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Disturbed Soil Properties and Geotechnical Design

Second edition

Andrew Schofield and Stuart Haigh

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Disturbed Soil Properties and Geotechnical Design, Second edition describes the developments leading to the original Cam Clay model, focusing on fundamentals of the shearing of soil. The first edition explained and illustrated fallacies in past work of engineering geologists, and laid groundwork for the understanding that should form the basis of modern geotechnical design.

With the changing environment, and the increasing size of construction projects, engineers now need a better understanding of ground behaviour to prevent future catastrophes such as the 1976 Teton Dam failure shown on the cover. The further additions in this book will help geotechnical engineers acquire this knowledge.

Disturbed Soil Properties and Geotechnical Design, Second edition

- provides an outline of the energy-based Cam Clay approach that can predict geotechnical deformations
- illustrates further fallacies in commonly used c-ϕ Coulomb soil mechanics
- describes the use of centrifuge modelling in geotechnical design, based on examples from the last four decades.

Once armed with the simple concepts of wet/weepy and dry/thirsty sides of the critical state line, readers will better understand if soil will tend to contract or dilate in drained shearing, and if pore pressures caused by undrained shearing will be positive or negative.

Full of technical and personal insights, this is a rewarding book that forces the rethinking of modern geotechnical engineering. Much like the first edition, this book remains an invitation for the unconverted to re-examine the basic understanding of soil behaviour, and for the converted to ensure that the teaching, vocabulary and nomenclature used in describing strength models for soil, accurately reflect the underlying concepts.

The cover image is a photograph of the Teton Dam.

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ISBN 978-0-7277-6155-2

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Published by ICE Publishing, One Great George Street, Westminster, London SW1P 3AA.

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A catalogue record for this book is available from the British Library.

ISBN 978-0-7277-6155-2

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Commissioning Editor: Laura Balchin
Production Editor: Madhubanti Bhattacharyya
Market Development Executive: Elizabeth Hobson

Typeset by Academic + Technical, Bristol
Index created by Milla Hills
Printed and bound by TJ International, Padstow

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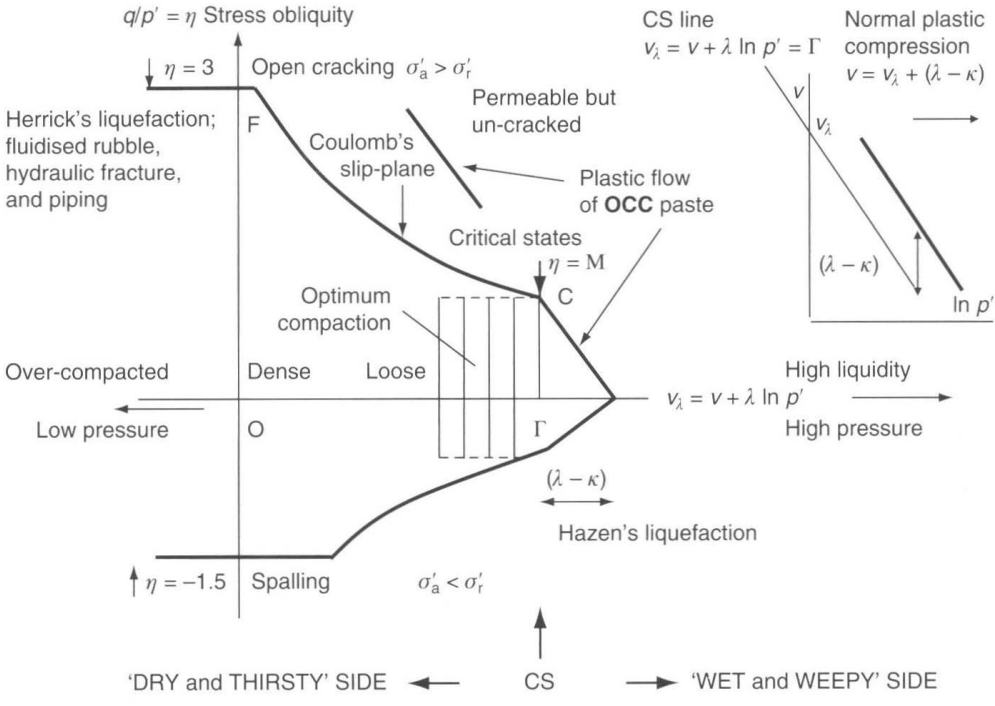
Disturbed Soil Properties and Geotechnical Design

Frontispiece



(v_λ, η) map of disturbed saturated soil behaviour

For Margaret

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

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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

Acknowledgements

The authors would like to express their thanks to Arul Britto and Chris Szalwinski for their help in reading through the text.

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