

CREEP STRENGTH OF SATURATED CLAYS

Thesis submitted to the Indian Institute of Technology, Delhi

by

Raghunath Purushottam Kulkarni, M.Tech.(Engg.)

for the degree of

Doctor of Philosophy in the Faculty of Engineering,

December, 1969

ACKNOWLEDGEMENT

The author wishes to express his thanks to Professor R.N.Dogra, Director, Indian Institute of Technology, Delhi, Professor Saranjit Singh, Professor of Civil Engineering, I.I.T., Delhi, Professor B.K.Kaul, Head of the Civil Engineering Department, Regional College of Engineering, Kurukshetra, Shri N.G.K. Murti, Chief Engineer, Maharashtra P.W.D., Shri E.C.Saldhana, Chief Engineer, Maharashtra P.W.D., Shri V.B. Menerikar, Chief Engineer, Maharashtra P.W.D., Shri M.G. Padhye, Director, Maharashtra Engineering Research Institute, Nasik and Shri K.R. Darye, Consultant, Bombay, for providing him the opportunity to undertake this work. He is particularly indebted to the guide, Professor Saranjit Singh, for the continuous encouragement he has received throughout the work. The author was in continuous correspondence with Professor D.J.Henkel who had given very useful suggestions for the research work and he is indebted to him for his interest.

The author also wishes to thank Dr.(Mrs.)S.Z.Ali, Head, Materials Analysis Division, National Physical Laboratory, Delhi for the identification of clay minerals by X-ray diffraction method and to Dr. S.K.Sharma, Scientist, P.L. for providing the stereoscopic electron microphotographs of the soil samples, to Dr. Mandel, Assistant Professor, Indian Institute of Technology, Bombay, for allowing him to conduct the D.T.A. experiments on Bombay marine clay and to Dr. P.K.Katti, Professor of Physics, I.I.T. Delhi, for giving the advise taking the microphotographs of clay slides.

He is grateful to his colleagues, particularly to Dr. Ramamurthy for going through the manuscript of the thesis.

R. P. Kulkarni
R.P.Kulkarni

CONTENTS

Title page	i
Acknowledgement	ii
Table of Contents	iii
List of Figures	viii
List of Tables	xviii
List of Symbols	xx
Introduction	.
A. General	1
B. Variables Studied	3
C. The Thesis	4
D. Description of Some Terms	5
I LITERATURE REVIEW	
A. Introduction	7
B. Literature Review	7
1. General	8
2. Laboratory Evidence	8
3. Field Evidence	10
4. Stress-Strain-Time Relations	11
C. Points requiring additional Study	11
II INFLUENCE OF TIME OF FAILURE ON SHEAR STRENGTH GENERATION IN A CLAY SOIL - A REVIEW	
A. Introduction	13
B. Phenomenological Description of the Shear Strength Generation	13

1.	General	13
2.	Phenomenological Description	14
3.	Creep Theories	16
C.	Development of Shear Resistance-Mechanical Concepts	21
1.	General	21
2.	Theory of Friction by Bowden and Tabor	21
a.	Concepts of friction	21
b.	Points of Similarities	22
c.	Points of Dissimilarities	23
d.	Discussion	24
e.	Effect of Time of Failure on Friction	25
3.	Theory of Shear Resistance in Clay-Water System by Terzaghi	26
4.	Summary	27
D.	Shear Strength Generation as Explained by Physico-Chemical Properties of Soil	28
1.	Interparticle Forces	28
2.	Effect of Fabric on Electro-Chemical Forces between Clay Particles	28
3.	Effect of Leaching on Interparticle Forces	30
4.	Cohesion and Friction Components	30
a.	Cohesion Component	30
b.	Friction Component	33
E.	Conclusions	34
F.	Influence of Consolidation and Shear Deformation on the Orientation of Clay Particles	35

III	EXPERIMENTAL PROCEDURE AND TEST RESULTS	
A.	Introduction	43
B.	Classification Tests	43
C.	Bombay Marine Clay	44
1.	Preparation of Samples with Different Structures	44
2.	a. Preparation of Slurry Samples	45
	b. Preparation of Flocculated Samples	45
2.	Storing Arrangement	46
3.	Test Procedure	46
	a. Sample Erection	46
	b. Ko-consolidation	47
	c. Ko-overconsolidation	48
	d. Changing the Salt Concentration in Triaxial Samples	49
	e. Controlled Stress Rate Tests	50
	f. Controlled Strain Rate Tests	51
	g. Consolidated Drained Tests, Controlled Stress Rate Type	51
D.	Kaoline Clay and Bentonite	52
E.	Shear Tests by Direct Shear Apparatus	52
F.	Schedule of Shear Tests	54
IV	EFFECT OF STRUCTURE ON ENGINEERING PROPERTIES OF BOMBAY MARINE CLAY.	
A	Introduction	55
B.	Atterberg Limits	56
C.	Shear Strength Characteristics	57

1.	Yield Stress	57
2.	Cohesion Intercept and Angle of Shearing Resistance at Failure	57
3.	Cohesion Intercept and Angle of Shearing Resistance at Creep Condition	58
4.	Change in Pore Water Pressure with Time	59
5.	Hvorslev Parameters at Failure	60
6.	Relationship between Water Content and Average Effective Stress	60
	a. At the end of Consolidation Stage	61
	b. At failure Condition	62
7.	Relationship between Water Content and Failure Stress	62
8.	Relationship between Water Content and Major Principal Stress Difference at the Yield Stress Condition	63
9.	Relationship between $(\sigma_1 - \sigma_3)_f / \frac{1}{3} (J'_1)_c$ and $\Delta u_f / \frac{1}{3} (J'_1)_c$ with Overconsolidation Ratio	64
10.	Relationship between A_f and Overconsolidation Ratio	65
11.	Relationship between $(\sigma_1 - \sigma_3)_f / \frac{1}{3} (J'_1)_f$ and Overconsolidation Ratio	65
D.	Summary	66
V	INFLUENCE OF TIME OF FAILURE ON SHEAR STRENGTH PARAMETERS	
A.	Introduction	70
B.	Influence of Time of Failure on Shear Strength Parameters - Controlled Stress Rate and Controlled Strain Rate Test Results	71

1.	Angle of Shearing Resistance	71
a.	Normally consolidated soil	71
b.	Overconsolidated soil	72
2.	Water Content-Strength Relationships	72
a.	Relationship between Water Content and Average Effective Stress at Failure	72
b.	Relationship between Water Content and Shear Strength	74
3.	Relationship between A_f and Overconsolidation Ratio	75
4.	Hvorslev Parameters	76
5.	Summary of Test Results	76
C.	Influence of Time of Failure on Shear Strength Parameters - Controlled Stress Rate Tests with Different Constant Stress Rates	77
1.	Tests Conducted	77
2.	Test Results	78
3.	Relationship between Water Content and Shear Strength	79
4.	Summary	79
VI	HVORSLEV PARAMETERS	
A.	Introduction	80
B.	Previous Work	81
C.	Present Study	84
1 (a & b)	Influence of Structure on Hvorslev Parameters	85
1 (c)	Influence of Orientation of Clay Particles with reference to that of Plane of Failure on Hvorslev Parameters	89

2.	Effect of Strain History on Hvorslev Parameters	90
3.	Influence of Nature of Pore Fluid on Hvorslev Parameters	92
4.	Influence of Time of Failure on Hvorslev Parameters	94
5.	The Direction of Influence of Different Factors on Hvorslev Parameters	96
D.	Summary	96
VII	THE YIELD STRESS	104
A.	Introduction	104
B.	Evidence for the Presence of Yield Point	104
C.	Mechanical Concepts of Yield Stress	106
D.	Concepts of Yield Stress according to Physico-Chemical Theory	106
E.	New Concept of Yield Stress	107
1.	The Concept	107
2.	Supporting Evidence	108
3.	Evidence from the Present Study	109
F.	Influence of Cation Concentration in Pore Fluid on Yield Stress	110
G.	Summary	112
VIII	DISTRIBUTION OF WATER CONTENT IN A SOIL SAMPLE AFTER FAILURE	113
A.	Introduction	113
B.	Literature Review	113
C.	1. Water Content Distribution in a Soil Sample Tested in Triaxial Apparatus	115

2.	Variation of Pore Water Pressure in a Soil Sample	115
C.	Causes of Uneven Distribution of Observed Water Content in a Soil Sample after Failure	116
D.	Causes of Difference in 'Actual' and 'Observed' Water Content	118
E.	Distribution of Water Content in a Soil Sample Tested in a Direct Shear Box	120
F.	Experimental Observations of Water Content Distribution	122
1.	Samples Tested in Triaxial Apparatus	122
2.	Samples tested in Direct Shear Apparatus	123
G.	Conclusions	124
IX	STRESS-STRAIN-TIME AND CLAY CONTENT-VISCOSITY RELATIONSHIP STRESS-STRAIN TIME RELATIONSHIP	128
A.	Introduction	128
B.	Previous Work	128
C.	Stress-Strain-Time relationship	130
1.	General	130
2.	Relation between Vertical Strain and Time in the Secondary Stage of Creep	132
3.	Graphical Procedure to Determine the Creep Strength of Soil	134
4.	Relation between Deviator Stress and Rate of Strain	136
5.	Derivation of Stress-Strain-Time Relation	138
D.	Influence of Structure on Stress-Strain-Time Relationship	140
1.	Normally Consolidated Soil	140
2.	Overconsolidated Soil	141
E.	Influence of Clay Mineral on Stress-Strain-Time Relationship	141

1.	Normally Consolidated Soil	141
2.	Over-consolidated Soil	142
F.	Stress-Strain-Time Relationship for Drained Tests	142
G.	Summary	143
	CLAY CONTENT-VISCOSITY RELATIONSHIP	144
A.	Literature Review	144
B.	Present Study	148
X	THE CORRELATION OF RESULTS FROM VARIOUS TYPES OF TESTS	152
A.	General	152
B.	Strength	153
1.	Bombay Marine Clay	153
a.	Cohesion Intercept and Angle of Shearing Resistance at Creep Condition	153
b.	Relationship between strength Parameters in Dimensionless Form	153
2.	Kaoline Clay and Bentonite	154
a.	Cohesion Intercept and angle of shearing Resistance at Creep Condition	154
b.	Relationship between Strength Parameters in Dimensionless Form	155
3.	Hvorslev Parameters	155
C.	Creep Strength-Water Content Relationship	157
1.	General	156
2.	Relationship between Average Effective Stress and Water Content at Creep Condition	157
a.	Bombay Marine Clay	157
b.	Kaoline Clay	158
c.	Bentonite	158

D.	Summary	159
E.	Relation between Angles of Shearing Resistance at Creep Condition and at Residual Condition	160
	1. General	160
	2. Bombay Marine Clay	161
	3. Kaoline Clay	161
	4. Bentonite	162
F.	Relation between Water Content and Shear Stress at Residual Condition	162
G.	Conclusions	163
XI	DISCUSSIONS	165
	MECHANISM OF CREEP	165
A.	The Stress Strain and Volume Change-Strain Characteristics of a Saturated Clay Soil	165
	1. Assumptions	165
	2. Stress-Strain and Volume Change Strain Characteristics of a Normally Consolidated Soil	167
	a. Soil having an Ideal Flocculated Structure	167
	b. Soil having an Ideal Dispersed Structure	168
	c. Soil having an Intermediate Fabric	168
	3. Stress-Strain and Volume Change-Strain Characteristics of Overconsolidated Soil	170
	a. General	170
	b. Soil having an Ideal Flocculated Structure	171
	c. Soil having an Ideal Dispersed Structure	172
	d. Soil having Intermediate Fabric	173
B.	Influence of Time of Failure on Stress-Strain and Volume Change-Strain Characteristics of Soil	175

1.	Assumptions	175
2.	Stress-Strain and Volume Change-Strain Characteristics of a Normally consolidated Soil	175
a.	Soil having an Ideal Flocculated Structure	175
b.	Soil having an Ideal Dispersed Structure	176
c.	Soil with Intermediate Structure	177
3.	Stress-Strain and Volume Change-Strain Characteristics of Overconsolidated Soil	179
4.	Inferences	180
C.	Type of Soil of which Creep Shear Strength could be Determined, in Laboratory	182
1.	Type of Consolidation	182
2.	Plasticity of Soil	182
3.	Amount of Coarse grains in Soil	183
4.	Thixotropy of Soil	184
5.	Sensitivity of Soil	186
6.	Stiff Clays	186
7.	Clays used for the present Study	190
D.	Relation between 'Creep Shear Strength' and 'Residual Shear Strength'	192
E.	The Stress-Strain-Time Relationship	195
F.	Influence of Type of Clay Mineral in a Soil on its Creep Strength	197
XII	CONCLUSIONS	199
	BIBLIOGRAPHY	201
	Appendix A	
	Appendix B	