Centrifuge Modelling for Civil Engineers

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To my parents for allowing me the freedom to pursue my dreams.
To my beloved Raji for supporting me every step of the way.
To Spandana for becoming an independent young doctor and for not being too demanding on my time and Srikanth for coming of age and discussing intelligently the contents of this book.

Foreword

Every textbook reflects the character and experience of its author. Gopal Madabhushi arrived in Cambridge in 1988 to study soil dynamics for a PhD under Andrew Schofield. He used both finite element simulations and centrifuge models to investigate the dynamic response of towers on spread foundations resting on saturated sands. In his thesis he was at pains to discuss the required nature and remoteness of the system boundary, whether numerical or physical, if the interaction of interest was to be displayed without untoward distortion. Having achieved that, he went on to introduce some rather simple single-degree-of-freedom characterizations that could capture the essence of the behaviour that he had observed, without disregarding the complex and varying response of the soil. This mixture of interests, abilities, and concerns provided a firm foundation for his future academic career, all but one year of which has been spent in Cambridge. It also forms the basis of this book, which is much enhanced by Professor Madabhushi's generous use of examples drawn from the shelves of the Roscoe Library at the Schofield Centre, which record the successful exploits of scores of centrifuge modellers who have worked there since the 1970s.

The reader is invited in Chapter 1 to consider whether the conventional routines of civil engineering, with its limit analyses and safety factors, will provide an adequate level of assurance regarding the safety and serviceability of the planned facility. If performance is to be guaranteed, the designer is advised to consider both numerical and physical modelling to clarify the issues. The complementarity of these techniques is considered further in Chapter 2, where the best attributes of each are drawn out. This provides a purposeful context for a book on physical modelling, whether it is to be read by an advanced student or by a project engineer who is wondering what benefits there may be in additionally commissioning centrifuge tests.

Chapters 3 to 6 cover the basic principles of centrifuge modelling, starting from a revision of circular motion in Chapter 3 in case the reader has forgotten the difference between centripetal accelerations and centrifugal forces, or has previously skated too quickly over Coriolis. Scaling factors and the meaning of "prototype" in relation to "model" are carefully discussed in Chapter 4, including how to harmonize the timescales arising from different behavioural mechanisms—so central to the modelling of seismic liquefaction phenomena which Professor Madabhushi has done much to clarify. The various alternative configurations of geotechnical centrifuges are introduced in Chapter 5, together with the classes of problems for which they are best suited. And Chapter 6 covers the various respects in which a centrifuge differs from a planet, with its inside-out body force that converges to a point "above" the soil surface, for example, and the Coriolis "wind" that seems to blow fast-moving particles sideways as they "fall." Of course, all this is done properly, from first principles.

Chapters 7 to 9 cover the essential technology that enables centrifuge modelling, and do so bearing in mind the needs of a nonexpert. So while soil containers are introduced in Chapter 7, so are the means of getting the soil into the containers in the desired condition. The author takes special care to explain how to create saturated sand layers of known relative density, and saturated clay layers of known stress history, prior to illustrating how to verify that the model soils have the intended characteristics through the use of in-flight investigation tools such as CPTs and seismic waves. Chapter 8 deals with instrumentation and image analysis, and Chapter 9 with data acquisition, again from the perspective of an interested and intelligent novice.

Chapters 10 to 14 cover some of the geotechnical applications that have benefited from insights that arose through centrifuge modelling shallow foundations in Chapter 10, retaining walls in Chapter 11, piles in Chapter 12, and in Chapter 13 sequence-dependent construction interactions such as excavations with propping, or tunnel construction that affects existing piled foundations. The final Chapter 14 covers dynamic centrifuge modelling, with application to earthquake-induced soil–structure responses. This has been the central research mission of Professor Madabhushi, so it is no surprise that the issues are described in detail, and dispatched authoritatively.

Indeed, the whole book reflects the hands-on style of its author. So it should serve as an excellent primer and a thorough introduction to the topic of centrifuge modelling, as well as to its variety of uses in geotechnical and foundation engineering. As I retire from the position of director of the Schofield Centre, and as Gopal Madabhushi takes over from me, I wish him well. And I recommend this thoughtfully crafted book to its future readers.

Malcolm Bolton, FREng

Preface

The first time I ever heard the word centrifuge modelling was during the late afternoon lectures given by Professor Chandrasekaran at the Indian Institute of Technology, Bombay. The course was about finite element methods in geomechanics but Professor Chandrasekaran would philosophise that if we wanted a "real" understanding of failure mechanisms we should really be doing centrifuge modelling. On my arrival in Cambridge Professor Andrew Schofield drove me to the centrifuge centre to show me the beam and drum centrifuges. In those days I was still an ardent numerical modeller so I was looking for the big mainframe computers. Only a year later did I slowly come to realise the unique opportunity centrifuge modelling provided, and started my first centrifuge tests on tower structures subjected to earthquake loading. Over the last 25 years I have been involved in a wide variety of centrifuge tests and often complement them with numerical analysis. This combination of centrifuge modelling to clarify mechanisms and use of centrifuge data to verify numerical procedures is a powerful one and is reflected in this book.

The origins of this book took shape from my lecture course that introduces new research students to centrifuge modelling. It also benefits from the various short courses I gave at IIT Bombay with support from the Royal Society, United Kingdom, and the Department of Science and Technology, India, and the training course offered at the IFSTTAR centrifuge facility in Nantes, France, under the European Union–funded SERIES project. I felt that there was a need for a book that makes the principles of centrifuge modelling, the scaling laws and the techniques used accessible to practicing civil engineers. They can refer to this book and see how they can use it effectively in solving complex geotechnical problems. The applications chapters of this book should provide an overview of the kinds of problems that can be studied effectively using centrifuge modelling. For graduate research students it offers detailed descriptions of the equipment used in centrifuge modelling, the instrumentation that can be deployed in centrifuge models and the signal processing techniques required to make the best use of the centrifuge test data. Early in their research they can use the applications chapters to see what types of tests are possible.

The book begins with an outline of a generalized design process employed for civil engineering projects. With the modern shift towards performance-based design, it is inevitable that geotechnical engineers will be called upon to estimate deformations and not just the ultimate load-carrying capacities. This requires a good understanding of the fundamental failure mechanisms at play and the mobilised strains in the soil under a given loading. The second chapter emphasizes the need for both physical and numerical modelling and aims to establish the complementarity of the two techniques. Chapter 3 is a brief revision of basic mechanics that is useful for an understanding of centrifuge modelling. The use of polar coordinate systems for expressing acceleration and velocity of centrifuge models is quite useful and these are derived from first principles in this chapter.

Chapter 4 introduces the basic principles of centrifuge modelling and explains the concepts of a prototype and a centrifuge model. It builds up to the derivation of scaling laws that relate the behaviour of a prototype and the centrifuge model. Scaling laws for seepage velocity, consolidation time, force and so on, are derived. In addition, the ability of centrifuge testing itself to validate the scaling laws is presented using the so-called modelling of models. Chapter 5 introduces the various types of centrifuges, such as beam and drum centrifuges, along with examples of each type. The suitability of different centrifuges for various problems is also explained. Chapter 6 describes some of the errors and limitations of centrifuge modelling. Each of these is considered in detail and an effort is made to quantify them.

Centrifuge modelling requires some specialist equipment and these are presented in Chapter 7. This chapter describes the model containers and actuators that are used routinely in centrifuge testing. The techniques used for sample preparation are elaborated. In-flight characterization of soil samples is described using various methods such as miniature CPT and shear wave velocity measurement. Chapter 8 describes the instrumentation that is commonly used in centrifuge models. Of course this area is constantly growing and this chapter aims to provide a comprehensive overview of instrumentation currently being used. Chapter 9 deals with centrifuge data acquisition systems and signal processing techniques. It introduces the concepts of electrical noise removal using digital filtering with increasing levels of sophistication.

Chapters 10 to 14 cover different applications of centrifuge modelling. Each chapter reviews the physical testing pertaining to that problem and builds to show the types of experiments that were carried out and the main outcome of the centrifuge test data. Shallow foundations are considered in Chapter 10, and the main emphasis of this chapter is the visualization of the failure mechanism generated below the foundation. Retaining walls are considered in Chapter 11 and in this chapter the main focus is on the measurement of bending moments in the wall, lateral displacement suffered by the walls and soil deformations in front and behind the wall. Pile foundations are considered in Chapter 12 and the main emphasis here is the modelling of axial and laterally loaded piles. Piles wished into place and piles driven in-flight are also discussed. Chapter 13 deals with modelling of construction sequences in a centrifuge test. This chapter deals with constructing new geotechnical structures in the vicinity of existing infrastructure and effects the new build may have on the older structures.

Chapter 14 deals with modelling of dynamic events. One of the advantages of centrifuge modelling is that we can model devastating or extreme load scenarios well before they occur in real life. This allows us to predict accurately how either existing or new structures would behave under a strong earthquake event or under extreme wind loading caused by a hurricane. This chapter deals with additional scaling laws required for dynamic events and the specialist actuators and model containers required. Emphasis is placed on earthquake loading, although the same principles could be applied for other types of dynamic events. Examples of dynamic soil–structure interaction problems and soil liquefaction problems are considered.

Graduate students may wish to go through Chapters 1 to 9 and then pick the applications chapter that is closest to the problem they wish to investigate. Of course they can read other applications chapters later to provide a more comprehensive view of centrifuge modelling. Practicing engineers who want to learn about centrifuge modelling may wish to concentrate on Chapters 3 to 8 to obtain a good overview of the modelling techniques and instrumentation used and then move on to the applications chapters to see what types of problems can benefit from centrifuge modelling.

Finally I would like to say that much of the book relies on developments that took place in centrifuge modelling at Cambridge. This is mainly due to my own experiences, and readers must realize that there are other excellent centers where centrifuge modelling is flourishing. The contents of this book bring together the research carried out by many researchers. However, any omissions or errors in this book are entirely mine.

Acknowledgements

The list of acknowledgements is vast but I wish to start by thanking all the researchers past and present at the Schofield Centre, for the stimulating atmosphere they create. I wish to thank Prof. Andrew Schofield for introducing me to centrifuge modelling and for providing a historical perspective to this book. I must also thank Prof. Malcolm Bolton for supporting me over the years and writing the foreword to this book on very short notice. My other geotechnical colleagues in the Cambridge Soil Mechanics group, particularly Prof. Robert Mair must be acknowledged for their support. I must also thank Prof. V. S. Chandrasekaran for the interactions we had during the development of the Indian centrifuge as these gave me a good insight into the design aspects. Similarly I must thank Prof. Bruce Kutter for the interactions and use of their centrifuge facilities during my sabbatical at the University of California, Davis. I must thank Prof. Sarah Springman of ETH, Zurich, for her support over the years.

Special mention must be made of Dr. Ulas Cilingir for the finite element analyses used in Chapter 2. I must also thank Dr. Stuart Haigh for the discussions we had from the early stages of this book. I must thank Drs. Raji and Spandana Madabhushi and Mr. Srikanth Madabhushi for proofreading the draft chapters of this book. Dr. Giovanna Biscontin must also be thanked for the final proofreading of the book and her feedback, soon after her arrival from Texas A&M.

The success of centrifuge modelling depends to a large extent on excellent technical support, both mechanical and electronics/instrumentation. I have learned a lot over the years from the excellent technical team at Cambridge, from Chris Collison, Neil Baker and the late Steve Chandler to the current-day technicians at the Schofield Centre, John Chandler, Kristian Pather, Chris McGinnie, Mark Smith and Richard Adams. Special mention must also be made of the excellent administrative support provided by Anama Lowday.

Author

Dr Gopal Madabhushi is a professor of civil engineering at the University of Cambridge, UK and the director of the Schofield Centre. He has over 25 years of experience in the areas of soil dynamics and earthquake engineering. His expertise extends from dynamic centrifuge modelling to the time domain finite element analyses of earthquake engineering problems. He has an active interest in the areas of soil liquefaction, soil–structure interaction, and liquefaction-resistant measures and their performance. He has an active interest in the biomechanics of hip replacement surgeries.

He has acted as an expert consultant to the industry on many geotechnical and earthquake engineering problems, for example, Mott MacDonald, Royal Haskonig, and Ramboll-Whitby, UK. He has an active interest in post-earthquake reconnaissance work and has led engineering teams from the UK to the 921 Ji-Ji earthquake of 1999 in Taiwan, the Bhuj earthquake of 2001 in India, and many other missions. Dr Madabhushi served as the chairman of Earthquake Engineering Field Investigation Team (EEFIT) that runs under the auspicious of the Institute of Structural Engineers, London.

He was awarded the TK Hsieh award in 2005, 2010, and 2013 by the Institution of Civil Engineers, UK, the BGA medal in 2010 given by the British Geotechnical Association, the Shamsher Prakash Research Award in 2006, Medical Innovations Award in 2007, the IGS-AIMIL Biennial award in 2008, and the Bill Curtin Medal in October 2009 by the Institution of Civil Engineers, UK, for his contributions in the area of soil dynamics, tsunamis, and earthquake engineering. He has written 103 journal publications and 240+ papers in international conferences and workshops to date. He has authored a very successful book on the *Design of Pile Foundations in Liquefiable Soils* (Imperial College Press) and geotechnical chapters in the book *Designing to Eurocode 8* (Taylor & Francis).

A historical perspective

Geotechnical centrifuge model testing has a long history in the Department of Engineering at the University of Cambridge. For over 50 years several faculty members have formed a Soil Mechanics Group that has had 232 graduates writing PhD theses between 1951 and 2012. The first on a centrifuge modelling test was thesis number 25 in 1970 and the number of such tests has steadily increased. The author of this book, formerly my research student, graduated with a PhD in 1991, with thesis number 112, titled "Response of Tower Structures to Earthquake Perturbations"; it was one of the earliest of many contributions that followed in earthquake engineering. He later became a colleague, giving lectures to final-year students on centrifuge model testing that are the basis for this book. In this book the reader will learn about the basic principles of centrifuge modelling, along with a great variety of tests by him and others. This book expertly fills a gap on current centrifuge model testing in the literature of geotechnical engineering.

It is now 40 years since our early model tests. The early Japanese and British geotechnical centrifuge workers met our Soviet counterparts during the 1973 ISSMFE conference in Moscow. We arranged to meet at their Hydro project, met G. I. Pokrovsky, saw one of his very powerful centrifuges, and heard that tests it made had determined the choice of the location and the material used for their Nurek Dam in Tajikistan, at 300 m the world's tallest man-made dam. I was surprised when a railway engineer began to describe dynamic model tests, expecting Coriolis effects to have created difficulties; I asked if this was not so for any dynamic tests. At once Pokrovsky said, "No, it is all in my books." When I was given copies of the two books later I was surprised to see how well he had advanced Soviet dynamic testing; he compared model-cratering test data with U.S. atomic bomb crater data published by Vesic. We were later to learn that as an important defense scientist, Pokrovsky held the rank of Major General in the Red Army. At that time of the Cold War it was regrettable but inevitable that our groups could not make and maintain contact over the next 15 years. Independently the West developed earthquake and dynamic model testing with solid-state transducers giving new data for our computers to acquire and analyse. Research workers trained in the concepts behind and the performance of tests in centrifuges avoided the secrecy that hid Soviet model test experience. We got the ISSMFE to establish a technical committee and organized meetings that published many papers openly.

The modelling method is now well established. Past earthquake engineers had few observations at full scale. In $1/N$ small-scale model-tests an increased acceleration Ng acts on every grain of material in centrifuge models. A model structure is made of selected material. An observer, in safety, chooses what earthquake will perturb it. A series of models can be made of identical material, giving us very many possible research choices, and very many publication opportunities. Tests inconceivable at full scale can be proposed on this modelling principle. Once I tested a 1/300 scale model of a hazardous pollutant plume at 300 g for 100 hours in our drum centrifuge, hoping to win a research contract that modeled movement of a plume for 1000 years at full scale. All such proposals need a careful study to establish the physics of modelling. Soviet publications emphasize the importance of tests at different scales that "model a model test" in making such a study. The concept of modelling of models is introduced in Chapter 4 of this book.

Ladd and de Groot (2003) discussed a concept of soil strength that lies behind SHANSEP computation of the behaviour of soft ground; they base it on data of triaxial tests of samples representative of the site. In contrast in physical modelling I rely on the critical state concept that the strength of every aggregate of grains is the sum of two components (Schofield 2006); one due to dissipation of work in internal friction and one due to work done but not dissipated in interlocking. We use reconstituted soil such as Speswhite or E-grade kaolin to make models. I view apparent cohesion on Coulomb's slip surface as due to interlocking and dependent on the effective pressure in, and the relative density of, the aggregate of soil grains, rather than on soil chemistry. In this view an element in a model made of reconstituted soil that has followed an authentic stress path and is subject to a correctly scaled perturbation has properties that cause authentic behaviour. Our models exhibit mechanisms to be expected at full scale in the field. When engineers plan to use observational methods at full scale in the field, they should also make relevant tests at small scale in a centrifuge before the project and be prepared to make more tests if any emergency arises that needs study as the work progresses.

This book aims to cover all aspects of centrifuge modelling and make the principles of centrifuge modelling clear to practicing civil engineers and researchers new to centrifuge modelling. I wish the author every success with this book.

Andrew Schofield, FRS

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