

CONSTITUTIVE MODELLING OF ROCKFILL MATERIALS

by

ASHOK KUMAR GUPTA

Department of Civil Engineering

Submitted

in fulfilment of the requirements of the degree of

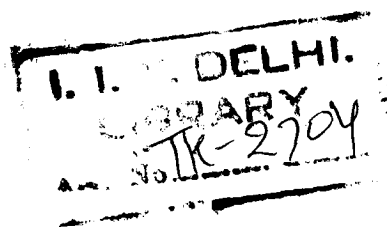
DOCTOR OF PHILOSOPHY

to the



INDIAN INSTITUTE OF TECHNOLOGY, DELHI

FEBRUARY, 2000



627.824.3
GUP-C

Dedicated

TO

MY PARENTS,

My Wife

MAMTA

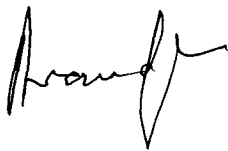
and

My Children

ASTHA & AKANKSHA

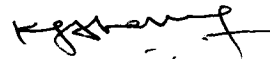
CERTIFICATE

This is to certify that the thesis entitled “**CONSTITUTIVE MODELLING OF ROCKFILL MATERIALS**” being submitted by **Mr. Ashok Kumar Gupta** 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. A. VARADARAJAN)

Professor



(DR. K. G. SHARMA)

Professor

Department of Civil Engineering

Indian Institute of Technology

New Delhi- 110 016

ACKNOWLEDGEMENTS

I feel great pleasure in expressing my deepest gratitude to my supervisors, Professor (Dr.) A. Varadarajan and Professor (Dr.) K. G. Sharma for their valuable guidance, keen interest, constant encouragement, and continuous support besides inspiration and kind help rendered to me during the entire period of this research work.

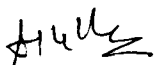
I am grateful to the authorities of Regional engineering college (REC), Hamirpur, (HP), All India Council for Technical Education (AICTE), New Delhi and Ministry of Human Resource Development (MHRD), Government of India, for sponsoring me for Ph.D. at Indian Institute of Technology, Delhi under Quality Improvement Programme (QIP) scheme. I would like to thank my colleagues in the Department of Civil Engineering at REC Hamirpur for sharing my work load during my absence for this study.

I take this opportunity to thank Dr. K. Venkatachalam, Director, Central Soil and Materials Research Station (CSMRS), New Delhi for allowing me to carry the experimental work at CSMRS. I also thank his team of scientists and the staff members of rockfill technology unit, CSMRS for their help during the experimental work.

I would like to express my gratitude to my friends Dr. Anand S. Gupta, Dr. Mahmoud Hashemi Esfahaniam, Mr. A. Ravi Kumar, and Mr. Syed Mohd Abbas for their help and lively discussions at various stages of work.

I extend grateful appreciation to my father-in-law, mother-in-law and their family members who have contributed in many ways.

I am deeply indebted to my parents, wife Mamta and my children Astha and Akanksha for the immense patience and encouragement which inspired me to do this research work.


(Ashok K. Gupta)

ABSTRACT

Rockfill dams are increasingly used in the hydro-power projects. The behaviour of rockfill material used in the construction of these dams is affected by number of factors such as mineral composition, particle size, shape, grading and relative density of the rockfill. The understanding and characterisation of the behaviour of rockfill material are of considerable importance for the analysis and the design of the rockfill dams.

For the present investigation two different types of rockfill materials from two dam sites have been chosen. Drained triaxial tests have been conducted on three modelled rockfill materials under various confining pressures. For the tests, large size triaxial test apparatus have been used. From the results of the experimental investigations it is found that both the materials show increase in the axial strain at failure and the breakage factor, with increase in particle size. The volumetric strain at failure, and the value of ϕ increase with the size of the particles for the river bed material but, these values decrease with the size of the particles for the blasted material.

The behaviour of the modelled rockfill materials has been characterised using the elasto-plastic theory based on disturbed state concept (DSC). Material parameters for the two modelled rockfill materials have been determined. Comparing the material parameters for the two modelled materials, it is found that i) the value of k increases and value of ν decreases with maximum particle size of both materials. But the variations of n' value shows opposite trend, ii) the variation of ultimate constants with maximum particle size is opposite in nature, iii) phase change parameter is same and is constant, iv) variation of hardening parameters with maximum particle size shows opposite trend, v) non-associative parameter is almost constant for both, vi) variation of disturbance parameters with maximum particle size shows opposite trend.

The stress-strain-volume change responses have been predicted for the two types of modelled rockfill materials using the single point method (SPM) and finite element method (FEM). The predicted stress-strain-volume change response by SPM and FEM are same and close to the observed experimental results for both the modelled materials. Material parameters for the prototype rockfill material have been predicted using the material parameters for the various sizes of the modelled rockfill material. A curve fitting procedure has been adopted for this purpose.

Ranjit Sagar rockfill dam has been analysed under construction loading using finite element method. Two dam sections viz. one consisting of only rockfill and another consisting of rockfill in the upstream and down stream shells and a clay core have been used. The two dam sections have been analysed using the two different constitutive models i.e. elasto-plastic model based on DSC and hyperbolic model to compare the results. The material parameters predicted for the prototype size of rockfill material have been used in the analysis. From the results of the two analyses, the following conclusions are drawn:

- (i) The nature of displacement contours predicted by the two constitutive models are somewhat similar in nature.
- (ii) The magnitudes of the displacements predicted by the hyperbolic model are higher than those predicted by the model based on DSC. The location of the maximum displacement is significantly different in the two cases.
- (iii) The nature of variation of the stresses as well as the magnitude of stresses as predicted by the two models are comparable to each other.

In general, it appears that for the prediction of stresses any of the constitutive models can be used but, to predict the accurate displacements more realistic constitutive model (such as DSC) should be adopted in the analysis.

CONTENTS

	Page No.
<i>CERTIFICATE</i>	i
<i>ACKNOWLEDGEMENTS</i>	ii
<i>ABSTRACT</i>	iii-iv
<i>CONTENTS</i>	v-xii
<i>LIST OF FIGURES</i>	xiii-xxi
<i>LIST OF TABLES</i>	xxii-xxiii
<i>LIST OF SYMBOLS AND ABBREVIATIONS</i>	xxiv-xxx
CHAPTER 1 INTRODUCTION	1-5
1.1 GENERAL	1
1.2 OBJECTIVES	3
1.3 SCOPE	3
1.4 ORGANISATION OF THE THESIS	4
CHAPTER 2 LITERATURE REVIEW	6-40
2.1 GENERAL	6
2.2 SPECIMEN SIZE	7
2.3 ROCKFILL MODELLING	7
2.4 PARTICLE BREAKAGE	8
2.5 TESTING OF ROCKFILL MATERIALS	9
2.6 BEHAVIOUR OF ROCKFILL MATERIALS	12
2.7 CONSTITUTIVE MODELLING	17
2.7.1 Empirical Models	19
2.7.2 Elasticity Models	19

2.7.3	Plasticity Models	21
2.7.3.1	Mohr-Coulomb Criterion	21
2.7.3.2	Drucker-Prager Yield Criterion	23
2.7.3.3	Critical State Model	26
2.7.3.4	Hierarchical Single Surface Model	29
2.7.3.5	Disturbed State Concept	32
2.7.3.5.1	Relatively Intact (RI) State	33
2.7.3.5.2	Fully Adjusted (FA) State	34
2.7.3.5.3	Disturbance Function	34
2.8	ANALYSIS OF EMBANKMENT DAMS USING FINITE ELEMENT METHOD	35
2.9	CONCLUSIONS AND SCOPE OF THE INVESTIGATION	39
CHAPTER 3	EXPERIMENTAL INVESTIGATION	41-66
3.1	GENERAL	41
3.2	THE PROJECTS	41
3.3	MATERIAL USED	46
3.3.1	Material of Ranjit Sagar Dam Site	46
3.3.2	Material of Purulia Dam Site	46
3.4	GRADATION OF MATERIAL	48
3.4.1	Gradation of Prototype Materials	48
3.4.2	Gradation of Modelled Materials	48
3.5	MATERIALS USED FOR TESTING	49
3.6	EXPERIMENTAL PROGRAMME	52
3.7	EXPERIMENTAL SETUP	53
3.7.1	Triaxial Shear Setup (1)	54

3.7.1.1 Axial Loading Unit	54
3.7.1.2 Confining Pressure Unit	57
3.7.1.3 Measurement of Strains	57
3.7.1.4 Rubber Membranes	57
3.7.2 Triaxial Shear Setup (2)	57
3.7.2.1 Axial Loading Unit	57
3.7.2.2 Confining Pressure Unit	60
3.7.2.3 Measurement of Strains	60
3.7.2.4 Sleeve	60
3.8 EXPERIMENTAL PROCEDURE	60
3.8.1 Preparation and Setting up of Specimen	60
3.8.2 Assembling the Triaxial Cell	61
3.8.3 Consolidation	61
3.8.4 Shearing the Specimen	63
3.8.5 Dismantling of the Specimen	63
3.9 REPRODUCIBILITY OF RESULTS	63
3.10 DATA REDUCTION	66
CHAPTER 4 EXPERIMENTAL RESULTS AND DISCUSSION	67-100
4.1 GENERAL	67
4.2 MODELLED ROCKFILL MATERIAL-RANJIT SAGAR	67
4.2.1 Stress-Strain-Volume Change Behaviour	67
4.2.2 Elastic Parameters	71
4.2.3 Strength Parameters	74
4.2.4 Particle Breakage Factor	75

4.3	MODELLED ROCKFILL MATERIAL-PURULIA	80
4.3.1	Stress-Strain-Volume Change Behaviour	80
4.3.2	Elastic Parameters	85
4.3.3	Strength Parameters	85
4.3.4	Particle Breakage Factor	87
4.4	COMPARISON	91
4.4.1	Axial and Volumetric Strain	92
4.4.2	Elastic Parameters	94
4.4.3	Strength Parameters	94
4.4.4	Breakage Factor	97
4.5	CONCLUSIONS	100
4.5.1	Effect of Confining Pressure	100
4.5.2	Effect of Size	100
CHAPTER 5	CONSTITUTIVE MODELLING	101-120
5.1	GENERAL	101
5.2	CONSTITUTIVE MODEL	101
5.3	DETERMINATION OF MATERIAL PARAMETERS	105
5.3.1	Determination of RI State	105
5.3.2	Material Constants	107
5.3.2.1	Elastic Constants	107
5.3.2.2	Disturbance Parameters	107
5.3.2.3	Ultimate Parameters	110
5.3.2.4	Phase Change Parameters	113
5.3.2.5	Hardening Parameters	113
5.3.2.6	Non-associative Parameter	114

5.4 PREDICTION	115
5.5 COMPUTER PROGRAM (PARDMR)	115
5.6 VALIDATION OF THE COMPUTER PROGRAM	119
CHAPTER 6 FINITE ELEMENT FORMULATION	121-138
6.1 GENERAL	121
6.2 FINITE ELEMENT FORMULATION	121
6.2.1 Discretisation	122
6.2.2 Approximation Model	122
6.2.3 Stress-Displacement and Stress-Strain Relations	123
6.2.4 Element Equations	123
6.2.5 Assembly of Stiffness Matrix and Introduction of Boundary Conditions	123
6.2.6 Solution for Primary Unknowns	125
6.2.7 Computation of Secondary Unknowns	125
6.2.8 Interpretation of Results	125
6.3 JOINT ELEMENTS	125
6.4 ANALYSIS	127
6.4.1 Non-Linear Analysis: Hyperbolic Model	127
6.4.2 Elasto-Plastic Analysis	128
6.4.2.1 The Solution Algorithm	129
6.4.2.2 Drift Correction Procedure	129
6.4.2.3 Convergence	130
6.5 SIMULATION FOR EMBANKMENT (SEQUENTIAL CONSTRUCTION)	131
6.6 FEATURES OF COMPUTER CODE (DSC-SST-2D)	133

6.7 THE VALIDATION OF THE COMPUTER CODE	134
6.7.1 Test Problem of Dam	134
6.7.2 Test Problem of Triaxial Test	135
CHAPTER 7 VERIFICATION OF THE CONSTITUTIVE MODEL	139-182
7.1 GENERAL	139
7.2 MATERIAL PARAMETERS FOR THE MODELLED ROCKFILL MATERIALS	139
7.3 PREDICTIONS FOR THE MODELLED ROCKFILL MATERIALS	142
7.3.1 Procedure	142
7.3.1.1 Single Point Method (SPM)	142
7.3.1.2 Finite Element Method (FEM)	142
7.3.1.2.1 Discretisation and Boundary Conditions	143
7.3.1.2.2 Loading	143
7.3.1.2.3 Material Parameters	144
7.3.1.2.4 Analysis	144
7.4 RESULTS AND DISCUSSION (MODELLED ROCKFILL MATERIALS)	144
7.4.1 Yield Surface	145
7.4.1.1 Ranjit Sagar Modelled Rockfill Material	145
7.4.1.2 Purulia Modelled Rockfill Material	145
7.4.2 Stress-Strain-Volume Change Response	145
7.4.2.1 Ranjit Sagar Modelled Rockfill Material	148
7.4.2.2 Purulia Modelled Rockfill Material	161

7.5 PREDICTIONS FOR PROTOTYPE ROCKFILL MATERIAL	161
7.6 CONCLUSIONS	175
CHAPTER 8 ANALYSIS OF A ROCKFILL DAM	183-224
8.1 GENERAL	183
8.2 THE DAM SECTION	183
8.3 FINITE ELEMENT DISCRETISATION	183
8.4 MATERIAL PROPERTIES	186
8.5 ANALYSIS	188
8.6 RESULTS AND DISCUSSION	190
8.6.1 Dam Section-I (Section with only Rockfill Material)	190
8.6.1.1 Displacements	190
8.6.1.2 Stresses	194
8.6.2 Dam Section-II (Section with Rockfill and Clay Core)	206
8.6.2.1 Displacements	206
8.6.2.2 Stresses	212
8.7 DISCUSSION	212
8.8 CONCLUSIONS	224
CHAPTER 9 SUMMARY AND CONCLUSIONS	225-228
9.1 GENERAL	225
9.2. EXPERIMENTAL STUDY	225
9.3 CONSTITUTIVE MODELLING	226
9.4 ANALYSIS OF ROCKFILL DAM	227
9.5 SUGGESTIONS FOR FURTHER WORK	228
REFERENCES	229-242
APPENDIX I	243

<i>APPENDIX II</i>	<i>244-245</i>
<i>APPENDIX III</i>	<i>246-249</i>
<i>APPENDIX IV</i>	<i>250-253</i>
<i>BRIEF BIO-DATA OF THE AUTHOR</i>	<i>254</i>