Geotextile tensile strength
w_l	Liquid limit
w_p	Plastic limit
κ	Slope of the unloading/reloading line
λ	Slope of the normal consolidation line
σ_v	Applied vertical stress