BEHAVIOR OF GEOPOLYMER STABILIZED DEEP MIX COLUMN FOUNDATION IN SOFT SOIL UNDER STATIC AND CYCLIC LOADING

Thesis submitted in partial fulfilment for the

Award of Degree

Doctor of Philosophy

By

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SON AYAANSH, HUSBAND,

AND FAMILY.

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ABSTRACT

In fast-growing economies like India, there is a significant demand for large-scale infrastructure projects. The Government of India (GOI) has initiated extensive plans to establish bullet trains, or high-speed rail (HSR) routes, that connect important cities and regions. These initiatives are essential for accelerating the nation's economic growth and development. Furthermore, GOI has started Bharatmala Pariyojana as one of the most extensive road infrastructure development programs, aiming to construct and upgrade about 34,800 km of National Highway. The project includes the development of economic corridors, inter-corridors, feeder routes, coastal and port connectivity roads, and border roads to improve connectivity and facilitate freight movement. Therefore, there is a requirement to construct more embankments, even over soft soil, to satisfy the demand for rapid construction of railways, highways, and expressways in India.

The construction of an embankment over soft soil requires implementing suitable ground improvement techniques to enhance the bearing capacity and stability of the ground beneath the embankment. Among numerous ground improvement techniques, deep soil mixing (DSM) has proven to improve the bearing capacity and reduce the settlement of soft or very soft soils. The deep soil mixing method of soft ground reinforcement has been used worldwide for several reasons, such as reducing settlements and increasing stability of the highway and railway embankments built over soft soils, enhancing the earthquake resilience of civil infrastructures, short realization time, and significant cost savings over alternative methods.

Traditionally, Ordinary Portland Cement (OPC), lime, or a mix of OPC and lime in either dry powder or slurry form, has been used as a binder in the DSM method.

However, a considerable portion of natural resources and energy are exploited/utilized during cement production, releasing about 8-10% of the anthropogenic CO_2 into the atmosphere. Geopolymer, also called "green cement," provides the strength and durability required for engineering applications and can potentially replace OPC completely with a lower carbon footprint.

Moreover, moving vehicles cause cyclic loading on embankments that support roads, highways, trains, and other transportation infrastructure. The repetitive vehicle movement produces cyclic stress and strain variation in the subgrade, which can lead to fatigue and deformation over time. However, proper guidelines and specifications regarding the performance of deep soil mix columns under cyclic loads are not available in the literature.

Considering these two objectives, this study presents a novel approach to addressing two important challenges in environmental sustainability and geotechnical engineering. An attempt has been made to study the efficacy of ground granulated blast furnace slag (S) and dolomite (D)-based geopolymer with sodium hydroxide (NH) and sodium silicate (NS) as an alkali activator to stabilize soft soil for DSM technique. The optimum mix proportion of geopolymer was obtained by analyzing the various parameters that affect the strength improvement of geopolymer stabilized soil, such as the effect of precursor content, GGBS-dolomite ratio, NH:NS ratio, water content of kaolin clay, alkali activator/precursor (L/P) ratio and curing time using unconfined compressive strength (UCS) tests and consolidated undrained static and cyclic triaxial tests, and the microstructural analysis was done using scanning electron microscopy (SEM) and Fourier transform infrared spectroscopy (FTIR) test. The optimum mix was determined to consist of an 8M NaOH concentration, a 25:75 NH:NS ratio, a 16:4 S:D ratio (precursor/kaolin clay = 20%), and a 1 L/P ratio. Furthermore, the findings of the toxicity characteristic leaching procedure (TCLP) test showed that the concentration of leached heavy metals in dolomite, GGBS, and GGBS-dolomite-based geopolymer was below the USEPA (U.S. Environmental Protection Agency) limit.

A set of 1-g physical model tests have been conducted to examine the behavior of a single geopolymer-stabilized soil column (GPSC) as a DSM column in soft soil ground treatment under static and cyclic loading. Moreover, a series of tests have been carried out on the reduced-scale designed embankment model resting on soft soil (c_{us} = 5-5.5 kPa) reinforced with end-bearing and floating GPSCs with different area replacement ratios (A_r) to analyze the vertical stress-settlement behavior and failure pattern of the improved ground under static and cyclic loading. During the test, measurements were taken for surface settlement, excess pore water pressure, and the stresses on both the GPSC and the surrounding soil.

The main findings indicate that both end-bearing and floating GPSCs enhanced the ultimate bearing capacity and stiffness of the composite soft ground. End-bearing GPSCs were more effective than floating GPSCs at the same A_r under static and cyclic loading. For installing floating GPSCs, a higher area replacement ratio is required for better load bearing under static and cyclic loading. In the end-bearing case, GPSC failed due to shearing and bending, whereas in the floating columns, punching with slight outward displacement and horizontal cracks in GPSCs was observed. A general expression of N_c was developed for GPSCs improved soil under the embankment with variation in A_r and length of column (l/h) ratio, which was valid for A_r ranging between 12.7% to 21.2%, the l/h ratio between 0.75 to 1 for soil with undrained shear strength of 5-5.5 kPa. Under the same vertical stress conditions, the ground improved with both end-bearing and floating GPSCs exhibited 1.11 to 1.68 times greater settlement under 10,000 cycles of cyclic loading compared to static loading.

In addition, a life cycle assessment of geopolymer in comparison to OPC was performed, showing that geopolymer is a sustainable and eco-friendly construction material. A three-dimensional finite element analysis of embankment model tests on soft ground improved with soil-geopolymer deep mix columns under static loading has been conducted to validate the measured embankment model test results using PLAXIS 3D software.

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NOTATIONS AND ABBREVIATIONS

NOTATIONS

English symbols

A_c	Cross-section area of the column
A_r	Area replacement ratio
B	Width of the footing
C	Cement content
c_a	Unit skin friction resistance along the column
c_{av}	Average shear strength along the assumed failure surface
c_{uc}	Undrained shear strength of the column
c_{us}	Undrained shear strength of the soil bed
c_v	Co-efficient of consolidation
d	Diameter of the column
D	Number of days
e_o	Natural void ratio
E_{50}	Modulus of elasticity
f	Cyclic loading frequency
G	Dynamic shear modulus
G_{max}	Maximum dynamic shear modulus
G_s	Specific gravity
Hc	Height of the group of columns
h	Height of soft soil ground

I_p	Plasticity index
k_c	Cohesion ratio
l	Length of the column
l_1, l_2	Center-to-center spacing between deep mix column
Nc	Bearing capacity factor
N	Number of cycles
n	Stress concentration ratio
P_{max}	Maximum excess pore water pressure
q_c	Cyclic stress
q_u	Undrained shear strength
$q_{ult, soil}$	Ultimate bearing capacity of a single column at soil failure
$q_{ult, col}$	Ultimate bearing capacity at column failure
q_{ult}	Ultimate bearing capacity of the composite ground
Q_f	Creep load
Δq_{cyc}	Variable deviatoric stress
S_f	Scaling factor
V_f	Foundation velocity
V	Normalized velocity
w	Water content
w_l	Liquid limit
w_p	Plastic limit
w_c	Clay water content

Greek symbols

σ_c	Vertical stress on the column
σ_c'	Effective confining pressure
σ_h	Earth pressure acting on the column
σ_s	Vertical stress on the surrounding soil
σ_v	Total overburden pressure
γ_d	Dry unit weight
ν	Poisson's ratio
θ	Angle of arrangement of DSM column
ϕ	Angle of internal friction
β	Depth improvement ratio
λ	Damping ratio
Υ	Shear strain developed during cyclic loading
Υ_r	Reference strain

ABBREVIATIONS

CP	Confining pressure
CSR	Cyclic stress ratio
DSM	Deep soil mixing
EB	End-bearing
EDS	Energy-dispersive X-ray spectroscopy
EP	Earth pressure cell
FEA	Finite element analysis
FL	Floating
FTIR	Fourier Transform Infrared Spectroscopy

GOI	Government of India
GGBS	Ground granulated blast furnace slag
GPSC	Geopolymer-stabilized soil column
L	Liquid alkali activator
NH	Sodium hydroxide
NS	Sodium silicate
USCS	Unified soil classification system
UCS	Unconfined compressive strength
OMC	Optimum moisture content
OPC	Ordinary Portland cement
P	Precursor or binder
PPT	Pore pressure transducer
SEM	Scanning Electron Microscopy
SCR	Stress concentration ratio
TCLP	Toxicity Characteristic Leaching Procedure