# LIQUEFACTION RESISTANCE AND DYNAMIC PROPERTIES OF COAL ASH

*by*

RAVI SANKAR J.

CIVIL ENGINEERING DEPARTMENT

**Submitted**

**in fulfillment of the requirements of the degree of**

**DOCTOR OF PHILOSOPHY**

**to the**

**INDIAN INSTITUTE OF TECHNOLOGY, DELHI**
**HAUZ KHAS, NEW DELHI-110016**
**INDIA**

**NOVEMBER 2007**

coal ash & liquefaction

*Dedicated*

*to*

*My Beloved Parents*

# CERTIFICATE

This is to certify that the thesis entitled **"LIQUIFACTION RESISTANCE AND DYNAMIC PROPERTIES OF COAL ASH"** being submitted by **Mr. Ravi Sankar Jakka** to the Indian Institute of Technology, Delhi is a record of bonafide research work carried out by him under our supervision and guidance. The thesis work, in our opinion has reached the standard, fulfilling the requirements for **DOCTORATE OF PHILOSOPHY** degree. The research report and the results presented in this thesis have not been submitted, in part or full, to any other university or institute, for the award of any degree or diploma.


Dr. G.V.Ramana
(Associate Professor)

Prof. Manoj Datta
(Professor)

Department of Civil Engineering
Indian Institute of Technology, Delhi
New Delhi – 110016.

## ACKNOWLEDGEMENTS

I would like to initiate my acknowledgement with the praise of All-Mighty, Lord SRI KRISHNA - most gracious and most merciful, who has bestowed upon me all his mercy and blessings to enable me to complete this work.

I would like to express my heartful gratitude and deep sense of indebtness to my supervisors, Prof. Manoj Datta and Dr. G. V. Ramana for their valuable guidance, constant encouragement and inspiration during all the stay of this research work. I am grateful for their cooperation and kind help they rendered from time to time.

I would like to express my sincere thanks to my SRC members Prof. Ashok Gupta, Dr. J. T. Sahu and Dr. S. P. Singh for their valuable suggestions during the review of my research work. I would like to express my sincere thanks to Prof. G. V. Rao for his prompt help whenever I approached him with a problem. I am also thankful to Prof. K. G. Sharma, Prof. K. S. Rao, Dr. K. K. Gupta, Prof. J. M. Kate and Dr. K. Ramachandra Rao for their constant encouragement. I am very grateful to Prof. P.V. Krishnan for his constant moral support and encouragement.

My sincere thanks to National Thermal Power Corporation, New Delhi for allowing me to collect ash samples from and conducting field tests at Indraprastha and Badarpur ash ponds to carryout this research. Special thanks are to Dr. D. N. Naresh, Deputy General Manager, NTPC, New Delhi, India for sharing his experiences and knowledge during my field testing.

The cyclic triaxial system used in the current work was procured through the generous financial support provided by Seismology Division, Department of Science and Technology and is greatly acknowledged. My sincere thanks to Olson Instruments Co., USA, Wykeham Farrance International Ltd., UK and Ultra technologies Ltd., New Delhi for rendering support during the tough times I had with the equipments. I specially acknowledge Neeraj Chadda, Saif Mobin, K.P Singh and Larry Olson for sharing their experiences and help rendered during the course of my research.

The assistance rendered by the staff of Soil and Rock Mechanics Laboratory, Transportation Laboratory, Civil Engineering Department and Workshop is gratefully acknowledged. Special thanks to Prof. A. Ramanan and Ms. Jency Thomas of Chemistry Department and Dr. D. C. Sharma of Scanning Electron Microscopy laboratory at IITD, and Dr. Chitra, Chief Research Officer, Center for Soil and Material Research Station, New Delhi, India, for extending their laboratory facilities to carry out various analyses for this research.

I would like to thank to my fellow researchers and friends Dr. Gayatri, Dr. Hanumantha Rao, Dr. Sanjay Kumar, Dr. Altaf, Mr. Prakash, Mrs. Kamatchi, Dr. Raveendra babu, Mr. Mallikharjuna, Mr. Bullu Pradhan, Mr. Ramana Reddy, Mr. Aravind Jain, Mr. R. Ganesh and Mr. Maheedhar for their constant support and encouragement through out this work.

Last but not least, I would like to express my heartful gratitude to my parents and my wife without whose constant moral support and encouragement the thesis would not have seen the daylight. I specially thank my wife for being with me in every aspect through out this research work.

(Ravi Sankar J.)

# ABSTRACT

Coal ash, a by-product of thermal power generation is most commonly disposed off in the form of slurry and occupies valuable land due to low rates of utilization. The problem can be minimized by utilizing ash in large earthworks for geotechnical applications like raising of dykes, construction of highway embankments and filling low lying areas. However, with increasing use of ash, a need for further understanding of its engineering behavior is required. So far, most of the studies conducted on ash have been confined to its basic characterization and geotechnical behaviour under static loading. Ash is an artificial material and its particles lie in the range of fine sand to silt that could cause the embankments to be susceptible to liquefaction and/or slope failures during or following seismic events. Hence, utilization of ash in earthquake prone areas requires knowledge of liquefaction susceptibility. Additionally, the dynamic properties (stiffness and damping characteristics) are also required, to assess the response and resulting instability of the structures under seismic loading conditions. Due to limited availability of literature which deals with liquefaction susceptibility and dynamic properties of coal ash, an attempt has been made here to comprehensively characterize liquefaction behaviour and dynamic properties of coal ash materials through various laboratory and field tests.

Bottom ash and fly ash produced at thermal power plants are typically mixed with large quantity of water and then sluiced into ash ponds. Two distinct types of materials are commonly observed in ash ponds due to settlement of coarser particles near inflow point and finer particles near outflow point. Hence, ash samples collected separately from inflow and outflow points of two ash ponds have been subjected to laboratory testing. Yamuna sand, a fine to medium sand, has been considered as a reference material to compare various test results.

Physical, chemical, mineralogical and morphological characterizations have been carried out in addition to basic geotechnical characterization for all the samples. Some special morphological characteristics that are distinctly different from typical soils are exhibited by both types of ash materials. Most of the fine ash particles (ash from outflow) are spherical in shape with varying sizes and with smooth surfaces. Coarse ash particles (ash from inflow) are irregular in shape with complex pore structure. Both coarse ash particles and some of larger fine ash particles are observed to be agglomerations of smaller particles with intra particle voids.

All ash samples from outflow point are in silt range (referred as 'fine ash' hereafter) whereas all ash samples from inflow point are predominantly in fine sand range (referred as 'coarse ash' hereafter). All the ash samples are observed to be non plastic and belong to class *F* category of ash as per *ASTM C 618 (1993)*.

Both coarse ash and fine ash exhibit compaction behaviour in the Proctor test akin to natural sands i.e. the compacted density decreases as one moves from dry state to moist and again increases as one approaches saturation. Coarse ash samples reach a plateau of maximum dry density as water content becomes close to 100% saturation as is also the case in natural sands. In contrast the fine ash samples show an inverted 'V' and thus a peak just before saturation is reached. In general, the values of maximum dry density of compacted ashes are found to be lower than those of compacted soils because of lower specific gravity and presence of intraparticle voids.

Coarse ash samples have high permeability, comparable with that of fine sands while permeability of fine ash samples is in the range of silt materials. Results of one dimensional consolidation tests indicated that compressibility is predominantly of immediate nature, implying that settlements would occur in the field during construction stage itself.

Consolidated drained and undrained triaxial (*CD* and $\overline{CU}$) tests were conducted on the specimens of ash and Yamuna sand, prepared by static compaction method at two different densities (representing loose (deposited state) and dense (compacted) states), under different confining pressures to determine shear strength characteristics. Coarse ash samples exhibited higher strengths than Yamuna sand in both loose and dense states, whereas fine ash exhibited strength comparable with Yamuna sand. Residual strengths of the ash materials are comparable with that of sand. Development of pore water pressures in undrained tests and volume change behaviour in drained tests are observed to be well correlated.

To evaluate the liquefaction resistance of the samples in the laboratory, stress controlled cyclic triaxial tests were conducted and influence of various factors were investigated. Liquefaction behaviour of ash materials is observed to be similar to natural materials (Yamuna sand), but an appreciable amount of scatter in the cyclic strengths of samples from inflow (coarse ash) and outflow (fine ash) points within the same pond is observed. Samples of outflow point exhibit lower cyclic strengths in both dense and loose states as compared to inflow samples. These observations highlight the importance of proper investigations prior to using ash from outflow point in geotechnical constructions in earthquake prone areas. Influence of confining pressure, density and initial shear stress on liquefaction resistance of ash materials is also observed to be similar to that of sands.

Liquefaction susceptibility of ash was further examined fundamentally by determining Steady State Line (*SSL*) and correlating volume change and pore water pressure development together to understand the occurrence of liquefaction. The states of the ash material which lie above the steady state line exhibit flow type of liquefaction (under cyclic testing) and those which lie below this line exhibit cyclic mobility (under cyclic testing) as expected according to steady state concepts in soils, validating the applicability of *SSL* concepts to ash materials.

Strain controlled cyclic triaxial tests were also conducted on all the materials for both loose and dense states to determine the dynamic properties of the materials. Variation of modulus and damping with strain and other factors, such as density, have been studied for all the ash samples and sand. Modulus reduction curves of various the ash materials (both fine and coarse) tested in dense state are observed to lie in between the standard curves given in the literature for soils of plasticity index 0 and 15, whereas their damping ratio curves lie mostly in between the curves of plasticity index 15 and 30.

To evaluate the field liquefaction resistance and dynamic properties, various field tests (*SASW* and *SPT*) have been conducted at inflow and outflow points of both the ash ponds. Additionally, some crosshole tests were also conducted to confirm shear wave velocities measured from SASW tests. The shear wave velocities measured on slurry deposited ash (in ash ponds) using different techniques are observed to be significantly lower compared to the velocities of natural soil deposits. Consequently the maximum shear modulus values are also estimated to be low for the slurry deposited ash (in ash ponds). The unusually low values of shear wave velocities of slurry deposited ash can be attributed to low density of the slurry deposited material and the special nature of ash particles containing intra-particle voids. There are some variations in the measured shear wave velocities from pond to pond and also within the pond, signifying the importance of obtaining low strain shear modulus for each of the material to arrive at a realistic response of structures built with ash. Low liquefaction resistance is estimated from the shear wave velocities measured using SASW and crosshole tests, and also from *N* values on slurry deposited ash. The measured shear modulus from SASW and crosshole tests, and estimated modulus from *SPT* tests (*N* values) are significantly different, thus indicating a need for development of a separate empirical relation for ash materials to relate *N* values and shear modulus.

Dynamic response and slope stability of ash embankments constructed around ash ponds with different methods of construction using coarse and fine ash materials under different seismic loading conditions have been assessed using properties of ash materials determined at through laboratory and field studies as per standard numerical procedures adopted in Quake/w, and Slope/w softwares. The dynamic response and stability of embankments constructed with ash is similar to the response of the structures constructed with natural materials. The analysis reveals that embankments constructed with fine ash are vulnerable to liquefaction hazards under high earthquake magnitudes. It also shows that embankments constructed by upstream method of construction for raising height of ash ponds are more prone to instability under seismic conditions. Downstream method of construction is found to be the best method to use with both coarse and fine ash materials for embankment raising in earthquake prone areas. Coarse ash should be the first choice as construction material wherever possible. Whenever fine is used, it is important to ensure high uniformity of compaction during construction.

Further analysis carried for road embankments with ash also shows favorable response. It is clear from the studies conducted on compacted fills that both the fine and coarse ash materials in compacted state are suitable for filling of low lying areas. However, one has to be cautious in using fine ash in high seismic regions as fine ash in compacted state is observed to be prone to liquefaction under high earthquake magnitude.

Based on the results obtained from this study, it is concluded that the coal ash from ash ponds are suitable for use in construction of dykes of ash ponds, road embankments and fills for filling of low lying areas, under seismic loading conditions. While having the advantage of smaller dry unit weights, coal ash from ash ponds can provide fill materials of comparable strength and compressibility to soils typically used in constructions of fills. Though both types of ash materials (fine and coarse) are found to be suitable to use under seismic conditions, proper precautions are necessary in using fine ash materials as they are more vulnerable to liquefaction. It is very important to ensure proper compaction in case of fine ash as their liquefaction resistance decreases substantially with decrease in density. As ash materials have shown response similar to natural materials under both static and dynamic (seismic) loading conditions, they can be used in low seismic regions in their well compacted state without any further special studies for assessing their liquefaction resistance and dynamic properties as is the case for natural materials.

# TABLE OF CONTENTS