Parametric Study on Dynamic Characterization of Homogeneous and Stratified Soil-Ash Deposit under Low-Strain and High-Strain Conditions

Thesis submitted in partial fulfillment

for the Award of Degree

Doctor of Philosophy

by

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18061002 ***June 2023***

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I, **AMIT KUMAR RAM,** certify that the work embodied in this thesis is myown bonafide work and carried out by me under the supervision of **Dr. SUPRIYA MOHANTY** from **July 2018** to **June2023** at the **Department of Civil Engineering, Indian Institute of Technology, (BHU) Varanasi**. The matter embodied in this thesis has not been submitted for the award of any other degree/diploma. I declare that I have faithfully acknowledged and given credits to the research workers wherever their works have been cited in my work in this thesis. I further declare that I have not willfully copied any other's work, paragraphs, text, data, results, *etc*., reported in journals, books, magazines, reports dissertations, thesis, *etc*., or available at websites and included them in this thesis and cited as my own work.

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THIS THESIS IS DEDICATED TO MY PARENTS

For their endless love, devotion, support, and inspiration

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ABSTRACT

The energy is the driving force of human inventions which make our day to day activities easier and effortless. The outmost demand of the energy compels us for the exertive utilization of the fossil fuel (coal, oil, natural gas) in order to meet the demand. Among all the fossil fuel available, the coal is the most abundantly available fossil fuel in India. Because of its availability and reasonable cost, it has been primarily utilized for the electricity production followed by steel & iron industries and cement & chemical industries. In India, the production of coal in the year 2021-22 was found to be 778.19 million tonnes (MT) which was increased by 8.67% as compared to the previous year. Also, the ash content potential of the Indian coal is around 35-45%. Taking this ash content percentage into account, the total amount of coal ash produced must be between 272.37 to 350.19 MT in the year 2021-22 and this is projected to cross 1000 MT by the upcoming decades. These generated coal ashes consist of a higher percentage of fly ash than that of the bottom ash, i.e., approximately 70-80%. In India, the amount of fly ash produced over a period of 25-year is approximately 3335.9 MT, of which only 55% (1834.83 MT) have been used and the remaining 45% (1501 MT) is still in their unutilized form. The generated ash usually dumped in slurry form near to the thermal power plant that causes scarcity of the valuable agricultural land. The dependency on the non-renewable energy resources will take another 2-3 decades to eliminate considering the current rate of development of the renewable resources.

The production of large amounts of coal ash and its land requirements for disposal is an alarming situation for the present scenario. Also, the very limited

fraction of it has been utilized in different sectors like cement, brick, soil stabilization, mine filling etc. Its bulk utilization is the major point of concern and that can only be possible by broadening its application area such as; embankment fill material, subgrade/sub-base material, foundation material for construction etc. Before this material can be used in bulk in fields as geomaterials in structures, it is important to check the behaviour of the considered material under realistic loading conditions (monotonic or dynamic). Contributing to this objective, a comprehensive experimental program has been planned in the present study.

In the present study, an attempt has been made to examine the insight behaviour of the fly ash and local soil collected from Renukoot (U.P), India and IIT(BHU), Varanasi campus respectively. Also, the implementation of coal ashes is generally done over the existing soil and follows the stratification of multiple layers. In order to simulate the realistic field condition, the interaction between the fly ash and local soil has also been investigated in the stratified form. Furthermore, along with the comprehensive physical, geotechnical, and chemical assessment, the dynamic behaviour of the homogeneous and stratified soil-ash deposits have been examined under large and small-strain conditions. A set of 105 strain-controlled cyclic triaxial test were performed under consolidated undrained conditions for dynamic behaviour and liquefaction study. In addition, the influence of independent parameters such as relative compaction, frequency of loading, effective confining pressure, shearing strain has been incorporated for the wider assessment of the shear modulus (G) and damping ratio (D) of the material. Furthermore, normalized modulus reduction and damping ratio curves of all the homogeneous and stratified soil-ash deposits have been plotted using the results of the cyclic triaxial and bender element tests.

The present fly ash contains a higher fraction of sand (61.52%) size particles followed by silt (33.19%) and clay (5.29%). Similarly, local soil is composed of maximum silt (81.77%) size particles followed by clay (16.11%) and sand (2.12%). Since, both the soils are satisfying the desirable condition of well graded soil, hence classified as well graded silty sand (fly ash) and silt of intermediate plasticity (local soil). In the same way, the outcome of the standard Proctor test shows that local soil has higher maximum dry density and lower optimum moisture content and vice-versa for fly ash. Also, significant improvement in the shear strength parameters of the considered local soil through a soil-waste layered system was observed in the saturated drained and undrained condition. From the dynamic study, the stratified soil-ash shows higher shear modulus than that of the fly ash and local soil for a shear strain of 0.3% & 0.6% and beyond 0.6%, it shows the comparable shear modulus as compared to the homogeneous one. Similarly, the damping ratio of the stratified soil-ash and local soil is slightly higher than that of the other soil, although the damping ratio of the fly ash is equivalent to that of the sand and clayey soil. Based on the results, it is highly recommended to use the asymmetric hysteresis loop (ASHL) approach, especially under large strain conditions irrespective of the soil type. In addition, the liquefaction assessment using energy method reveals that the energy required for liquefaction is dependent on all the considered parameters, whereas it is independent of the cycle needed to liquefy. From the experimental investigation, this can be concluded that the stratified soil-ash deposit shows enhancement in shear strength parameters (cohesion: 55-69 kPa & internal friction: 25-35°) and CBR value (Unsoaked: 13-30% and Soaked: 1.5-4.5%). Similarly, it shows high dynamic shear modulus (G: 2-8 MPa) that ultimately improve the liquefaction resistance. In the same way, the stratified soil exhibits reduction in pavement thickness as compared to local soil. But with geosynthetic reinforcement a significant reduction in pavement thickness between 19-32% has been observed for different traffic loading conditions. According to the performance, this layered arrangement can be recommended as a subgrade or fill material under moderate seismic conditions.

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NOMENCLATURE

ε - Axial strain

ρ - Bulk mass density

υ - Poisson's ratio

η - Porosity

λ - Wavelength

°C – Degree Celsius

γ_d – Dry unit weight

°F – Fahrenheit

μm – micrometre

ΔW – Dissipated energy

3D – Three dimensional

Å – Angstrom

AASHTO- American association of state highway and transportation officials

A_L - Area of hysteresis loop

Al_2O_3 – Aluminum oxide

AMD – Arithmetic mean diameter

ASHL - Asymmetric hysteresis loop

ASTM - American Society for Testing and Materials

B – Width

B - Skempton's pore pressure parameter

BA – Bottom ash

BC – Bituminous course

BE- Bender element

c' – Effective cohesion

c - Cohesion

CBR - California bearing ratio test

CC – Cross correlation

CD - Consolidated drained

CIF – Central instrumental facility

CO_2 – Carbon dioxide

CP – Confining pressure

CPT- Cone penetration test

CSH – Calcium silicate hydrate

CSIR- IMMT - Institute of Minerals and Materials Technology Council of Scientific and Industrial Research

CSM – Cement stabilized macadam

Cu – Coefficient of uniformity

CU - Consolidated undrained

D – Damping ratio

D – Depth

DBM – Dense bound macadam

E – East

E – Young's modulus

EDX - Energy dispersive x-ray

E_{eq} – Equivalent modulus

E_i - Initial tangent modulus

E_s – Secant modulus

ESP - Electrostatic precipitator

f – frequency

FA – Fly ash

FAM – Fly ash mission

Fe_2O_3 – Iron oxide

FVD – Free vibration decay

G – Dynamic shear modulus

g/cc – Gram per cubic centimetre

G/G_{max} – Normalized shear modulus

GG – Geogrid

GGBFS – Ground granulated blast furnace slag

G_{max} – Maximum shear modulus

GN – Geonet

G_s – Specific gravity

G_{sec} – Secant shear modulus

Ha – Hectare

HEI – Health energy initiative

HR-SEM – High resolution scanning electron microscope

Hz – Hertz

IRC – Indian road congress

IS- Indian standard

JCPDS - Joint committee on powder diffraction standards

k – Coefficient of permeability

kg – Kilogram

kHz – Kilohertz

km^2 – Square kilometre

kN – Kilo newton

kPa – Kilo Pascal

kV – Kilo volt

L_{iv} – Volumetric binder content

LS – Local soil

M1, M2, & M3 – Method one, two, and three

M^3 – Cubic metre

MASW - Multichannel analysis of surface wave

MDD- Maximum dry density

ml – Millilitre

mm – Millimetre

MPa – Mega Pascal

M_R – Resilient modulus

MSA – Million standard axle

MSW – Municipal solid waste

MT – Million tonnes

Mw – Moment magnitude

N – North

NOx – Oxides of Nitrogen

OMC- Optimum moisture content

PA – Pond ash

PAHS - Pneumatic ash handling system

pH – Power of hydrogen

PI – Plasticity index

PP – Peak to peak

PRPP - Petroshield rock protection padding mesh

q_{ul} – Ultimate bearing capacity

q_u – Unconfined compressive strength

RAP – Reclaimed asphalt pavement

RC – Relative compaction

RDSO - Research Designs and Standards Organisation

r_u – Excess pore pressure ratio

SASW - Spectral analysis of surface waves

SCC – Self compacting concrete

SEM - Scanning electron microscope

SHL – Symmetric hysteresis loop

SiO_2 – Silicon dioxide

SO_2 – Sulfur dioxide

SPT – Standard penetration test

SS – Start to start

SSA – Specific surface area

SSV – Steady state vibration

t – thickness

TPS – Thermal power station

UCS- Unconfined compression strength

US EPA – United states environmental protection agency

UU - Unconsolidated undrained

V_S – Shear wave velocity

W/W_{Liq} – Strain energy ratio

XR – X-Ray

XRD- X-ray diffraction

XRF- X-ray fluorescence

Δu - Change in pore pressure

$\Delta\sigma_c$ - Change in confining pressure

Φ' – Effective angle of friction

ϕ - Internal friction/ Angle of friction

γ - Shear strain

σ'_c - Effective confining pressure

σ_c- Confining pressure

σ_d- Deviator stress