

**BEHAVIOR OF STONE COLUMN FOUNDATION UNDER PLANE STRAIN
CONDITION SUBJECTED TO MONOTONIC AND CYCLIC LOADING**

SURESH KUMAR



**DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
SEPTEMBER 2018**

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by

SURESH KUMAR

Department of Civil Engineering

Submitted

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

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

HAUZ KHAS, NEW DELHI-110016, INDIA

SEPTEMBER 2018

To
My Parents

CERTIFICATE

This is to certify that the thesis entitled “**BEHAVIOR OF STONE COLUMN FOUNDATION UNDER PLANE STRAIN CONDITION SUBJECTED TO MONOTONIC AND CYCLIC LOADING**” being submitted by **Mr. Suresh Kumar** to the **Indian Institute of Technology Delhi** is a record of bonafide research work carried out by him under my supervision and guidance. The thesis work, in my 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.

Dr. J.T. Shahu

Professor

Department of Civil Engineering
Indian Institute of Technology Delhi
Hauz Khas, New Delhi-110016
INDIA

ACKNOWLEDGEMENTS

I express my sincere gratitude and indebtedness towards my respected guide **Prof. J. T. Shahu**, Professor, Department of Civil Engineering, Indian Institute of Technology, Delhi, for his invaluable guidance, cooperation, encouragement and for providing all assistance required for the completion of this work. His painstaking efforts in going through the manuscript and giving suggestions for its improvement are gratefully acknowledged.

I express my sincere thanks to Student Research Committee members, namely, Prof. K. C. Iyer, Dr. Bappaditya Manna and Prof. B. P. Patel for their suggestions and support during the entire period of my research work.

I extend my thanks to Soil and Rock Mechanics Laboratory staff members, namely, Mr. Manoj Kumar Neelam and Mr. D. S. Gusain for their help in conducting the experimental work. I am also thankful to the contract workers, Mr. Rajendra, Mr. Ram Janam, Mr. Ramesh, Mr. Danji and Mr. Sandeep for their help in preparing the huge quantity of soft soil for model testing.

My special gratitude is due to Prof. R. Sanghal, Director, Indian Institute of Technology (Banaras Hindu University), Varanasi, for his constant motivation and encouragement during the Ph.D. work. I am also thankful for his full support in sanctioning the extension of study leave. I express my sincere gratitude to the Indian Institute of Technology (Banaras Hindu University) administration for granting study leave and extensions, whenever needed, without any problem.

It is a pleasure to acknowledge the support extended by my friends, namely, Prof. Kausar Ali, Dr. L. S. Sowmiya, Dr. Shantanu Patra, Dr. Amit Kumar, Mr. Nidal and Ms. Mamata Mohanty during this research work. I would 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, I acknowledge and record my deep sense of love and gratitude to my wife, Sonal Nupur Modi; daughter, Aditi Barnwal; and son, Aayansh Barnwal; for their affection, continuous encouragement, and moral and emotional support during the entire research programme.

(SURESH KUMAR)

ABSTRACT

Stone column installation is one of the most commonly used and worldwide accepted ground improvement techniques. This technique is used to provide support to lowrise structures and transportation routes to be constructed on soft soils that can tolerate some settlement. However, in case of very soft soils, ordinary stone columns fail due to excessive lateral deformation (bulging) due to insufficient confinement provided by the surrounding soil. Stone columns in such soils can be strengthened against bulging by encasement with geosynthetic material.

Most of the transportation routes are subjected to cyclic loading. However, presently neither proper guidelines nor specifications are available in literature regarding the design and construction of stone columns considering cyclic loading. Relative improvement in settlement response of stone column foundations subjected to monotonic and cyclic loading needs to be evaluated as a first step in this direction. The response should be studied for both ordinary and encased group of stone columns. For proper simulation, the response should be investigated under plane strain condition relevant to transportation route applications.

In the present study, small scale model tests on groups of long, floating and end-bearing, ordinary and encased, stone columns of 30 mm, 40 mm and 60 mm diameter installed in very soft clay with different undrained shear strength are performed. The effect of important parameters, like area replacement ratio, length and diameter of stone columns and encasement length of the geogrid, etc., on performance of the improved ground is evaluated by performing a total of 40 model tests under monotonic and cyclic loading. The results under different loading conditions are presented in the form of bar chart, to assess the settlement of composite ground improved with identical ordinary and encased floating and end bearing group column

foundations. Finally, three-dimensional, elasto-plastic, finite element analyses of model stone column group foundation, under monotonic loading are carried out using a commercially available Midas GTS software. These analyses are used to determine the settlement of ordinary and encased stone column group foundation, to confirm the findings of the model tests.

It is shown that the ultimate failure stress of the ground improved with fully encased floating and end bearing stone columns, under monotonic loading, increase with the increase in undrained shear strength of the soil. Under monotonic loading, the ground improved with fully encased stone columns, both floating as well as end-bearing types, yields higher equivalent bearing capacity factor compared to corresponding ordinary stone column group foundation. The cumulative settlement reached after 500 load cycles under cyclic loading was 92-79% of the settlements at failure under monotonic loading for ordinary stone columns depending upon the undrained shear strength of soil. The corresponding settlement under cyclic loading reduces to 44-20% for full length geogrid encased floating columns. For both encased floating and end-bearing columns, the cumulative settlements reached in 500 load cycles at maximum applied stress of 22.4 kPa vary between 4 to 7 times the corresponding settlements during monotonic loading at the same value of applied stress.

सार

स्टोन कॉलम इंस्टॉलेशन सबसे अधिक इस्तेमाल और दुनिया भर में स्वीकृत ग्राउंड सुधार तकनीकों में से एक है। इस तकनीक का उपयोग नरम मिट्टी पर बनाए जाने वाले लोअर संरचनाओं और परिवहन मार्गों को समर्थन प्रदान करने के लिए किया जाता है जो कुछ निपटारे को सहन कर सकते हैं। हालांकि, बहुत नरम मिट्टी के मामले में, आस-पास की मिट्टी द्वारा प्रदान की गई अपर्याप्त बंधन के कारण अत्यधिक पार्श्व विरूपण (उभरा) के कारण सामान्य पत्थर स्तंभ विफल हो जाते हैं। भू-संश्लेषक सामग्री के साथ ईन्केशमेन्ट द्वारा उभरा के खिलाफ ऐसी मिट्टी में पत्थर स्तंभों को मजबूत किया जा सकता है।

अधिकांश परिवहन मार्ग चक्रीय लोडिंग के अधीन हैं। हालांकि, वर्तमान में न तो उचित दिशा-निर्देश और न ही चक्रीय लोडिंग पर विचार करते हुए पत्थर के स्तंभों के डिजाइन और निर्माण के संबंध में साहित्य में विनिर्देश उपलब्ध हैं। मोनोटोनिक और चक्रीय लोडिंग के अधीन पत्थर कॉलम नींव के निपटारे की प्रतिक्रिया में सापेक्ष सुधार इस दिशा में पहले चरण के रूप में मूल्यांकन किया जाना चाहिए। पत्थर स्तंभों के सामान्य और संलग्न समूह दोनों के लिए प्रतिक्रिया का अध्ययन किया जाना चाहिए। उचित सिमुलेशन के लिए, परिवहन मार्ग अनुप्रयोगों के लिए प्रासंगिक विमान तनाव की स्थिति के तहत प्रतिक्रिया की जांच की जानी चाहिए।

वर्तमान अध्ययन में, लंबे, तैरने वाले और अंत-असर वाले समूहों पर छोटे पैमाने पर मॉडल परीक्षण, सामान्य और घुमावदार, ३० मिमी, ४० मिमी और ६० मिमी व्यास के पत्थर स्तंभ बहुत ही कम कतरनी शक्ति के साथ बहुत मुलायम मिट्टी में स्थापित किए जाते हैं। बेहतर मानकों के प्रभाव पर क्षेत्रीय प्रतिस्थापन अनुपात, लंबाई और व्यास के पत्थर कॉलम और भूगर्भीय की समाप्ति लंबाई आदि के महत्वपूर्ण मानकों का प्रभाव मोनोटोनिक और चक्रीय लोडिंग के तहत कुल ४० मॉडल परीक्षण करके मूल्यांकन किया जाता है। अलग-अलग लोडिंग स्थितियों के तहत परिणाम समान सामान्य और घुमावदार फ्लोटिंग और अंत असर समूह कॉलम नींव के साथ मिश्रित समग्र जमीन के निपटारे का आकलन करने के लिए बार चार्ट के रूप में प्रस्तुत किए जाते हैं। अंत में, मॉडल-पत्थर कॉलम समूह नींव के मॉडल-

पत्थर स्तंभ समूह नींव के त्रि-आयामी, इलास्टो-प्लास्टिक, परिमित तत्व विश्लेषण, व्यावसायिक रूप से उपलब्ध मिडास जीटीएस सॉफ्टवेयर का उपयोग करके किए जाते हैं। मॉडल विश्लेषणों के निष्कर्षों की पुष्टि करने के लिए, इन विश्लेषणों का उपयोग सामान्य और घुमावदार पत्थर स्तंभ समूह नींव के निपटारे को निर्धारित करने के लिए किया जाता है।

यह दिखाया गया है कि जमीन के अंतिम विफलता तनाव पूरी तरह से अस्थायी फ्लोटिंग और अंतराल पत्थर कॉलम के साथ, मोनोटोनिक लोडिंग के तहत, मिट्टी की अनियंत्रित कतरनी शक्ति में वृद्धि के साथ वृद्धि हुई है। मोनोटोनिक लोडिंग के तहत, ग्राउंड फ्लोटिंग के साथ-साथ अंत-असर वाले प्रकारों के साथ पूरी तरह से समेकित पत्थर कॉलम के साथ जमीन में सुधार हुआ, इसी सामान्य पत्थर कॉलम समूह नींव की तुलना में उच्च समकक्ष असर क्षमता कारक पैदा करता है। चक्रवात लोडिंग के तहत ५०० लोड चक्रों के बाद संचयी निपटान पहुंच गया था, जो मिट्टी की अनियंत्रित कतरनी शक्ति के आधार पर साधारण पत्थर स्तंभों के लिए मोनोटोनिक लोडिंग के तहत विफलता पर ९२-७९% बस्तियों का था। चक्रीय लोडिंग के तहत संबंधित निपटान पूर्ण लंबाई भूगर्भकृत फ्लोटिंग कॉलम के लिए ४४-२०% तक कम हो जाता है। दोनों घुमावदार फ्लोटिंग और एंड-असर कॉलम के लिए, २२.४ केपीए के अधिकतम लागू तनाव पर ५०० लोड चक्रों में संचयी बस्तियों में लागू तनाव के समान मूल्य पर मोनोटोनिक लोडिंग के दौरान संबंधित निपटान ४ से ७ गुना के बीच भिन्न होता है।

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LIST OF NOTATIONS

2D	two-dimensional
3D	three-dimensional
A	total area within the unit cell
A_c	area of cohesive soil within the unit cell
A_r	area replacement ratio
B	foundation width
C_1	Constant
c	Cohesion of the surrounding soil
c_{avg}	Average cohesion on the shear surface
c_u	undrained shear strength within the unreinforced cohesive soil
D_e	equivalent diameter of stone column
D_r	relative density
d_{50}	effective size of particles for 50%
d	diameter of stone column
E	Young's modulus
EN(GG)	encased with geogrid
E_s	modulus of elasticity of stone chips
e_o	initial void ratio
FEM	finite element analysis
FHWA	Federal Highway Administration
F'_c, F'_q	Vesic cavity expansion factors
G	shear modulus
GTS	geotechnical and tunnel analysis system
GUI	graphic user interface

H	thickness of layer
HDPE	high-density polyethylene
I_p	plasticity index
J	secant stiffness of the geosynthetics
k	coefficient of permeability
K_o	average coefficient of lateral earth pressure
K_p	coefficient of passive earth pressure
k_{pc}	passive earth pressure coefficient of stone column
l	length of stone column
m_v	modulus of volume compressibility
$N_c, N_\gamma,$ N_q	dimensionless factors
n	stress concentration factor
PP	polypropylene
PST	polyester
PVC	polyvinyl chloride
q	mean stress within the zone of failure
q_s	bearing capacity of soft soil expressed as $(2/3) C_o N_c$
q_{ult}	ultimate bearing capacity
$(q_{ult})_g$	ultimate bearing capacity of group columns
R	settlement reduction factor
r	radius of stone column
S	settlement of unimproved ground
S_g	settlement of stone column group
S_t	settlement of composite ground
S_u	settlement of unit cell
S_o	settlement of unimproved ground

S_1	settlement of single granular pile
s	center-to-center spacing of the granular piles
t	thickness of the geosynthetics
W	width of equivalent granular pile strip
w_L	liquid limit
w_P	plastic limit
x	length of reinforced part of the column
z	depth from surface of composite foundation
β	failure surface inclination
δ	settlement of footing
ϕ	friction angle
ϕ_{avg}	composite angle of internal friction
γ	effective unit weight of soil within the influence zone
γ_c	saturated (wet) unit weight of the cohesive soil
γ_{dmax}	dry density corresponding to densest state
γ_{dmin}	dry density corresponding to loosest state
γ_{sat}	saturated unit- weight of the cohesive soil
γ_{sub}	submerged unit- weight
Δp	applied intensity of loading
ν	Poisson's ratio
μ_c	ratio of the stress in clay to average stress
μ_{gp}	ratio of the stress in stone column to average stress
θ	vertical angle of sliding surface at each sand pile
ρ_{max}	settlement corresponding to p_{max}
σ	vertical stress
σ_c	stress in the surrounding cohesive soil

σ_{gp}	stress in the granular pile
σ'_n	normal stress
σ_{ro}	initial radial stress along the granular pile
σ_v	applied vertical stress
σ_{vm}	past maximum past consolidation pressure
σ_{vo}	geostatic stress
σ'_1	effective major principal stress
σ'_2	effective intermediate principal stress
σ_3	minor principal stress
σ'_3	effective minor principal stress
τ_f	shear stress at failure
ψ	dilatancy angle