

**LIQUEFACTION RESISTANCE AND
DYNAMIC PROPERTIES OF COAL ASH**



by

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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.



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(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

CERTIFICATE	i
ACKNOWLEDGEMENTS	iii
ABSTRACT	v
TABLE OF CONTENTS	xi
LIST OF FIGURES	xix
LIST OF TABLES	xxxvii
NOTATIONS	xxxix
Chapter 1 INTRODUCTION	1
1.1 Background	1
1.2 Research Objectives	3
1.3 Scope of Work	3
1.4 Organization of Thesis	5
Chapter 2 LITERATURE REVIEW	7
2.1 General Characterization	7
2.1.1 Physical Properties	7
2.1.2 Chemical Composition	9
2.1.3 Mineralogy	10
2.1.4 Morphology	11
2.2 Geotechnical Characterization	12
2.2.1 Grain Size Distribution	12
2.2.2 Atterberg Limits	13
2.2.3 Compaction Characteristics	14
2.2.4 Permeability Characteristics	15

2.2.5	Compressibility Characteristics	16
2.2.6	Strength Characteristics	18
2.3	Steady State Behaviour	20
2.3.1	Theory and Definitions of Various Terms	20
2.3.2	Undrained Behaviour of Saturated Sands	21
2.4	Liquefaction Resistance	23
2.4.1	Definitions of Various Technical Terms	23
2.4.2	Liquefaction Resistance of Coal Ash	25
2.4.3	Liquefaction Resistance of Tailings	26
2.4.4	Liquefaction Resistance of Silts	27
2.4.5	Factors Affecting Liquefaction Resistance of Sands	28
2.5	Dynamic Properties	30
2.5.1	Maximum Shear Modulus, Modulus Reduction and Damping Ratio Curves	30
2.6	Dynamic Stability of Embankments	34
Chapter 3	EXPERIMENTAL AND ANALYTICAL INVESTIGATION	39
3.1	Experimental Investigations	39
3.1.1	Materials Used for Testing	39
	<i>3.1.1.1 Background</i>	39
	<i>3.1.1.2 Selection of Materials</i>	42
	<i>3.1.1.3 States of Materials Considered for Testing</i>	43
3.1.2	Experimental Program	44
3.1.3	Details of Experimental Procedures	46

3.2	Analytical Investigations	51
3.2.1	Statement of Problem	51
3.2.2	Details of Investigations	51
3.3	Summary	53
Chapter 4	CHARACTERIZATION OF ASH	55
4.1	General Characterization	55
4.1.1	Physical Properties	55
4.1.2	Chemical Composition	56
4.1.3	Mineralogy	57
4.1.4	Morphology	57
4.2	Geotechnical Characterization	57
4.2.1	Grain Size Distribution	67
4.2.2	Atterberg Limits	67
4.2.3	Compaction Characteristic	69
4.2.4	Permeability Characteristics	73
4.2.5	Compressibility Characteristics	74
4.3	Strength Characteristics	76
4.3.1	Testing Program	77
4.3.2	Test setup	77
4.3.3	Preparation of Specimen	80
4.3.4	Test Procedure	82
	<i>4.3.4.1 Saturation</i>	84
	<i>4.3.4.2 Consolidation</i>	85
	<i>4.3.4.3 Shearing</i>	89

4.3.5	Consolidated Drained Triaxial Tests (<i>CD</i>)	90.
4.3.6	Consolidated Undrained Triaxial Tests (\overline{CU})	107
4.4	Summary and Conclusions	125
Chapter 5	LIQUEFACTION RESISTANCE OF COAL ASH	129
5.1	Liquefaction Resistance from Laboratory Tests	129
5.1.1	Cyclic Triaxial Testing	130
	<i>5.1.1.1 Testing Program</i>	<i>132</i>
	<i>5.1.1.2 Test Setup</i>	<i>133</i>
	<i>5.1.1.3 Test Procedure</i>	<i>135</i>
	<i>5.1.1.4 Results and Discussions</i>	<i>138</i>
5.1.2	Factors Affecting Liquefaction Resistance	168
	<i>5.1.2.1 Effect of Density</i>	<i>168</i>
	<i>5.1.2.2 Effect of Confining Pressure</i>	<i>174</i>
	<i>5.1.2.3 Effect of Initial Shear Stress</i>	<i>174</i>
	<i>5.1.2.4 Effect of Grain size</i>	<i>177</i>
	<i>5.1.2.5 Comparison of Static and Cyclic (liquefaction) Strengths</i>	<i>178</i>
5.2	Assessment of Liquefaction Susceptibility using Static and Cyclic Tests	178
5.2.1	Steady State Strength	179
	<i>5.2.1.1 Different types of stress strain behaviours of soils</i>	<i>180</i>
	<i>5.2.1.2 Steady State Line from \overline{CU} Tests</i>	<i>182</i>
	<i>5.2.1.3 Steady State Line from <i>CD</i> Tests</i>	<i>185</i>
5.2.2	State Parameter for Liquefaction Susceptibility	187
5.2.3	Occurrence of Flow Liquefaction from Monotonic Loading	189

5.2.4	Flow Liquefaction from Cyclic Loading	189
5.2.5	Cyclic Mobility under Cyclic Loading	191
5.3	Liquefaction Resistance from Field Tests	191
5.3.1	Testing Program	192
5.3.2	SASW testing	192
	5.3.2.1 <i>Equipment Setup</i>	193
	5.3.2.2 <i>Test Procedure</i>	194
	5.3.2.3 <i>Analysis of Test Data</i>	195
	5.3.2.4 <i>Test Results</i>	199
	5.3.2.5 <i>Estimation of Liquefaction Resistance from</i> <i>Shear Wave Velocity Measurements</i>	202
5.3.3	Cross Hole Testing	220
	Equipment Setup	220
	5.3.3.1 <i>Test Procedure</i>	221
	5.3.3.2 <i>Test Data and Processing</i>	224
	5.3.3.3 <i>Test Results and Liquefaction Resistance</i>	227
5.3.4	Standard Penetration Tests	227
	5.3.4.1 <i>Test Procedure</i>	228
	5.3.4.2 <i>Evaluation of Liquefaction Resistance using</i> <i>N values</i>	231
5.4	Summary and Conclusions	236
Chapter 6	DYNAMIC PROPERTIES	239
6.1	Determination of Maximum Shear Modulus from Field Tests	240

6.1.1	Using Shear Wave Velocity Measurements from <i>SASW</i> and Crosshole Tests	240
6.1.2	Using Correlations with <i>N</i> values	241
6.2	Modulus Reduction and Damping Ration Curves from Cyclic Triaxial Tests	243
6.2.1	Testing Program	244
6.2.2	Methodology	245
6.2.3	Test Results	248
6.3	Summary and Conclusions	271
Chapter 7	ASSESSMENT OF DYNAMIC STABILITY OF EMBANKMENTS AND ASH PONDS AND COMPACTED FILLS	273
7.1	Procedures for Analysis of Dynamic Stability	274
7.1.1	Static Analysis	275
7.1.2	Dynamic Analysis	275
	<i>7.1.2.1 Input Motion</i>	275
	<i>7.1.2.2 Dynamic Properties</i>	276
7.1.3	Evaluation of Occurrence/Extent of Liquefaction	282
7.1.4	Post Earthquake Stability	282
7.1.5	Evaluation of Permanent Deformations	283
7.2	Problems Analyzed	283
7.2.1	Dynamic Stability of Embankments	284
	<i>7.2.1.1 Analysis of Embankment Constructed with Fine and Coarse Ash Materials using Different Methods of Construction</i>	289
	<i>7.2.1.2 Analysis of Ash Embankments under different Earthquake Scenarios appropriate for Delhi Region</i>	304

7.2.2	Road Embankment	310
7.2.3	Compacted Fill and Ash Pond	320
7.3	Summary and Conclusions	333
Chapter 8	CONCLUSIONS	335
8.1	Characterization of Materials	335
8.2	Static Strength Characteristics	336
8.3	Cyclic Strength Characteristics	337
8.4	Steady State Behaviour and Liquefaction	338
8.5	Dynamic Properties (Modulus Reduction and Damping Ratio Curves)	339
8.6	Field Tests	340
8.7	Numerical Analysis	341
8.8	Final Conclusions	342
8.9	Suggestions for Future Study	343
	REFERENCES	345
	APPENDIX A: Plots of Stress Controlled Cyclic Triaxial Tests Conducted for Evaluation of Liquefaction Resistance	359
	APPENDIX B: Plots of Strain Controlled Cyclic Triaxial Tests Conducted for Evaluation of Dynamic Properties	415
	APPENDIX C: Plots showing Repeatability of Test Results	455