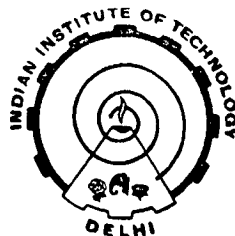


**RELATIONSHIP BETWEEN STRENGTH AND
STRESS - STRAIN BEHAVIOUR OF COHESIONLESS SOILS
IN TRIAXIAL AND PLANE STRAIN**

VIJAY KUMAR TOKHI

*Thesis submitted
in fulfilment of the requirements
of the degree of
DOCTOR OF PHILOSOPHY*



**DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY, DELHI**

OCTOBER 1982

CERTIFICATE

This is to certify that the thesis entitled "RELATIONSHIP BETWEEN STRENGTH AND STRESS-STRAIN BEHAVIOUR OF COHESIONLESS SOILS IN TRIAXIAL COMPRESSION AND PLANE STRAIN" being submitted by Mr. V.K. Tokhi to the Indian Institute of Technology, Delhi for the award of the degree of DOCTOR OF PHILOSOPHY is a record of the bonafide research work carried out by him. Mr. V.K. Tokhi has worked under my guidance for the submission of this thesis which to my knowledge has reached the requisite standard.

The thesis or any part thereof, has not been submitted to any other University or Institution for the award of any degree or diploma.

(Prof. T. Ramamurthy)

Soil Mechanics and Foundation Engineering
Department of Civil Engineering
Indian Institute of Technology
New Delhi

ACKNOWLEDGEMENTS

The author has great pleasure in recording his profound gratitude and indebtedness to Dr. T. Ramamurthy, Professor of Soil Mechanics and Foundation Engineering for his inspiring guidance, constant encouragement and immense help which enabled the author to undertake the work reported in this thesis. The author appreciates his understanding, untiring enthusiasm and the great care he took in bringing up the thesis in the present form.

The author wishes to express his deep appreciation and sincere thanks to the faculty members of Soil and Rock Mechanics section with whom the author had useful discussions.

The author is thankful to Dr. B.L. Mehrotra, Principal, M.A. College of Technology, Bhopal for sponsoring him to carry out the present research and to Government of India for providing scholarship under the Quality Improvement Programme.

The author is thankful to his friends and colleagues Mr. Nambiar and Mr. Rajbal. He is specially grateful to Mr. V.K. Gokhale and to Mr. Sheshagiri Rao for the cooperation and help the author has received from them.

The author wishes to acknowledge with gratitude the encouragement and forbearance contributed by his wife Jaya and daughters Kiran and Supriya during the course of studies, particularly in the last phase of the work.

ABSTRACT

Appropriate parameters are a pre-requisite to evolving any rational design in geotechnical engineering. For this, tests on representative soil specimens are conducted under simulated conditions in the laboratory to obtain these parameters. In geotechnical engineering design, the triaxial compression test has been widely used to obtain the strength and stress-deformation characteristics. This test, however, simulates axisymmetric stress conditions which occur only infrequently in practice. In general the three stresses in a stressed element are different, however, a more commonly encountered situation is that of plane strain or nearly plane strain condition. The soil parameters in plane strain are different than those obtained in a triaxial test and it is desirable to use the parameters obtained from plane strain tests in situations where such a condition exists. However, equipment for plane strain testing of soils is not available in most laboratories.

This thesis attempts to solve the above problem for sands tested in drained condition. It endeavours to make predictions for the below mentioned parameters in plane strain from the results of triaxial compression test alone.

(iv)

- (i) Peak strength, for which three approaches have been presented. The associated value of $b = (\sigma_2^i - \sigma_3^i) / (\sigma_1^i - \sigma_3^i)$ is also predicted,
- (ii) Stress-axial strain curve upto peak in plane strain and also at any value of b (less than b for plane strain condition) ,
- (iii) Volumetric strain curve for which two approaches are presented, and
- (iv) Relationship between axial and lateral strains in plane strain.

In addition to predicting the above characteristics in plane strain exclusively from results of triaxial compression tests, a failure criteria is also developed which is valid for the cases where $\phi_p^i \geq \phi_e^i \leq \phi_c^i$.

All the above predictions are shown to give good agreement with the available experimental data.

CONTENTS

<u>ACKNOWLEDGEMENTS</u>	(ii)
<u>ABSTRACT</u>	(.iii)
<u>CONTENTS</u>	(v)
<u>LIST OF TABLES</u>	(x)
<u>LIST OF FIGURES</u>	(xii)
<u>LIST OF NOTATIONS</u>	(xvii)
<u>CHAPTER 1</u> <u>GENERAL INTRODUCTION</u>	1 - 7
<u>CHAPTER 2</u> <u>REVIEW OF LITERATURE</u>	8 - 121
2.1	Relevance of Laboratory Testing 8
2.2	Part I Testing Techniques 10
2.2.1	Cylindrical triaxial compression test 10
2.2.2	Equipment for plane strain test 13
2.2.3	Some comments on plane strain equipment 22
2.2.4	Equipment permitting application of general stress system 24
2.2.4.1	Truely triaxial apparatus with all flexible boundaries 25
2.2.4.2	Truely triaxial apparatus with all rigid boundaries 27
2.2.4.3	Truely triaxial apparatus with combination of rigid and flexible boundaries 29
2.3	General Remarks on Equipments 35
2.4	Part II Experimental Investigations 36
2.4.1	Peak strength 37
2.4.2	Effect of small strain in σ_2 direction 40
2.4.3	Effect of confining pressure 41
2.4.4	Effect of shape and size of specimen 46
2.4.5	Effect of nature of consolidation 48
2.4.6	Effect of anisotropy 49
2.4.7	Failure axial strain 50
2.4.8	Initial tangent modulus and secant modulus 52

2.4.9	Lateral strain and lateral strain ratio	54
2.4.10	Volumetric strain and volumetric strain rates	55
2.4.11.1	Value of intermediate principal stress	56
2.4.11.2	Value of $\sigma_2' / (\sigma_1' + \sigma_3')$	58
2.4.11.3	Value of b	59
2.4.12	General remarks on laboratory investigations	60
2.5	Part III Theoretical Studies	60
2.5.1	Peak strength	60
2.5.2	Axial failure strain	68
2.5.3	Lateral strain and strain ratio	68
2.5.4	Initial tangent modulus and secant modulus	69
2.5.5	Volumetric strain and volumetric strain rate	71
2.5.6	Intermediate principal strain	72
2.5.7	Remarks on experimental and theoretical investigations	76
2.6	Part IV Stress-Strain Relationships for soils	77
2.6.1	Use of elasticity in stress-strain behaviour of soils	78
2.6.2	Elastic-plastic models	81
2.6.3	Use of stress-dilatancy relations	83
2.6.4	Stress-strain relations based on SMP	85
2.6.5	Empirical stress-strain relations	89
2.6.6	Remarks on stress-strain curves	101
2.7	Part V Failure Criteria in Three Dimensional Stress Space	103
2.7.1	Classical theoretical criteria	104
2.7.2	Other failure criteria	109
2.7.3	Summary on failure criteria	120
<u>CHAPTER 3 OBJECTIVE OF PRESENT INVESTIGATION</u>		122-126
<u>CHAPTER 4 DATA AND MATERIALS USED</u>		127-139
4.1	Introduction	127
4.2	Description of materials used by different investigators	127
4.3	General observations on soils used in sources of data	134
4.4	Acquiring data for analysis	138

<u>CHAPTER 5</u>	<u>RELATIONSHIP BETWEEN TRIAXIAL AND PLANE STRAIN STRENGTH</u>	140-236
5.1	Introduction	140
5.2	Theoretical development	142
5.2.1	Estimation of b_p and prediction of ϕ'_p in loose state	145
5.2.2	Estimation of b_p and prediction of ϕ'_p in dense state	152
5.3	Examination of assumptions	154
5.4	Peak strength at any relative density	160
5.4.1	Variation of ϕ'_p with relative density	162
5.4.2	Variation of ϕ'_p with $(D_{max})_f$	166
5.5	Comparison of predicted plane strain strength with predictions of other investigators	179
5.6	Prediction of b_p and $\sigma'_2 / (\sigma'_1 + \sigma'_3)$ and comparison with experimental data	189
5.7	Prediction of Plane Strain Strength by use of Stress Invariants	192
5.8	Theoretical development	192
5.8.1	Variation of strength in plane strain compression with b_p	200
5.9	Examination of assumptions	206
5.10	Peak strength at any relative density	209
5.11	Comparison of prediction of values of b_p with experimental data	215
5.12.1	Comparison of predictions of strength in plane strain based on p-q plot and octahedral stress ratio	219
5.12.2	Comparison of predicted plane strain strengths with experiments	221
5.13	Prediction of plane strain strength based on elasto-plastic stress-strain theory and p-q plot	224
5.14	Method of prediction of ϕ'_p	233
5.15	Comparison of prediction with experimental results	233
5.16	Summary	233

<u>CHAPTER 6</u>	<u>STRESS-STRAIN RELATIONSHIP IN TRIAXIAL AND PLANE STRAIN CONDITIONS</u>	237-355
6.1	Introduction	237
6.2	Applicability of hyperbolic stress- strain model to plane strain condition	238
6.3	Prediction of stress-strain curves in plane strain	252
6.3.1	Relationship between ϵ_{1fc} and ϵ_{1fp}	253
6.3.1.1	Form of required equation	254
6.3.2	Relationship between R_{fc} and R_{fp}	259
6.4	Prediction of stress-strain curve in plane strain at any lateral pressure	271
6.5	Prediction of stress-strain curve at any value of b ($0 < b < b_p$)	280
6.5.1	Comparison of predicted and experimental stress-strain curves	283
6.6	Prediction of volumetric strain by 'equi- valent lateral stress' method	289
6.6.1	Prediction of volumetric strain from concept of equivalent lateral stress	289
6.6.2	Calculation of equivalent lateral pressure	297
6.6.3	Procedure to develop plane strain volumetric-strain curve in triaxial test	302
6.6.4	Applicability of concept of equivalent lateral pressure	305
6.7	Prediction of volumetric strain (and volumetric strain rate) from stress- dilatancy theory	315
6.7.1	Relationship between K_c and K_p	317
6.7.2	Prediction of dilatancy factor in plane strain	328
6.7.3	Prediction of volumetric-strain curve	329
6.8	Prediction of strength in plane strain	338
6.8.1	Development of method	338
6.8.2	Verification of predictions	343
6.9	Prediction of lateral strain	348
6.10	Summary	352

<u>CHAPTER 7</u>	<u>FAILURE CRITERIA IN GENERAL STRESS STATE</u>	<u>356-385</u>
7.1	Introduction	356
7.2.1	Relative magnitude of strength in triaxial compression and extension	357
7.2.2	Relative magnitude of strength in triaxial compression and plane strain	358
7.2.3	Relative magnitude of strength in plane strain and triaxial extension	359
7.3	Shapes of $b-\phi'$ curve	359
7.4.1	Development of proposed failure criteria	369
7.4.2	Proposed failure criteria	377
7.5	Concluding remarks	379
<u>CHAPTER 8</u>	<u>CONCLUDING REMARKS-SUMMARY OF CONCLUSIONS</u>	<u>386-390</u>
	REFERENCES	391-409

* * *