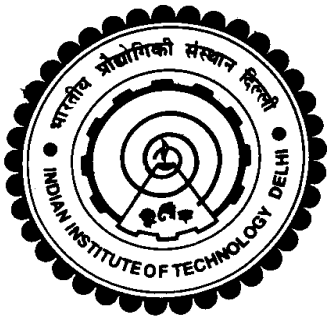
INCLINED PULLOUT BEHAVIOUR OF ANCHORED GEOGRIDS USED AS VENEER REINFORCEMENT IN COVER SYSTEMS OF LANDFILLS

RIYA BHOWMIK



DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
OCTOBER 2019

INCLINED PULLOUT BEHAVIOUR OF ANCHORED GEOGRIDS USED AS VENEER REINFORCEMENT IN COVER SYSTEMS OF LANDFILLS

by

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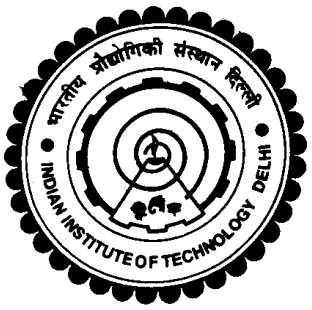
Department of Civil Engineering

Submitted

in fulfilment of the requirements of the degree of Doctor of Philosophy

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

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OCTOBER 2019

To

My Family

CERTIFICATE

This is to certify that the thesis entitled "**INCLINED PULLOUT BEHAVIOUR OF ANCHORED GEOGRIDS USED AS VENEER REINFORCEMENT IN COVER SYSTEMS OF LANDFILLS**" being submitted by **Ms. Riya Bhowmik** to the **Indian Institute of Technology Delhi** is a record of bonafide research work carried out by her under our supervision and guidance. The thesis work, in our opinion, has reached the standard fulfilling the requirements for **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 any degree or diploma.

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ACKNOWLEDGEMENTS

I express my deepest gratitude and indebtedness towards my respected supervisors, **Prof. J.T. Shahu**, and **Prof. Manoj Datta**, Professor, Department of Civil Engineering, Indian Institute of Technology Delhi for their inspiring guidance, pain-staking efforts, valuable suggestions, and unfailing support and encouragement throughout this study. I will forever be indebted towards their constant assistance provided during the course of this study. Their volunteered hours of valuable time helped me to put my best efforts in the completion of this study. Their vast knowledge and experience on the subject made this study possible and even more enjoyable.

My sincere thanks to all the faculty members in the Civil Engineering Department, Indian Institute of Technology Delhi for their constant support and encouragement during the entire period of my research work. I also express my sincere thanks to the members of the Student Research Committee, namely, Prof. A. K. Gosain, Prof. G. V. Ramana, and Prof. B. P. Patel for their suggestions during the course of this work.

I am thankful to the staff members of Soil Mechanics, Rock Mechanics, Geology, and Computational laboratories, namely Mr. Manoj Kumar Neelam, Mr. Alok Kumar, Mr. D. Biswas, and Mr. Amit Bundela, respectively, for their cooperation in carrying out the experimental and numerical work. I also extend my thanks to Mr. Amit and Mr. Raju for assisting me with labour work during model tests.

My sincere thanks to my friends and contemporaries, Mrs. Jahnavi Konduru, Ms. Payal Goyal, Dr. Sunita Mishra, Mrs. Mamata Mohanty, Dr. Amit Kumar, Dr. Suresh Kumar, Ms. Aali Pant, Ms. Heena Dhawan, Ms. Kavita Tandon, Ms. Sujata Fulambarkar,

Mrs. Apoorva Agarwal, Mr. Mayuresh Bakare, and Mr. Pranjal Mandhaniya for the support provided during the tenure of this study. I would also like to express my gratitude to all those who have contributed directly or indirectly in the course of my research work.

Last, but certainly not the least, words alone cannot express my deepest gratitude to my parents- Mr. Nitai Charan Bhowmik and Mrs. Jaya Bhowmik, my sisters- Mrs. Rumpa Pal and Dr. Sanghamitra Chatterjee, my brother-in-law Mr. Sanjoy Pal, and my nieces- Srijani and Sreetanuja for their love, constant support, understanding and affection during the tenure of my study that provided me necessary impetus to work on this thesis. It is to my family that this piece of work is gratefully dedicated.

Riya Bhowmik

ABSTRACT

The stability of geosynthetics along slopes in covers and liners of landfills depends partly on their mobilized tensile strength and partly on the efficiency of the anchors holding the geosynthetics at the berms or top of the slope. The pull induced on these geosynthetics in the lining or cover system is in an inclined direction parallel to the slope. But due to difficulty in modelling of inclined pullout behaviour experimentally, very few studies have so far been conducted on geosynthetics embedded in anchor trenches and even these studies are limited to sheet-type geosynthetics. For this purpose, an inclined pullout device was conceptualized and developed during the course of this study. This device can perform pullout tests on geosynthetics at continuously varying inclinations.

Since geogrids are widely used as veneer reinforcement, inclined pullout tests are conducted on geogrids embedded in run-out, I-type and L-type anchors in the sand under low confinement. The influence of the angle of inclination of pullout force on the anchor capacity of the geogrid and the variations in the failure mechanism for different types of anchors have been studied. The inclined pullout behaviour has also been studied for sheet geosynthetic embedded in run-out, I-type and L-type anchors under low confinement and compared with the corresponding behaviour of geogrid. For proper comparison, the surface characteristics of the sheet and the geogrid were kept the same by manually fabricating the sheet. The influence of the type of sand on the behaviour of the sheet and the geogrid is also investigated. The results show that the maximum pullout resistance in both the geogrid and the sheet increases by more than 20% as the pull inclination increases from 0° to 30° in all the three types of anchors. In both the sheet and

the geogrid, I-type anchor provides approximately 50% and L-type anchor provides more than 90% higher pullout force than the run-out anchor.

Model tests have also been conducted to investigate the effectiveness of longitudinal and transverse members of the bitumen-coated polyester-yarn geogrids under low normal stress. The tests compare the pullout behaviour of geogrids with different spacing of longitudinal and transverse members. The results show that the spacing between transverse ribs has very little influence on peak pullout resistance of the geogrids, but the residual pullout resistance increases significantly once the transverse rib spacing is greater than a critical value. Increase in spacing between longitudinal ribs reduces the peak pullout resistance considerably.

The model tests on the inclined pullout of geogrids embedded in three types of anchors have been simulated numerically using three-dimensional finite element analyses software PLAXIS 3D. The soil behaviour is represented by the elastic-perfectly plastic Mohr-Coulomb model and the geogrid behaviour with linear-elastic plate elements. The geogrid is modelled using the geometrical and index properties of the geogrid used in model tests. The results show that the peak pullout force values for different values of inclinations and types of anchors were predicted with reasonable accuracy by the numerical modelling approach used in the study. However, the post-peak response for run-out and I-type anchors and the stiffness in case of trench anchors (I- and L-type anchors) are not satisfactorily modelled.

A design formulation to determine the pullout capacity of geosynthetics embedded in run-out, I-type and L-type anchors in sand is proposed. The accuracy of this method is tested by comparing it with the results of the present study and reported results in the literature.

सार

लैंडफिल के कवर और लाइनर में ढलान के साथ जियोसिंथेटिक्स की संघटित स्थिरता आंशिक रूप से उनकी तन्य शक्ति पर और आंशिक रूप से ढलान के शीर्ष पर जियोसिंथेटिक्स को धारण करने वाले एंकर की दक्षता पर निर्भर करती है। अस्तर या आवरण प्रणाली में इन जियोसिंथेटिक्स पर प्रेरित खिंचाव ढलान के समानांतर एक झुकाव दिशा में आती है। प्रायोगिक रूप से प्रवृत्त पुलआउट व्यवहार के मॉडलिंग में कठिनाई के कारण, अब तक बहुत कम अध्ययनों से लंगर खाई में जियोसिंथेटिक्स पर आयोजित किया गया है और यहां तक कि ये अध्ययन शीट-प्रकार के जियोसिंथेटिक्स तक सीमित हैं। इस उद्देश्य के लिए, इस अध्ययन के दौरान एक प्रवृत्त पुलआउट डिवाइस की अवधारणा और विकास किया गया है । यह उपकरण जियोसिंथेटिक्स पर लगातार अलग-अलग झुकाव पर पुलआउट परीक्षण कर सकता है।

चूंकि जियोग्रिड को व्यापक रूप से लिबास के सुदृढीकरण के रूप में उपयोग किया जाता है, कम खींचा के तहत रेत में रन-आउट, आई-टाइप और एल-प्रकार के एंकर में एम्बेडेड भूगोल पर झुका हुआ पुलआउट परीक्षण किया जाता है। भूगर्भ की लंगर क्षमता पर पुलआउट बल के झुकाव के प्रभाव और विभिन्न प्रकार के लंगर के लिए विफलता तंत्र में भिन्नता का अध्ययन किया गया है। कम खींचतान के तहत रन-आउट, आई-टाइप और एल-टाइप एंकर में एम्बेडेड शीट जियोसिंथेटिक के लिए प्रवृत्त पुलआउट व्यवहार का भी अध्ययन किया गया है और इसकी तुलना जियोग्रिड के संबंधित व्यवहार से की गई है। उचित तुलना के लिए, शीट की सतह की विशेषताओं और जियोग्रिड को शीट को मैन्युअल रूप से तैयार करके समान रखा गया था। शीट के व्यवहार और जियोग्रिड पर रेत के प्रकार के प्रभाव की भी जांच की गई है। परिणाम बताते हैं कि जियोग्रिड और शीट दोनों में अधिकतम पुलआउट प्रतिरोध 20% से अधिक बढ़ जाता है क्योंकि सभी तीन प्रकार के एंकरों में पुल झुकाव 0 ° से 30 ° तक बढ़ जाता है। शीट और जियोग्रिड दोनों में, आई-टाइप एंकर लगभग 50% प्रदान करता है और एल-टाइप एंकर रन-आउट एंकर की तुलना में 90% अधिक पुलआउट बल प्रदान करता है।

कम सामान्य तनाव के तहत बिटुमेन-लेपित पॉलिएस्टर-यार्न जॉग्रिड्स के अनुदैर्ध्य और अनुप्रस्थ सदस्यों की प्रभावशीलता की जांच के लिए मॉडल परीक्षण भी किए गए हैं। परीक्षण अनुदैर्ध्य और अनुप्रस्थ सदस्यों के विभिन्न रिक्ति के साथ जियोग्रिड्स के पुलआउट व्यवहार की तुलना करते हैं। परिणाम बताते हैं कि अनुप्रस्थ पसलियों के बीच रिक्ति का जियोग्रिड्स के पीक पुलआउट प्रतिरोध पर बहुत कम प्रभाव पड़ता है, लेकिन एक बार जब ट्रांसवर्स रिब रिक्ति एक महत्वपूर्ण मूल्य से अधिक होती है, तो अवशिष्ट पुलआउट प्रतिरोध बढ़ जाता है। अनुदैर्ध्य पसलियों के बीच रिक्ति में वृद्धि शिखर पुलआउट प्रतिरोध को काफी कम कर देती है।

तीन प्रकार के एंकरों में एम्बेडेड ज्योग्रिड्स के प्रवृत्त पुलआउट पर मॉडल परीक्षणों को तीन आयामी परिमित तत्व विश्लेषण सॉफ्टवेयर PLAXIS 3D का उपयोग करके संख्यात्मक रूप से अनुकरण किया गया है। मृदा व्यवहार लोचदार-पूरी तरह से प्लास्टिक मोहर-कूलम्ब मॉडल और रेखीय-लोचदार प्लेट तत्वों के साथ भूगर्भिक व्यवहार द्वारा दर्शाया गया है। जियोग्रिड को मॉडल परीक्षणों में उपयोग किए जाने वाले जियोग्रिड के ज्यामितीय और सूचकांक गुणों का उपयोग करके मॉडल किया गया है। परिणामों से पता चलता है कि झुकाव के विभिन्न मूल्यों और तीन प्रकार के एंकरों के लिए शिखर पुलआउट बल मूल्यों का अध्ययन में उपयोग किए गए संख्यात्मक मॉडलिंग दृष्टिकोण द्वारा उचित सटीकता के साथ भविष्यवाणी की गई थी। हालांकि, रन-आउट और आई-टाइप एंकर के लिए पोस्ट-पीक प्रतिक्रिया और ट्रेंच एंकर (आई- और एल-टाइप एंकर) के मामले में कठोरता संतोषजनक ढंग से मॉडलिंग नहीं की गई है।

रन-आउट, आई-टाइप और एल-टाइप एंकर में रेत में एम्बेडेड जियोसिंथेटिक्स की पुलआउट क्षमता निर्धारित करने के लिए एक डिजाइन प्रस्तावित किया गया है। इस पद्धति की सटीकता को वर्तमान अध्ययन के परिणामों और साहित्य में रिपोर्ट किए गए परिणामों के साथ तुलना करके परीक्षण किया गया है।

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1D	One-Dimensional (analysis)
2D	Two-Dimensional (analysis)
3D	Three-Dimensional (analysis)
A	Area of the Particle
ASTM	American Society for Testing and Materials
AT	Anchor Trench
B	Width of the Anchor Trench
B_g	Width of the geosynthetic reinforcement in anchor
BS	Badarpur Sand
c	Cohesion intercept of soil
c_A	Adhesive force between cover soil of the active wedge and the geosynthetic
C_c	Coefficient of Curvature of particle size distribution of soil
CCL	Compacted Clay Liner
CSPE-R	Reinforced Chlorosulfonated Polyethylene
C_u	Coefficient of Uniformity
d	Thickness of the 'Plate' element in PLAXIS
D	Depth of Anchor Trench
D_{10}	Particle size (diameter) at which 10 percent of the soil is finer
D_{50}	Particle size (diameter) at which 50 percent of the soil is finer
D_{85}	Particle size (diameter) at which 85 percent of the soil is finer
DEG	Degree of Inclination of Pullout Force

DEM	Discrete Element Method
E	Young's modulus
E_A	Inter-wedge force acting on active wedge from passive wedge
E_P	Inter-wedge force acting on passive wedge from active wedge
ERF	Enhanced Resisting Force
f_b	The bond coefficient between soil and geosynthetic
FEA	Finite Element Analysis
FEM	Finite Element Method
FS	Factor of Safety
GCL	Geosynthetic Clay Liner
GG1 model	Numerical model in which the longitudinal ribs of the geogrid are modelled with axial element and the transverse ribs of the geogrid are modelled with bending element.
GG2 model	Numerical model in which both the longitudinal ribs and transverse of the geogrid are modelled with bending element.
GG-E	Experimental peak pullout resistance of geogrid
GG-GS-P	Predicted peak pullout resistance of geogrid using general failure mechanism
GG-LS-P	Predicted peak pullout resistance of geogrid using Prandtl local shear failure mechanism
GG-mPS-P	Predicted peak pullout resistance of geogrid using modified punching failure mechanism
GG-PS-P	Predicted peak pullout resistance of geogrid using punching failure mechanism
GM	Geomembrane
H	Thickness of overburden
H:V	Horizontal: Vertical indicating inclination of slope

H’	Height between berms
HDPE	High-Density Polyethylene
HS	Hullings and Sansone (1998) method
ISA	Infinite slope analysis method
J	Secant modulus of the geosynthetic in kN/m
J*	Ratio of the reinforcement stiffness to the axial pullout capacity
k	Coefficient of Permeability, m/s
K_a	Coefficient of active earth pressure
K_o	Coefficient of earth pressure at rest
Koe	Koerner (2005) method
K_p	Coefficient of passive earth pressure
K_1	Weighting Coefficient for increase in slip resistance at bends for inclination < 90° in run-out anchor
K_2	Weighting Coefficient for increase in slip resistance at bends for inclination = 90° in I-type anchor
K_3	Weighting Coefficient for increase in slip resistance at bends for inclination = 90° in L-type anchor
K_{new}	Weighting Coefficient for increase in slip resistance at bends in proposed design formulation
L	Run-out length of the reinforcement
L_r	Total length of the geosynthetic in anchors
L-ribs	Longitudinal ribs of geogrid
LT-specimens	Specimens in which the spacing between both longitudinal and transverse ribs is varied simultaneously.
M_1	Modification factor for weighting coefficient K_1
M_2	Modification factor for weighting coefficient K_2

M_3	Modification factor for weighting coefficient K_2 and K_3
M	Modification factor for weighting coefficient in the proposed design formulation
N	Effective force normal to the failure plane
N_A	Normal effective force of active wedge
N_P	Normal effective force of passive wedge
P	Perimeter of the Particle
$P_{r\text{-}bottom}$	Interface shear resistance at the bottom of the geosynthetic during pullout
P_{rg}	Pullout resistance of geogrids
P_{rgb}	Bearing resistance at the transverse ribs of the geogrid
P_{rs}	Pullout resistance of sheet
$P_{r\text{-}sides}$	Frictional resistance on the back and sides of the geosynthetic during pullout
PVC	Polyvinyl Chloride
QKG	Qian et al. (2002) method
RAM	Random Access Memory
Res.	Residual pullout resistance of geosynthetic
R_{inter}	Strength-reduction factor used to model the behaviour of interface elements in PLAXIS.
RO	Run-out
S	Spacing between transverse ribs of the geogrid
Sheet-E	Experimental peak pullout resistance of sheet
Sheet-P	Predicted peak pullout resistance of sheet
SP	Poorly graded sand
t	Thickness of cover soil, m

T	Long-term Design Strength of Geosynthetics, in kN/m
T1	Anchorage Capacity of veneer reinforcement
$T_{Experiment}$	Pullout capacity of the anchor obtained from model test
t_g	Thickness of the transverse rib of the geogrid
T-ribs	Transverse ribs of geogrid
VC	Villard and Chareyre (2004) method
VC-i	Villard and Chareyre (2004) method when pullout failure occurs at the interface
VC-s	Villard and Chareyre (2004) method when pullout failure occurs in soil
VFPE	very flexible polyethylene
W	Weight of cover soil
W_A	Weight of active wedge
W_P	Weight of passive wedge
YS	Yamuna Sand
α_b	Total frontal area available for bearing resistance
α_s	Fraction of geogrid solid area
β	Inclination of Slope
γ	Unit Weight of Soil
δ	Angle of shearing resistance at the soil-geosynthetic or geosynthetic-geosynthetic interfaces
ν	Poisson's ratio
σ_b	Bearing stress mobilized on transverse ribs
σ_n	Normal stress on the reinforcement
ϕ	Angle of shearing resistance of soil
ψ	Dilatancy angle