Disturbed Soil Properties and Geotechnical Design

Frontispiece

Disturbed Soil Properties and Geotechnical Design

Second edition

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For Margaret

Contents

	Foreword to the first edition	ix
	Foreword to the second edition	xiii
	Acknowledgements	xv
	About the authors	xvii
	Nomenclature	xix
01	Slip plane properties	1
	1.1. Introduction	1
	1.2. Coulomb's theory of strength	3
	1.3. Masonry in Coulomb's essay	11
	1.4. Soil properties in Coulomb's essay	14
	1.5. Recent thinking of ground as an aggregate of grains	18
	1.6. Liquefaction and critical state	23
	1.7. Coulomb's law	29
	References	31
02	Interlocking, critical states (CS) and liquefaction	35
	2.1. An interlocking soil strength component	35
	2.2. Frictional dissipation of energy and the CS	44
	2.3. Reynolds' dilatancy and Hazen's liquefied soil	48
	2.4. Hazen's liquefaction and Casagrande	51
	2.5. Herrick's liquefaction	56
	2.6. Failure at low effective stress	58
	References	60
03	Soil classification and strength	63
	3.1. Casagrande's soil classification and soil plasticity	63
	3.2. Variation of strength with water content	66
	3.3. Hvorslev's clay strength data and the CS line of clay	70
	3.4. CS interpretation of Hvorslev's shear-box data	78
	References	83
04	Limiting stress states and CS	87
	4.1. Strain circle, soil stiffness and strength	87
	4.2. Rankine's soil mechanics	96
	4.3. From the plasticity of steel frames to plastic strain in soils	101
	4.4. Skempton's parameters A and B , and CS values of c and ϕ	107
	References	116

05	Plasticity and original Cam Clay	119
	5.1. Baker's plastic design of steel frame structures	119
	5.2. The associated flow rule and Drucker's stability criterion	122
	5.3. Thurairajah's power dissipation function	125
	5.4. The OCC yield locus	128
	5.5. Test data, model modification and OCC teaching	137
	5.6. Design for deformation and mobilisable strength design	143
	5.7. Laboratory testing and geotechnical design	144
	References	145
06	Geotechnical plastic design	147
	6.1. The place of plastic analysis in design	147
	6.2. Lessons from the geotechnical centrifuge	149
	6.3. Herrick's liquefaction in models	153
	6.4. Geotechnical centrifuge developments	159
	6.5. Solving industry's problems	161
	6.6. Conclusions	163
	References	172
	Index	175

Foreword to the first edition

In my final year as an undergraduate at Oxford University, I undertook a project on the warping of asymmetrical steel beams with Dr Edgar Lightfoot. I took no formal lectures on soil mechanics, although Dr Lightfoot also gave a few lectures on slip lines and bearing capacity within an optional ‘speciality’ paper on civil engineering. He also gave me career advice along the lines that ‘there is this new theory called critical state soil mechanics, which seems to be worth investigating’. I duly bought a copy of Schofield and Wroth’s (1968) book on that subject, and so began my education in soil mechanics. I subsequently studied for my PhD with Professor Peter Wroth, and cut my teeth as a lecturer at Cambridge University in the group then headed by Professor Andrew Schofield. It is therefore with humility, and a sense of the wheel having turned full circle, that I find myself writing a foreword to this ‘retrospective’ new book by Andrew; indeed, I have a sense of being back under examination, wondering what grade my former professor will assign.

Much of this book describes the developments leading to the original Cam Clay model, focusing on fundamentals of the shearing of soil. The aim is to lay the groundwork of understanding that should form the basis of geotechnical design, guiding engineers towards the class of behaviour to be expected under different combinations of effective stress and water content. There are a few equations, but simple ones; much greater challenge rests in the arguments put forward regarding soil behaviour and the intellectual effort needed to keep pace with the author. After the Special Lecture that he delivered at the 2001 International Society of Soil Mechanics and Geotechnical Engineering in Istanbul, he commented that it was ‘heard without comprehension’. The lack of comprehension was not to do with the complexity of concepts or algebra, but with grasping the underlying message and appreciating the gap between the understanding that many experienced academic and practising engineers do indeed have, and the misleading language and teaching that pervades much education in soil mechanics.

The book is divided into six chapters, which progress from the simple planar sliding of soil towards plastic design in geotechnical engineering. But Andrew Schofield is not constrained by sequence, and rather than write a conventional textbook, he had in mind the sort of book that ‘engineers might read on a flight

and leave on their office coffee tables'. The 'coffee table' image came from a reviewer of the proposed book, perhaps meant as disparaging, but is excellent advice here: the book *invites* reading at a single sitting, both because it is intensely interesting, and because of the author's global approach, with much cross-referencing – across the centuries as well as between chapters. After reading, it is a book to be left readily available for frequent dipping, both for the pleasure in the historical anecdotes spread across the last 400 years and to reinforce the fundamental understanding of soil behaviour conveyed in the book.

The frontispiece illustration is the lynch-pin to the ideas the author wishes to convey, and is referred to throughout this book. Heroes (Coulomb, Hvorslev and Taylor) and villains (Terzaghi in particular) are identified in Chapter 1, with detailed discussion of the nature of friction, the role of interlocking, and the misinterpretation of Hvorslev's empirical envelope of peak strengths as indicating true cohesion. The second chapter focuses on the critical state, correcting Casagrande's critical void ratio to allow for the effective stress level, and liquefaction, contrasting extreme forms related to ultra-high void ratio, or to near-zero effective stress. Historical anecdotes replace the usual glossy pictures of a coffee table book.

There are frequent (positive) quotations from Terzaghi's writings in the literature, but inevitably for someone so fond of dogma it is not difficult to find negative examples. His assertion of cohesive bonding between soil grains, and rejection of the usefulness of Rankine's limiting stress states, are two such examples that are discussed at some length in Chapters 3 and 4. In defence of his (c , ϕ) strength model, Terzaghi did advocate that clay should be tested 'under conditions of pressure and drainage similar to those under which the shear failure is likely to occur in the field'. However, that caveat seems to have been overlooked and, even today, the (c , ϕ) strength model is taught widely and used inappropriately. Current teaching is littered with calculations where the effective stress differs significantly from the conditions under which the strength measurements used to generate the c - ϕ fit were derived. Modern teaching often applies such a model to bearing capacity analyses on sand, without adjustment for the resulting high stresses, or to the stability of slopes and cuts, where pore pressure dissipation would destroy any apparent c . Students who understand soil strength according to Andrew's approach

are wise to these dangers. A modest ambition for the present book might be to see the words ‘cohesion’ and ‘adhesion’ excised from our soil mechanics vocabulary, replacing them with, respectively, ‘shear strength’ (at a given water content and effective stress level) and, on the rather rare occasions where it is appropriate, ‘cementation’.

The basis of the original Cam Clay model, including its background in the theory of plasticity and the experimental evidence for the internal plastic work, is described in Chapter 5. Limitations of this simple model in terms of anisotropy, soil sensitivity and cyclic loading are readily acknowledged. As a basic framework for teaching, however, the model still has much to offer, and it is refreshing to be taken through the careful experimental data on reconstituted clays on which it is based, and the (now classic) examination questions from the Cambridge Tripos of nearly 40 years ago. Once armed with the simple concept of wet and dry of the critical state line, students will understand whether a sample will wish to contract or dilate, whether pore pressures generated during undrained shearing will tend to the positive or negative, and conditions where ductile plastic deformation might change to brittleness and fracture. The ability of the model to quantify these states is immediately appealing to modern students, rather than them having to digest purely qualitative explanations.

Andrew Schofield deserves to be regarded as one of the geniuses of soil mechanics of the latter half of the 20th century. His Fellowship of the Royal Society is based on his two remarkable contributions of original Cam Clay and the promulgation of centrifuge modelling in geotechnical engineering beyond its origins in Russia. It is appropriate, therefore, that the final chapter in this book is devoted to the application of the principles of critical state soil mechanics by means of centrifuge experiments conducted under conditions of stress similitude.

This is a rewarding book, full of insights, both technical and personal. It reinforces ideas described in the original Schofield and Wroth book *Critical State Soil Mechanics*, and in Schofield’s 1980 Rankine Lecture. For the unconverted, it is an invitation to re-examine your basic understanding of soil behaviour. For the converted who might be tempted to dismiss the book too lightly, it is a call to ensure that our

teaching, and the vocabulary and nomenclature we use
in describing strength models for soil, reflect
accurately the underlying concepts.

Professor Mark F. Randolph
The University of Western Australia, Perth

Foreword to the second edition

This second edition of an excellent book explaining critical state soil mechanics (CSSM) and geotechnical centrifuge model testing contains a considerable amount of new material of great interest to civil and geotechnical engineers. Much of this is a fascinating odyssey through many of the seminal engineering contributions in the past that have led to the key theories of shear strength, plasticity and CSSM.

On shear strength, the reader is taken through the exploits of Marshall Vauban (1633–1707), who built many forts to defend France and formed the army engineer corps (Corps Royal du Génie) to assist in the attack and defence of forts with earth-retaining structures. This led to Coulomb's experience of construction of similar fortifications as a young French Royal Engineer and to him proposing his famous equation to compute the stability of Vauban's defences. The book continues with interesting descriptions of how Amontons (1699) had proposed that interlocking caused friction, and much later of how Taylor (1948) in his seminal work found experimentally that ultimate steady friction and interlocking must be summed to give the peak strength on slip planes in dense sand. We read of Reynolds describing dilation of sand in his famous rubber balloon demonstration in 1902 and of Casagrande later introducing the concept of the critical void ratio in the context of flow slides, liquefaction and the failure of the Fort Peck Dam. All of this, combined with the powerful concepts of plasticity, is nicely brought together to explain the thinking behind the unified theory of the original Cam Clay model and of CSSM. The book also has new additions relating to recently published work on liquid and plastic limits and strength variation with water content.

Plastic design is an essential part of a well-grounded engineering education. Just as the upper- and lower-bound theories of plasticity allow the behaviour of structures to be bounded, plastic design is no less important in geotechnical engineering. This edition illustrates this very well and has also expanded the section on centrifuge modelling to reflect recent developments. It brings out the message that simple constitutive analysis based on CSSM, notably Bolton's mobilisable strength design (MSD), complemented by centrifuge modelling gives a route to effective safe design. It illustrates how geotechnical engineers can study ductile or brittle failures using model tests on soil under appropriate stress levels using a geotechnical centrifuge. Most importantly, it

shows how such model tests can inform engineers of failure and deformation mechanisms that might not have otherwise been evident. The probable mechanism of collapse of an already completed tunnel in Hull in 1999 was uniquely explained by a series of centrifuge model tests.

Tunnelling and excavation ground movement mechanisms obtained from centrifuge tests have had a seminal influence on the design and construction of urban tunnelling schemes around the world, particularly in relation to the prediction and control of settlements by new techniques such as compensation grouting.

Whether it be on such diverse topics as the behaviour of foundations of offshore structures under storm loading, the effects of earthquakes and liquefaction, or the understanding of tunnelling through soils under high stresses, this excellent second edition illustrates the myriad of opportunities for civil engineers to gain important insights from the powerful concepts of CSSM and geotechnical centrifuge testing. The book is also a wonderful tribute to Professor Andrew Schofield – a visionary civil engineer whose research in soil mechanics and geotechnical engineering has been transformational.

Professor Lord Robert Mair
President, Institution of Civil Engineers, 2017–2018

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About the authors

Andrew Schofield FREng, FRS is a soil mechanics engineer and an Emeritus Professor of geotechnical engineering at the University of Cambridge. Andrew studied engineering and graduated from Christ's College Cambridge in 1951. After a period in Malawi, researching lateritic soils and low-cost road construction, he returned to Cambridge University to work with Professor Kenneth H. Roscoe on his PhD, which he completed in 1961. He became an Assistant Lecturer in 1961 and was elected Fellow of Churchill College, Cambridge in 1964.

Andrew returned to Cambridge in 1974 and was appointed as a professor in the Cambridge University Engineering Department to lead the Soil Mechanics group. Working with a mechanical design engineer, Phillip Turner, he developed a 5 m radius geotechnical centrifuge at Cambridge University that continues to be used.

In 1993, on the joint nomination of the Presidents of the Institution of Civil Engineers (ICE) and the Royal Society, the ICE awarded Andrew the James Alfred Ewing Gold Medal for special meritorious contributions to the science of engineering in the field of research. He has also been awarded the US Army Distinguished Civilian Service Award. More recently, he was the recipient of the Royal Academy of Engineering Sir Frank Whittle Medal in recognition of sustained achievement throughout his career.

Andrew retired from the university in 1997, but his continued work is evidenced by his involvement in the Schofield Centre for Geotechnical and Environmental Research.

Stuart Haigh MEng, PhD is a University Senior Lecturer at the University of Cambridge, the Assistant Director at the Schofield Centre for Geotechnical Process and Construction Modelling, and has been involved in the field of geotechnical engineering for over 20 years.

Stuart obtained his BA, MA, MEng and PhD in Geotechnical Engineering from the University of Cambridge and has extensive experience using geotechnical centrifuge modelling to investigate a wide array of research problems, ranging from liquefaction of slopes during earthquakes to the long-term behaviour of foundations for offshore wind-turbines. He has published more than 100 journal and conference papers, and was a member of the Géotechnique Advisory Panel from 2012 to 2015.

Nomenclature

Abbreviations

ANS&A	Andrew N. Schofield & Associates Ltd
BRS	Building Research Station (now Building Research Establishment, BRE)
CS	critical state at which an aggregate of grains can flow steadily at constant stress and volume
CVR	critical voids ratio (an early name for CS)
FE	finite element, in a computation to solve a problem
ISSMFE	International Society of Soil Mechanics and Foundation Engineering (now International Society of Soil Mechanics and Geotechnical Engineering, ISSMGE)
NC	normal compression
OCC	original Cam Clay
OCR	over-compression ratio
PPT	pore pressure transducer
SOED	<i>Shorter Oxford English Dictionary</i>
SRC	Science Research Council
SSA	simple shear apparatus
TC2	Technical Committee 2 of the ISSMGE
USACE	US Army Corps of Engineers
WES	Waterways Experimental Station

Notation

A, B	Skempton's pore pressure parameters in Equation 4.15, $\Delta u = B[\Delta\sigma_3 + A(\Delta\sigma_1 - \Delta\sigma_3)]$
$\bar{B}$	Skempton's pore pressure parameter in Equation 4.16b, $\Delta u = BA \Delta\sigma_a = \bar{B}\Delta\sigma_a$
c	cohesion
c'	Hvorslev's true cohesion
e	voids ratio
G_s	specific gravity of soil solids
g	acceleration
I_L	liquidity index, $I_L = (w - w_p)/(w_L - w_p)$
n	porosity, $n = e/(1 + e)$
n_0	Casagrande's (1936) critical porosity
p'	mean normal effective stress
q	deviator stress
s	plane strain mean confining stress, $s = (\sigma_1 + \sigma_2)/2$
t	plane strain deviatoric stress, $t = (\sigma_1 - \sigma_2)/2$
u	pore pressure
v	specific volume of aggregate
w	water content ratio

w_L	water content at the liquid limit
w_P	water content at the plastic limit
x	shear box displacement (Figure 1.2(a))
y	shear box rise (Figure 1.2(a))
Γ	CS soil constant
γ	weight of a unit volume of soil, $\gamma = \gamma_w(G_s + e)/(1 + e)$
γ_w	weight of a unit volume of water
ε	strain
η	generalised stress obliquity in a triaxial test, $\eta = q/p'$
κ	slope of unload–reload behaviour (Figure 2.9(b))
λ	slope of critical state line (Figure 2.9(b))
M	CS friction constant
μ	friction coefficient
σ	total stress normal to a plane
σ'	effective stress
τ	shear stress on a plane (Figure 1.2(a))
ϕ	angle of friction
ϕ_d	drained angle of friction