

**TESTING AND CONSTITUTIVE
MODELING
OF BOMBAY HIGH MARINE SOIL
WITH APPLICATION TO
LATERALLY LOADED PILE**

by

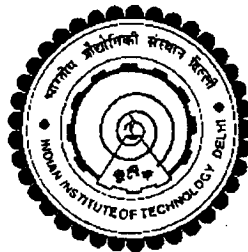
SANJAYA KUMAR V.

Department of Civil Engineering

Submitted in fulfilment of the requirements of the degree of

DOCTOR OF PHILOSOPHY

to the

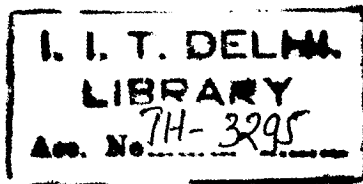


INDIAN INSTITUTE OF TECHNOLOGY, DELHI

DECEMBER, 2005

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off-line oil extraction

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DEDICATED TO

MY

PARENTS

**(Late) Shri. G. Velayudhan Pillai
Smt. K. Vilasini Amma**

WIFE

Revati

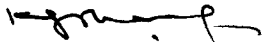
and

CHILDREN

**Akhil
Keertana**

CERTIFICATE

This is to certify that the thesis entitled “**TESTING AND CONSTITUTIVE MODELLING OF BOMBAY HIGH MARINE SOIL WITH APPLICATION TO LATERALLY LOADED PILE**” being submitted by **Mr. Sanjaya Kumar V.** 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 **DOCTOR 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. K. G. SHARMA)

Professor



(DR. A. VARADARAJAN)

Professor

Department of Civil Engineering

Indian Institute of Technology

New Delhi-110 016

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(Sanjaya Kumar V)

ABSTRACT

The crisis of energy is driving human mankind to explore oil and gas along with other non-conventional forms of energy to enhance their level of energy security. Even today oil and gas exploration takes the major share in new finds. The exploration of oil and gas, once restricted to the coastal areas has gone far into the ocean as the technology advanced. Since in the Indian scenario, the template type jacket structures with driven pipe piles are being designed, fabricated and installed for tapping the oil and gas resources, any improvement in the design of the facilities to be installed will not only improve the safety of the structure but also will economise the total project cost. For an optimal and safe design of the foundation system in the Bombay High region, an accurate determination of the soil parameters and improved analysis and design methods are needed. With this objective in mind the present study was planned.

As part of the present study, samples were taken from Bombay High region from the following depths in a bore hole: 9.10, 14.60, 22.20, 26.93, 28.43, 35.13 and 40.52m designated as BHE-9, BHE-14, BHE-22, BHE-26, BHE-28, BHE-35 and BHE-40 respectively. A series of tests were done at the IIT Delhi laboratory to study the behaviour of Bombay High Marine clay. First the classification and index properties were determined which showed that the clays differed mainly in the silt content. The clay mineralogy and structure determined using X-ray diffraction and scanning electron microscope also revealed the presence of needle like carbonate structures. The samples were remoulded and specimens were prepared using the slurry consolidation method for detailed triaxial testing. The preparation of one specimen by this method took around 21 to 30 days. The consolidation behaviour of all the

soils were determined by conducting isotropic consolidation tests which also lasted about 30 days for each soil. Subsequently 20 drained tests for five out of seven soil samples of 48 to 54 hours duration were conducted after consolidating the slurry consolidated sample to the required confining pressure in about 2 days. The drained stress-strain response and volumetric response of the soils were determined from these tests for four confining pressures namely 98.1, 196.2, 343.4 and 490.5 kPa. Consolidated undrained tests with pore water pressure measurement for the same above-mentioned confining pressures were also carried out for all the marine soils. The tests after the initial consolidation of about 2 days were sheared in a duration of about 4.5 hours. The undrained stress-strain response and the pore water pressure response were inferred from these tests.

Based on the detailed and elaborate testing, the seven soils could be broadly divided into two groups: Group 1 and Group 2. The composition of Group 1 soils (BHE-9, BHE-14 and BHE-22) consisted of approximately equal percentage of clay, silt and sand, whereas Group 2 soils (BHE-26, BHE-28, BHE-35 and BHE-40) consisted of 65% silt with sand less than 5%. The consolidation behaviour showed that for the same range of pressure, the change in void ratio was greater for Group 1 soils even though the clay content was less with the exception of BHE-22. There was a similarity in the drained shear behaviour of all the soils. However large volumetric volumetric strains were noticed in Group 1 soils. The undrained response obtained from the test results presented an altogether different perspective. For Group 1 soils the response under all confining pressures the soils behaved like a normally consolidated clay with their typical nature of effective stress paths. However in the case of Group 2 soils, except for the lowest confining pressure of 98.1 kPa,

considerable deviatoric hardening was noticed. This was also characterized by the change in the direction of the effective stress paths from left to right as the critical state line is approached. At the lowest confining pressure the behaviour was similar to that of a normally consolidated clay. The reason for this was the considerable amount of silt present in Group 2 soils as was also demonstrated in the case of Delhi and Swedish silts. However in all soils the amount of coarse content remained the same.

The strength envelope derived by plotting the results of both drained and undrained tests was unique for each of the soil studied. The angle of shearing resistance remained close to each other for all the soils except BHE-14. This behaviour is similar to that of a normally consolidated soil and is of practical importance. The existence of a unique water content- strength relationship and a unique water-content- effective stress at failure relationship were brought out and the similarity of these to the normally consolidated clay reinforces the practical significance of this study.

The behaviour of sand and clay has been extensively studied and is well understood. But the behaviour of silts and sand-silt-clay mixtures has hardly been investigated. The findings here on the soils of Bombay High area will significantly contribute to the understanding of these soils. Furthermore, these findings will be of great practical use for the analysis and design of offshore structures in the Bombay High region.

Having finalized the basic properties of the soils, the next step was to properly characterize the stress – strain – volume change behaviour and the stress-strain- pore water pressure behaviour. Two models, namely, modified Cam clay (MCC) and

modified Drucker-Prager (MDP) models were selected and predictions were carried out using the general purpose finite element software ABAQUS. The drained shear response was well predicted in both the models. The volumetric strains did not match at all in the MCC model while the range of volumetric strains was predicted in a reasonable manner by MDP model. Both the models predicted the undrained shear response in a satisfactory manner. The models could not predict the deviatoric hardening response for the Group 2 soils. Pore water pressure response were satisfactorily predicted for all the soils. However the initial part of the pore pressure response (upto 4 to 8% axial strain) has not been predicted very well.

Against the backdrop that the behaviour of sand-silt-clay mixture has hardly been studied an attempt has been made in the present research work to understand their behaviour. Perhaps, this is the first attempt made to depict the behaviour of these type of soils from Bombay High region. It is believed that this is a significant step and the models, notwithstanding the limitations, will have immense potential for use in the analysis and design of offshore structures in the Bombay High region.

A pile in an offshore environment if subjected to the environmental loading by waves, wind etc. essentially behaves in an undrained manner. All the analytical works on such piles are carried out using the total stress analysis with the undrained shear strength determined by unconsolidated undrained triaxial testing. This is partly because of the lower cost in terms of time and equipment involved in the on-board testing of samples and partly because the API recommended practice requires only these tests for the generation of p-y curves (to adequately represent the non-linear nature of the soil response for the full analysis involving soil-pile-structure

interaction). Although this has been accepted worldwide, one has to exercise caution in using the p-y curve approach for any site-specific application. The higher factor of safety taken for the environmental loads, the reserve strength due to aging of soil etc. often eclipses the other deficiencies in the well-established methods.

Therefore a three-dimensional analysis, which includes the undrained loading, is warranted till a correlation between the parameters used in industry and the standard methods is reached. In the present study, undrained effective stress three-dimensional analyses utilizing the modified Cam clay model and Modified Drucker-Prager model have been carried out. ABAQUS software has been used for the study. The soil continuum consisted of 20-noded brick coupled pore fluid- stress elements and the pile consisted of 20-noded stress elements. The slippage and gapping were also included in the analysis. The results obtained from the three-dimensional analyses showed broad similarities with the conventional approach obtained as per API recommended practice. However, the results from the conventional approach were found to be conservative.

The deflection pattern was almost similar in both the methods of analysis. The maximum bending moment and shear force obtained from the API method was higher than the three-dimensional analysis. A proper assessment of the stresses and strain in the continuum was done through this analysis. There is a clear indication of bulging of the soil as is expected near the pile as shown by the direction of the accumulated plastic strains and the displacements at the end of the loading. The pore pressure behaviour has also been satisfactorily represented. As such, the realistic analysis of the type conducted herein, not only provides understanding of the laterally

loaded pile behaviour, but also gives scope for the evaluation and improvement in the existing design procedures.

TABLE OF CONTENTS

TITLE	PAGE
CERTIFICATE	i
ACKNOWLEDGEMENT	ii
ABSTRACT	iv
TABLE OF CONTENTS	x
LIST OF FIGURES	xx
LIST OF TABLES	xxvii
LIST OF SYMBOLS AND ACRONYMS	xxviii
CHAPTER 1	
INTRODUCTION	1
1.0 GENERAL	1
1.1 OBJECTIVES	3
1.2 SCOPE	4
1.3 ORGANISATION OF THE THESIS	4
CHAPTER 2	
LITERATURE REVIEW	6
2.0 GENERAL	6
2.1 BEHAVIOUR OF MARINE CLAYS	6
2.1.1 Behaviour of Marine Clays	6
2.1.2 Description of Bombay High area – Geological	20
2.1.3 Description of Bombay High area – Geotechnical	21
2.2 CONSTITUTIVE MODELLING	25
2.2.1 Empirical Models	25

2.2.2	Elasticity Models	26
2.2.3	Plasticity Models	27
2.2.3.1	Mohr-Coulomb Yield Criterion	27
2.2.3.2	Drucker-Prager Yield Criterion	32
2.2.3.3	Cam Clay Model	33
2.2.3.4	Hierarchical Single Surface (HISS) Models	35
2.3	ANALYSIS OF LATERALLY LOADED PILES	38
2.4	SUMMARY AND SCOPE OF INVESTIGATION	47
CHAPTER 3		
EXPERIMENTAL INVESTIGATION		
		50
3.0	GENERAL	50
3.1	EXPERIMENTAL PLAN	50
3.1.1	Materials Tested	50
3.1.2	Specific Gravity and Dry Density	51
3.1.3	Atterberg Limits and Particle Size Distribution	52
3.1.4	Clay Mineralogy and Texture	54
3.2	EXPERIMENTAL STUDY AND PROGRAM	62
3.3	EXPERIMENTAL SETUP	65
3.3.1	Standard Triaxial Equipment	65
3.3.2	GDS Triaxial System	67
3.3.2.1	Axial Loading System	67
3.3.2.2	Digital Pressure Controllers	70
3.4	EXPERIMENTAL PROCEDURE	71
3.4.1	Sample Preparation	71
3.4.2	Isotropic Consolidation Test	73

3.4.3	Consolidated Drained Test	73
3.4.4	Consolidated Undrained Test with Pore Water Pressure Measurement	76
3.4.5	Reproducibility of Results	77
CHAPTER 4		
EXPERIMENTAL RESULTS AND DISCUSSION		78
4.0	GENERAL	78
4.1	SOIL BHE-9	78
4.1.1	Isotropic Consolidation (IC) Test	78
4.1.2	Consolidated Drained (CD) test	79
4.1.2.1	Deviatoric stress response	79
4.1.2.2	Volumetric strain response	80
4.1.3	Consolidated Undrained (\overline{CU}) Test	80
4.1.3.1	Deviatoric stress response	80
4.1.3.2	Pore water pressure response	83
4.1.3.3	Effective stress paths	83
4.1.4	Strength Envelope, Water Content-Strength- Effective stress Relationship	83
4.2	SOIL BHE-14	86
4.2.1	Isotropic Consolidation (IC)Test	86
4.2.2	Consolidated Undrained (\overline{CU}) Test	87
4.2.2.1	Deviatoric stress response	87
4.2.2.2	Pore water pressure response	87
4.2.2.3	Effective stress paths	87
4.2.3	Strength Envelope, Water Content-Strength- Effective stress Relationship	89
4.3	SOIL BHE-22	91
4.3.1	Isotropic Consolidation (IC) Test	91

4.3.2	Consolidated Drained (CD) Test	92
4.3.2.1	Deviatoric stress response	92
4.3.2.2	Volumetric strain response	92
4.3.3	Consolidated Undrained (\overline{CU}) Test	92
4.3.3.1	Deviatoric stress response	92
4.3.3.2	Pore water pressure response	93
4.3.3.3	Effective stress paths	93
4.3.4	Strength Envelope, Water Content-Strength- Effective stress Relationship	96
4.4	SOIL BHE-26	98
4.4.1	Isotropic Consolidation (IC)Test	98
4.4.2	Consolidated Drained (CD) Test	99
4.4.2.1	Deviatoric stress response	99
4.4.2.2	Volumetric strain response	99
4.4.3	Consolidated Undrained (\overline{CU}) Test	99
4.4.3.1	Deviatoric stress response	99
4.4.3.2	Pore water pressure response	100
4.4.3.3	Effective stress paths	100
4.4.4	Strength Envelope, Water Content-Strength- Effective stress Relationship	103
4.5	SOIL BHE-28	105
4.5.1	Isotropic Consolidation (IC) Test	105
4.5.2	Consolidated Undrained (\overline{CU}) Test	106
4.5.2.1	Deviatoric stress response	106
4.5.2.2	Pore water pressure response	106
4.5.2.3	Effective stress paths	106
4.5.3	Strength Envelope, Water Content-Strength- Effective stress Relationship	108

4.6	SOIL BHE-35	110
4.6.1	Isotropic Consolidation (IC) Test	110
4.6.2	Consolidated Drained (CD) Test	111
4.6.2.1	Deviatoric stress response	111
4.6.2.2	Volumetric strain response	111
4.6.3	Consolidated Undrained (\overline{CU}) Test	111
4.6.3.1	Deviatoric stress response	111
4.6.3.2	Pore water pressure response	112
4.6.3.3	Effective stress paths	112
4.6.4	Strength Envelope, Water Content-Strength- Effective stress Relationship	115
4.7	SOIL BHE-40	117
4.7.1	Isotropic Consolidation (IC) Test	117
4.7.2	Consolidated Drained (CD) Test	118
4.7.2.1	Deviatoric stress response	118
4.7.2.2	Volumetric strain response	118
4.7.3	Consolidated Undrained (\overline{CU}) Test	118
4.7.3.1	Deviatoric stress response	118
4.7.3.2	Pore water pressure response	119
4.7.3.3	Effective stress paths	119
4.7.4	Strength Envelope, Water Content-Strength- Effective stress Relationship	122
4.8	DISCUSSION OF THE RESULTS	124
4.8.1	Isotropic Consolidation (IC) Tests	124
4.8.2	Consolidated Drained (CD)Tests	126
4.8.3	Consolidated Undrained (\overline{CU}) Tests	126
4.8.4	Strength Envelope, Water Content-Strength- Effective stress Relationship	128

4.9	CONCLUSIONS	129
CHAPTER 5		
	FORMULATION IN ABAQUS	131
5.0	GENERAL	131
5.1	FORMULATION IN ABAQUS	132
5.1.1	Analysis of porous media	132
5.1.1.1	Effective stress principle for porous media	132
5.1.1.2	Discretized equilibrium statement for a porous medium	133
5.1.1.3	Continuity statement for the pore water phase in a porous medium	134
5.1.2	Constitutive Models	135
5.1.2.1	Modified Cam-clay models	135
5.1.2.2	Drucker-Prager model	141
CHAPTER 6		
	CONSTITUTIVE MODELLING	147
6.0	GENERAL	147
6.1	MATERIAL PARAMETERS	147
6.1.1	Material Parameters for Modified Cam Clay Model	148
6.1.2	Material Parameters for Modified Drucker-Prager Model	149
6.2	SOIL BHE-9	152
6.2.1	Consolidated Drained Test	152
6.2.1.1	Deviatoric stress response	152
6.2.1.2	Volumetric strain response	152
6.2.2	Consolidated Undrained Test	155
6.2.2.1	Deviatoric stress response	155
6.2.2.2	Pore water pressure response	155

6.3	SOIL BHE-14	158
6.3.1	Consolidated Undrained Test	158
6.3.1.1	Deviatoric stress response	158
6.3.1.2	Pore water pressure response	158
6.4	SOIL BHE-22	161
6.4.1	Consolidated Drained Test	161
6.4.1.1	Deviatoric stress response	161
6.4.1.2	Volumetric strain response	161
6.4.2	Consolidated Undrained Test	164
6.4.2.1	Deviatoric stress response	164
6.4.2.2	Pore water pressure response	164
6.5	SOIL BHE-26	167
6.5.1	Consolidated Drained Test	167
6.5.1.1	Deviatoric stress response	167
6.5.1.2	Volumetric strain response	167
6.5.2	Consolidated Undrained Test	170
6.5.2.1	Deviatoric stress response	170
6.5.2.2	Pore water pressure response	170
6.6	SOIL BHE-28	173
6.6.1	Consolidated Undrained Test	173
6.6.1.1	Deviatoric stress response	173
6.6.1.2	Pore water pressure response	173
6.7	SOIL BHE-35	176
6.7.1	Consolidated Drained Test	176
6.7.1.1	Deviatoric stress response	176

6.7.1.2	Volumetric strain response	176
6.7.2	Consolidated Undrained Test	179
6.7.2.1	Deviatoric stress response	179
6.7.2.2	Pore water pressure response	179
6.8	SOIL BHE-40	182
6.8.1	Consolidated Drained Test	182
6.8.1.1	Deviatoric stress response	182
6.8.1.2	Volumetric strain response	182
6.8.2	Consolidated Undrained Test	185
6.8.2.1	Deviatoric stress response	185
6.8.2.2	Pore water pressure response	185
6.9	DISCUSSION	188
6.9.1	Consolidated Drained Tests	188
6.9.2	Consolidated Undrained Tests	189
6.10	CONCLUSIONS	191
CHAPTER 7		
ANALYSIS OF A LATERALLY LOADED PILE		193
7.0	GENERAL	193
7.1	ANALYSIS OBJECTIVES	195
7.2	DEFINITION OF THE PROBLEM	196
7.3	THREE-DIMENSIONAL (3-D) ANALYSIS	196
7.3.1	Analysis Plan	196
7.3.2	Loading pattern/ boundary condition	197
7.3.3	Soil profile	198
7.3.4	Single Pile Analysis	201

7.4	DESCRIPTION OF THE MODEL	203
7.5	DISCRETISATION	203
7.5.1	Pile discretisation	203
7.5.2	Soil Discretisation	203
7.5.3	Interface	204
7.6	RESULTS AND DISCUSSION	208
7.6.1	Deflection, Shear Force and Bending Moment along the Pile	208
7.6.2	Stresses in soil	213
7.6.3	Pore Water Pressure in soil	213
7.6.4	Strains in Soil	213
7.6.5	Interaction between Pile and Soil	214
7.7	CONCLUSIONS	224
CHAPTER 8		
SUMMARY AND CONCLUSIONS		226
8.0	GENERAL	226
8.1	EXPERIMENTAL STUDY	226
8.2	CONSTITUTIVE MODELLING	228
8.3	ANALYSIS OF PILES	230
8.4	SUGGESTIONS FOR FURTHER WORK	232
REFERENCES		233
APPENDIX – I		
FEATURES IN ABAQUS		254
A1.0	GENERAL	254
A1.1	ABAQUS	254
A1.1.1	ABAQUS Modules	255

A1.1.2	Components of an ABAQUS Analysis Model	256
A1.1.2.1	Discretized geometry	256
A1.1.2.2	Element section properties	257
A1.1.2.3	Material data	257
A1.1.2.4	Loads and boundary conditions	257
A1.1.2.5	Analysis type	258
A1.1.2.6	Output requests	258
A1.1.3	Geostatic Equilibrium	258
A1.1.4	Finite Element Related Aspects in ABAQUS	259
A1.1.4.1	Elements	259
A1.1.4.2	Mesh density	261
A1.1.4.3	Step, Increment and Iteration	261
A1.1.4.4	Nonlinearities and method of solution	262
A1.1.4.5	Interaction and contact	263
A1.1.4.6	Solution method for contact	265
APPENDIX – II		
FEATURES IN SACS		268
A2.0	GENERAL	268
A2.1	SACS	268
A2.2	SACS Modules	268
A2.2.1	PSI/PILE MODULE	269
BRIEF BIO-DATA OF THE AUTHOR		274