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Soil Mechanics at Emmanuel College - Elegant, Rigorous and Relevant

J. Burland
Imperial College London
E-mail: j.burland@imperial.ac.uk

ABSTRACT: This paper was first presented by the author as a lecture at Emmanuel College, Cambridge in 2005 and was published in the College Magazine. Intended for non-experts it celebrates the contributions made to Soil Mechanics by Professor Ken Roscoe and many of his students at Emmanuel College. The author had the good fortune to be at Cambridge under Roscoe's supervision at a very important time when the basic concepts of Critical State Soil Mechanics were being developed. The paper focuses as much on the personalities of the key players as on their technical contributions.

KEYWORDS: Critical State, K.H.Roscoe, Simple Shear Apparatus, True Triaxial Apparatus, Camkometer, Leaning Tower of Pisa

1. INTRODUCTION

It is a huge honour to have been elected an Honorary Fellow of Emmanuel College and I am delighted to be invited to give this talk on the development of soil mechanics at Emmanuel College. Chris Burgoyne hinted that this is my inaugural lecture and I suppose, in a way, it is. When I gave mine at Imperial College I was told that a successful inaugural lecture requires that one should impress one's colleagues with scholarly gravitas while at the same time making the Vice Chancellor's wife laugh – or failing her, my wife Gillian! I cannot promise to do either. Neither can I possibly do justice to the whole range of soil mechanics activity at Cambridge, much of which was inspired and initiated by Ken Roscoe, Fellow of Emmanuel College from 1948 to 1970. Sadly I cannot include the centrifuge which was initiated under Roscoe's leadership and has been so ably developed and exploited by Andrew Schofield. I can only touch on the flavour of the early years under the leadership of Roscoe and talk a little about the Emma personalities who shaped the subject and who laid the foundations for what is now the foremost soil mechanics school in the world.

2. SOIL MECHANICS

Perhaps I should start by saying a little about soil mechanics and explaining my enthusiasm for the subject stressing that I am first and foremost an engineer – I like designing and building things. Soil is a highly complex and variable material. Unlike other construction materials like concrete and steel, the soil mechanics (geotechnical) engineer has almost no control over the mechanical properties of the ground – he or she has to make do with what Nature has deposited. As Nature is seldom straight forward it often requires a considerable amount of detective work, coupled with an understanding of geological processes, to unravel the geological and groundwater complexities of a site and appreciate their engineering significance. Next there is the matter of the mechanical properties of soil, which is essentially particulate having an extraordinarily wide range of particle sizes and shapes. Being particulate, soils are very difficult to sample and test without dramatically changing their properties. Hence great ingenuity is required to devise appropriate sampling and testing techniques. Again, because of the particulate nature of soil, the development of mathematical models to describe and predict its behaviour is a formidable task which must rank with any of the more esoteric sciences. In the middle of the complexity of the geology and the material properties stands the engineer who has to design and build on, in or with the soil. For the engineer, the ground offers a continuing and ever varying challenge which demands a wide range of skills and experience. Roscoe was never one to shirk a challenge and the relatively new discipline of soil mechanics offered him many.

3. KEN ROSCOE, THE EARLY YEARS

Kenneth Harry Roscoe was born on 13 December 1914 and died on 10 April 1970. He was educated at Newcastle-under-Lyme High School where he was Head Boy. We get a flavour of his character from one of the masters, John Taylor, who remembered him:

"with a dead-pan face and a model of manly rectitude – a junior three-quarter, hard tackling and apparently fearless but without guile of any sort. He ran hard – invariably into trouble. He took a lot of punishment, but never registered it, and was frequently kept at home the day after the match!"

Ken Roscoe

In 1934 Roscoe came up to Emmanuel College with an Exhibition and he became a senior scholar. While playing rugby for Harlequins during the Christmas vacation of 1936 he broke his right arm. Partially concussed, he went on playing for twenty minutes before someone realised that he was seriously hurt. His arm was badly set and it was never to be fully right again. When the tripos came he still could not use it, but he tried to sit the papers writing left-handed; he was awarded an aegrotat which did not satisfy him. So he stayed on an extra year and in 1938 was awarded first class honours in the tripos.

Roscoe was offered a research studentship at Emmanuel at £150 p.a. but opted for the £450 p.a. from Metropolitan Cammel so that he would not have to borrow from his father. He was appointed Assistant Works Manager in August 1939.

As an undergraduate Roscoe had been a keen member of the Sapper Wing of the Officer Training Corps and was commissioned in 1938 but, due to his arm, was classified as unfit for service overseas. He therefore set about getting his Medical Officer drunk at a wedding, made him fill up and post the form regarding him medically, and thus in September 1939 he was sent to France with the British Expeditionary Force. On his first leave, he met and got engaged to a gifted and beautiful doctor, Janet Gimson.

Retreating from Boulogne on the fall of France he took charge of a party of Welsh Guards *"doubtless with a command of barrack room language which would have won their immediate admiration"*. They held the pier for four days for which he was awarded the Military Cross. When the last round had been fired he slipped away to rejoin the fight. He was finally taken prisoner after three weeks behind the lines when swimming the Somme in civvies.

In prison Roscoe was soon helping to organise the camp university, teaching mathematics and engineering without text books. Through the Red Cross, prisoners were allowed to take external London Intermediate Examinations which Roscoe did in French and German, the latter proving particularly valuable. Under cover of these activities he became camp tunnelling officer – possibly his first encounter with soil mechanics. He got out on three occasions, but was always recaptured. He finally escaped in April 1945 by breaking away from the column when his camp was being marched east before the advancing Americans.

Six days after his return home Ken married Janet and he set his heart on returning to Cambridge. Emmanuel offered him a research grant and invited him to assist with teaching engineering at the College.

Two people were to exert a most important early influence on Roscoe's career, namely Baker and Cooling. In 1928 the Department of Scientific and Industrial Research had recruited John Baker (later Lord Baker) to undertake research for the constructional steel industry and he had been sent to the Building Research Station (BRS) at Garston Watford. At BRS Baker got to know Dr Leonard Cooling, a physicist, who had worked on the capillary properties of stone and had formed a group to study soils problems. So impressed was Baker with the work of the Soil Mechanics group at BRS that when he went to Bristol in 1933 one of his first actions was to set up a small soils laboratory. When he moved to Cambridge in 1943 Baker found that the subject was virtually unknown and he set about rectifying that. He suggested that Roscoe should carry out his research work on soil mechanics. After an abortive attempt to appoint A.W.Skempton (later Sir Alec Skempton) to the staff of the Engineering Department, Baker turned to Roscoe who was made a University Demonstrator and a College Lecturer in 1947.

Baker advised Roscoe to visit BRS to discover *"what soil mechanics was about"*. There he met Cooling and was introduced to the work of Hvorslev and Rendulic, both of whom worked in Vienna under the direction of the founder of soil mechanics, Karl Terzaghi, and published seminal work in 1936 and 1937, but in German. Roscoe set about translating their papers.

The work of Hvorslev and Rendulic showed that the voids ratio of soil has a very marked influence on its stiffness and strength (see Figure 1 for the definition of voids ratio). Roscoe soon came to appreciate that current methods of testing soils in the direct shear box and the triaxial apparatus made the accurate measurement of voids ratio during a test very difficult if not impossible. He therefore set about devising equipment that would impose uniform deformations on a sample of soil thereby making it possible to accurately determine the voids ratio at all stages of a test. The result was a very elegant piece of apparatus that imposes uniform simple shear on the soil sample (see Figure 2). Simple shear can be envisaged as deforming an initially rectangular object into a parallelogram. In Roscoe's drive for perfection in obtaining uniform samples throughout a test, the Simple Shear Apparatus underwent at least eight modifications over the years.

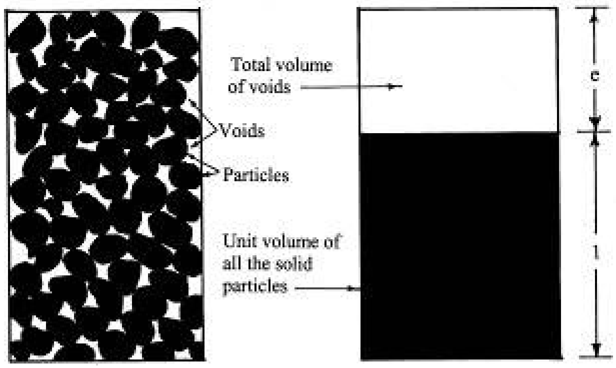

Figure 1 Definition of voids ratio

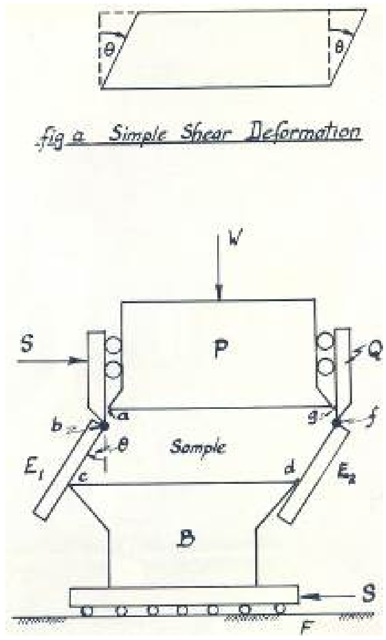

Figure 2 Roscoe's Simple Shear Apparatus

In 1951 Sir John Baker asked Roscoe to participate in the extensive programme of research he was carrying out into the plastic behaviour of steel frame structures. He was asked to design foundations that would fail when the steel portal frame was on the point of collapse. On studying the problem in detail Roscoe realised how limited were the available methods for calculating the ultimate resisting foundation forces and any rational method of calculating the movements up to failure was non-existent. Such a gross gap in knowledge was unacceptable to Roscoe and he set about rectifying it with huge determination. The scene was now set for Roscoe's research for the next decade and beyond. Peter Wroth and Andrew Schofield were two of his earliest Research Students and they worked closely together.

4. CRITICAL STATE SOIL MECHANICS

In 1954 Peter Wroth joined the Department as a research student to work on the Simple Shear apparatus. Charles Peter Wroth was born in 1929, was educated at Marlborough and, after two years' commissioned service in the Royal Artillery, entered Emmanuel College in 1949 as a scholar. He read mathematics followed by part I of the mechanical sciences tripos. After graduating he spent a year teaching at Felsted school before returning to Cambridge. Peter modified the original Simple Shear apparatus and carried out a number of tests on steel balls, glass beads and sand.

To do justice to Wroth's work I am going to have to give a brief course in Critical State Soil Mechanics – this normally takes me eight lectures for post graduate students! Figure 3(a) illustrates the behaviour of a granular material for an initially very loose sample (high voids ratio) and an initially very dense sample (low voids ratio) when undergoing simple shearing at the same vertical load (pressure). As the samples are deformed in the apparatus the loose sample contracts and the voids ratio reduces whereas the dense sample expands (dilates) and the voids ratio increases. After large shearing deformation both samples end up at the same voids ratio, defined as the *critical voids ratio* (or later the *critical state*) at which:

"unlimited deformation can take place at constant shear stress, constant voids ratio and constant normal effective stress"

By carrying out tests at various vertical pressures it was shown that the critical voids ratio of a soil is not constant but depends on the vertical pressure. The various critical states form a line in a three-dimensional space of shear stress, normal stress and voids ratio. This is known as the Critical State Line which is independent of the initial voids ratio or stress history of the soil sample – see Figure 3(b).

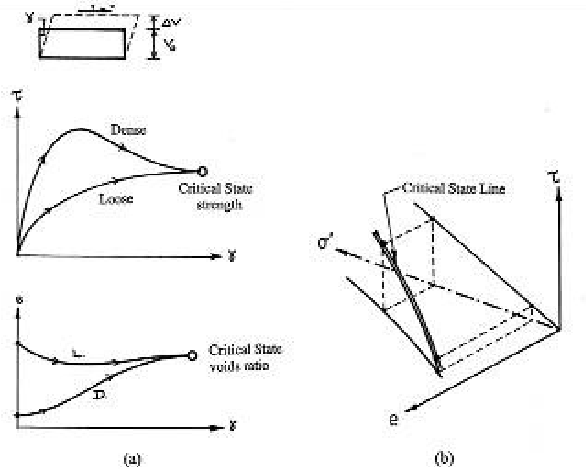

Figure 3 (a) Wroth's results for a loose and dense granular soil undergoing simple shear at the same vertical stress, (b) The Critical State Line in a three-dimensional space of shear stress, normal stress and voids ratio

Peter Wroth and Andrew Schofield then went on to study the work of Hvorslev on clays which was published in 1937 and which Roscoe had translated from the original German. Hvorslev had carried out drained shear box tests on clays at various degrees of overconsolidation. (The degree of overconsolidation is the ratio of the maximum previous vertical pressure experienced by the soil to the current pressure. A *normally consolidated* soil is one that has not experienced a higher pressure than the current one). He measured the voids ratio corresponding to maximum strength in the plane of failure and developed an equation for the strength in terms of the voids ratio and the normal stress. Wroth showed that Hvorslev's equation meant that the strengths lie on a unique surface in three-dimensional space (now known as the Hvorslev state boundary surface) as shown in Figure 4(b).

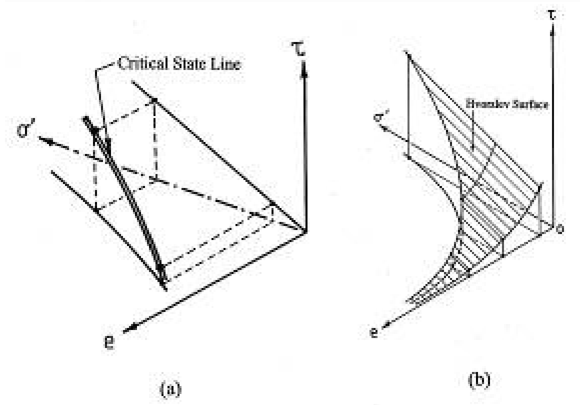

Figure 4 (a) The critical state line compared with (b) the Hvorslev surface in a three-dimensional space of shear stress, normal stress and voids ratio

With Professor Skempton's agreement Wroth set about analysing the experimental data from triaxial tests on Weald Clay which were obtained at Imperial College. For *normally consolidated* clays the results revealed the existence of another state boundary surface. Moreover it was very clear that these normally consolidated clays reached failure at a state corresponding very closely to Critical States i.e. *"continuing shear at constant shear stress, constant voids ratio and constant normal stress"*. It is interesting that Rendulic's 1937 results showed very clearly the existence of this boundary surface for *normally consolidated* clays but, like Hvorslev for overconsolidated clays, Rendulic never explicitly stated it. This surface is now called the Roscoe surface although I feel sure that Roscoe would have rather it had been called the Rendulic (or perhaps the Roscoe/Rendulic) surface. Clearly the Critical State Line formed the junction between the Hvorslev state boundary surface and the Roscoe/Rendulic state boundary surface as shown in Figure 5.

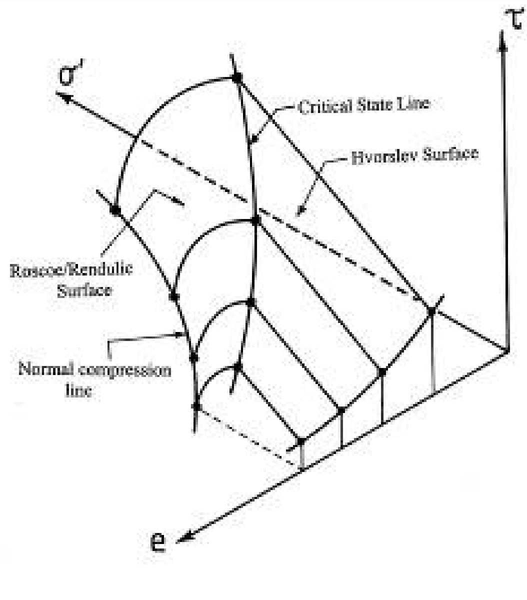

Figure 5 The Hvorslev surface and the Roscoe/Rendulic surface separated by the critical state line

If clays were to behave like the granular materials Wroth had tested, then all samples irrespective of stress history should eventually reach the Critical State Line. Wroth therefore set about examining the Imperial College triaxial test results for evidence of this. The idea worked for *normally consolidated* and lightly overconsolidated clays that contract during shear.

For heavily overconsolidated clays difficulties emerged. This is because such materials dilate during shear and become non-uniform so that it is no longer valid to use the overall volume changes to deduce the local voids ratio – a limitation of the triaxial apparatus. However the indications were clear from the Imperial College data, that the state paths were always heading towards the Critical State Line and it was taken as a leap of faith that eventually they would always reach it. This idea was persuasively argued by Roscoe, Schofield and Wroth in their seminal paper *"On the yielding of soils"* which was published in Géotechnique, March 1958. The paper describes a bold and simple unifying model that forms the basis of modern Critical State Soil Mechanics. The paper won the inaugural prize of what is now the British Geotechnical Association. It also generated one of the most lively and controversial discussions ever published in Géotechnique. In view of this controversy it is interesting to note that, in their obituary of Roscoe, Scholfield and Wroth report that his concern about the reliability of the experimental data from heavily overconsolidated clays caused him to hold back on the submission of the paper

Following the publication of *"On the yielding of soils"*, work focussed particularly on the Roscoe/Rendulic state boundary surface. Harry Poorooshasb, Research Student and Research Fellow at Emmanuel, showed that, by the use of plastic flow laws, it was possible to predict with considerable accuracy both the volumetric and the shearing strains for standard tests with paths moving on the surface. Calladine was able to show that this behaviour was consistent with the classical concepts of elastic work-hardening plasticity. At the same time Roscoe, Schofield and Thurairajah developed an energy equation which laid the foundations for the mathematical framework of the Critical State Model which is now routinely used world-wide for the numerical analysis of soil mechanics problems.

6. ALAN BISHOP

At this stage it is right for me to mention, if only briefly, another very eminent Emmanuel soil mechanics engineer – Alan Bishop. Bishop was five and a half years younger than Roscoe. He was educated at King's School, Wimbledon and won a senior scholarship to Emmanuel College, taking his Mechanical Sciences Tripos in 1942. He became Professor of Soil Mechanics at Imperial College in 1965, retired due to ill health in 1980 and died in 1988. Without doubt he is recognised as a world figure. His main interests lay in the experimental determination of the strength of soils and he did much consulting, mainly on embankment dams and stability of slopes.

Temperamentally he and Roscoe were poles apart. Whereas Roscoe was robust and sporty, Bishop was effete, and an intellectual. Bishop was a pacifist and his stay at Cambridge coincided with Roscoe's incarceration in Germany. Worse still, he reminded Roscoe in looks and mannerisms of his Gestapo interrogator. Even worse still, Bishop was a strong proponent of the triaxial apparatus and published a widely read book on it. There was no love lost between them and tales of their encounters abound. Whereas Roscoe developed and championed a bold and simple model for soil behaviour, almost instructing the soil as to how it should behave, Bishop never lost an opportunity to point out how his own latest experimental results exposed defects in this model. He refused to use the term Critical State other than when criticising it.

Alan Bishop

But both men revelled in the design and construction of apparatus and excelled at it. In short, they were both brilliant mechanical engineers. This tradition of elegant and innovative testing equipment has been, and remains, an outstanding feature of Cambridge work and I attribute this in no small measure to the breadth of the Mechanical Sciences Tripos.

7. DEVELOPMENTS IN APPARATUS AND EXPERIMENTAL TECHNIQUES

Having assisted Ken Roscoe in his work on the foundations of steel portal frames, Andrew Schofield's main task was to study the forces and displacements associated with the rotation of a stiff, rough, vertical plate embedded in a body of sand for which he built some apparatus which came to be called *"the footing rig"*. Schofield obtained his PhD in 1959.

Robin Arthur, research student at Emmanuel, took over from Schofield on the footing rig obtaining his PhD in 1962. He developed and used the technique of X-ray photographs with a grid of lead shot placed in the sand to study the local movements and deformations in the sand associated with the rotation of the footing. A lead shot, being much denser than a grain of sand, leaves a clear image on an X-ray photographic plate. Hence a succession of X-ray photographs taken during a test can be used to determine the changes in the coordinates of each lead shot during the test. This technique came to be widely used by the Cambridge Soil Mechanics Group both for model testing and for investigating the uniformity of deformation within testing apparatus. Arthur also worked on the design and construction of a miniature load cell for placing on the vertical face of the footing so as to measure both normal and shear forces locally on the face – another measuring technique that came to be, and still is, widely used by the Group. Arthur became Professor of Soil Mechanics at University College London and continued to develop highly innovative testing equipment there.

R.G. (Jimmy) James worked closely with Robin Arthur and his task was to develop and build a much larger footing rig (see Figure 6). James, who obtained his PhD from Emmanuel in 1965, was able to show that the failure planes in dense sands were in fact planes of zero extension. One of his immense contributions, for which generations of research students should be eternally grateful, was to develop an automatic system for determining the coordinates of the lead shot X-ray images – thereby saving days and months of tedious work.

Figure 6 Jimmy James' large footing rig

8. WORKING WITH ROSCOE

I first met Roscoe in Paris at the fifth International Conference on Soil Mechanics in 1961 on my return to the UK, having obtained a Masters degree at the University of the Witwatersrand in South Africa (my family had emigrated there in 1948). Later that year I visited Cambridge with my supervisor, Professor Jere Jennings. Typically, the Roscoe's were very hospitable and, having first been completely baffled by the latest Cambridge theories, we were entertained to dinner in Roscoe's rooms at Emmanuel College (Room B3 in Front Court).

I was excited by the fundamental work being done at Cambridge and was keen to start applying it to practical ground engineering problems. In February 1963 I visited Cambridge to discuss doing a PhD with Roscoe. Gillian came with me to investigate getting a job (in order to keep me!). It was the year of the big freeze. We were both invited to the Roscoe's family home in Millington Road for lunch and it was suggested that we might like to stay on and skate on the 'Backs'. We had an energetic afternoon on the ice along King's reach, and the invitation was extended to include dinner and to stay the night, for which Ken kindly lent me a pair of his pyjamas which I had, literally, to wrap myself up in. The next morning we skated up to Grantchester in glorious sunshine.

My three years at Cambridge (1963 to 1966) amply fulfilled my hopes of applying the Cambridge approach to practical problems. I built a model of a foundation on clay to study the detailed processes involved in the settlement of buildings on such soils. In applying the Critical State Model to such problems I concluded that it was necessary to introduce a modification to the energy equation of Roscoe, Schofield and Thurairajah to more accurately represent the initial conditions of *normally consolidated* clay in the ground. To challenge something as fundamental as the basic energy equation meant going "through the crucible" and for one not brought up in the rigours of the Cambridge school this was a trying experience. I learnt that success with Roscoe meant a complete commitment of one's whole personality to the Cambridge line. To deviate from that line was very serious indeed and generated a crisis point (Critical State?) in my relationship with him. I now believe that a close relationship with Roscoe required a crisis of some sort. It was as if one had to go to the brink together before a mutual respect and comradeship could develop.

My last memories of Ken Roscoe are typical of my fondest. I had come up to Cambridge to go over some work. We had a gruelling afternoon. Anyone who has been through a paper word by word with Roscoe will appreciate how I felt by late afternoon. As always I was invited back to Millington Road. With the rough 'bargaining' behind us we relaxed over a meal which Janet had expertly prepared while at the same time maintaining a full and lively conversation as we sipped sherry in the kitchen. The evening was then rounded off with a glass of port and a needle game of snooker. It was occasions such as this that gave one the opportunity to appreciate Roscoe's ability to work with incredible intensity over long hours and then to switch off and indulge in a relaxed and entertaining evening with his family.

Janet and Ken Roscoe entertaining in Roscoe's room at Emmanuel College in 1961

9. EDMUND HAMBLY AND THE TRUE TRIAXIAL APPARATUS

Edmund (or Tim as we knew him) Hambly was in his final undergraduate year when I was in my first year of research and I supervised his final year project. I was immediately struck by the intense and original way he set about studying and tackling any problem. He became a Research Fellow at Emmanuel (1967-1969) but felt that specialisation was inhibiting his creativity and he then went into practice.

Edmund Hambly

Without doubt he was one of the most creative and perceptive engineers with whom I have ever worked. He was able to tackle a very wide range of engineering problems from soil mechanics through to prestressed concrete bridges and offshore oil rigs. He published books on these subjects and, as a visiting Professor of Design at Oxford, revelled in sharing the challenges of creative design with students.

He was also very highly principled and when he had doubts about the safety of an offshore rig he took it upon himself to inform the owners – he was proved correct. It was through him that the Royal Academy of Engineering ran a conference and produced guidance on engineers' responsibilities in warning of potential disasters.

Hambly was elected President of the Institution of Civil Engineers in 1994 at the age of 52, the second youngest in the twentieth century, and sadly died of a heart attack during his term of office. Without doubt, Roscoe's demanding standards of thought, presentation and commitment had a profound influence on Hambly who remains a shining example of the sort of broadly based, creative engineer that Cambridge produces.

Hambly conceived a most ingenious mechanical means of subjecting a cubical soil sample to controlled three dimensional loading by means of sliding plates operated by jacks. Figure 7 shows his original sketch for a preliminary simplified biaxial version which he then had built for his PhD research with a photograph of the apparatus alongside. He obtained his PhD in 1969.

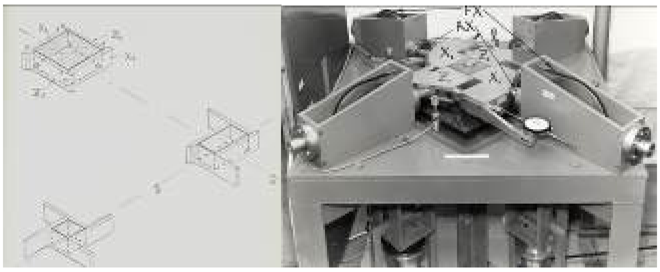

Figure 7 Hambly's biaxial apparatus showing his original sketch on the left

John Pearce, research student and Research Fellow at Emmanuel, followed Hambly and designed and built the three-dimensional apparatus that Hambly had conceived, a photograph of which is shown in Figure 8. Pearce was engaged to the Master's secretary and he tells the story of how, when he was on holiday, his advice was urgently needed in the workshop. Roscoe immediately picked up the 'phone, dialled Emma and asked the Porter to get the Master's Secretary. *"When's that bugger Pearce coming back"*? Embarrassed silence: *"Er, sorry Master, I wonder if you could ask your secretary when John Pearce will be returning?"*

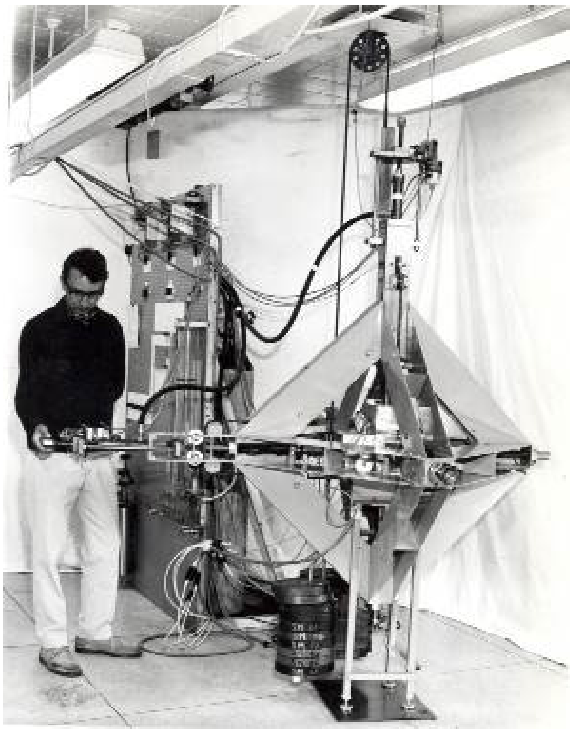

Figure 8 John Pearce with the True Triaxial Apparatus

David Muir Wood, Fellow at Emmanuel from 1975 to 1987, took on the True Triaxial from Pearce and carried out a huge range of verycomplicated experiments with it. Following Roscoe's death Muir Wood worked very closely with Wroth. They developed a course in Critical State Soil Mechanics which they took around the world and this did much to alert practising engineers to its relevance. After Emmanuel, Muir Wood went first to Glasgow and then to Bristol where he has been Head of Department and Dean of Engineering.

10. PETER WROTH

Peter Wroth personified elegance and rigour in all that he did, perhaps stemming from his early schooling in mathematics. His lecturing was always a model of clarity and he had an enviable knack of presenting a difficult topic in a clear and compelling manner with complete conviction. I have certainly picked up many tips from him – including the importance of taking the time to describe to the audience the axes of any graph.

Peter Wroth

One of his favourite diagrams was the one shown in Figure 9(a). Soils with states to the right of the Critical State Line tend to contract when sheared and hence they get denser and stronger. They are therefore well behaved – they are "the sheep". On the other hand the soils that are situated to the left of the Critical Sate Line tend to dilate when sheared and hence they tend to get less dense and weaker with the risk of failing and collapse. They are therefore badly behaved – they are "the goats". I find that students appreciate this analogy and I use it in my lectures. A couple of years ago I received a card from a student reproduced in Figure 9(b). Clearly Wroth's biblical analogy had made a profound impression!

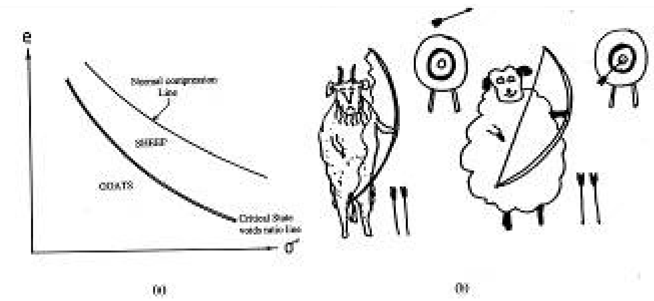

Figure 9 The sheep and the goats

When I was up at Cambridge, while very aware of Wroth's achievements and abilities, I had felt that his administrative work in the Departmental teaching office was deflecting him from new research. Taking over as leader of the group, following Roscoe's death in April 1970, seemed to release in him a new creative energy. Although visitors had always been welcome, he attracted many more. Moreover contacts with industry increased. The group suddenly became more outward looking.

Wroth began to take an interest in insitu testing and took on the challenge of measuring the insitu horizontal effective stresses in the ground without in any way disturbing it – one of the most difficult problems in soil mechanics. For this he developed what has been called the Camkometer (K_o being the ratio between the horizontal and vertical effective stress in the undisturbed ground). The instrument was designed to bore its way into the ground by means of a rotating cutter and the earth pressure is measured by miniature load cells mounted just behind the sharpened leading edge. The instrument was developed further into a self boring pressuremeter and led naturally on to work on piled foundations. He also supervised work leading on to the development of numerical methods of analysis and the CRISP computer programs.

In 1979 Peter Wroth was appointed Professor of Engineering Science at Oxford University and Fellow of Brasenose College. His ten years as Head of Department saw the development of a lively research group in Soil Mechanics, the introduction of two new undergraduate courses, the erection of a new building partly funded by industry, and the extension of the Engineering Science course from three years to four years.

I had the good fortune to work with Peter on a number of occasions. The first was in 1962 in connection with the foundations for the Westway elevated motorway in London which was being designed by G.M. Maunsell & Partners, the firm with which he was closely associated throughout his professional career. I was a lowly research student at the time, but he drew me into the design team as an equal. To work with Peter was to experience encouragement, loyalty, confidence and support. He was an enabler in that he could recognise other's abilities and give them the confidence to exploit and develop them. Working with him was also great fun – he had a mischievous sense of humour and a give-away twinkle in the eye! Together we developed work on soil-structure interaction and building damage due to settlement which was published in 1974. This ultimately led to us both acting as expert witnesses for the Parliamentary enquiry into construction of the Jubilee Line Extension underground in London – work that we were doing together at the time of his death in February 1991, shortly after he had become Master of Emmanuel College.

11. PISA

It is perhaps appropriate to talk a little about my work on stabilising the Leaning Tower of Pisa that draws significantly on Critical State Soil Mechanics. The tower is founded on loose silt underlain by very soft normally consolidated clay that is uniform in its properties from north to south. Beside leaning to the south by 5.5 degrees the tower is not straight; the Pisans call it banana-shaped. This is because it began leaning from very early after building commenced in 1173 and corrections were made during construction. We worked out a hypothesis as to how the masons would have progressively corrected for the increasing inclination and came up with the history of tilting as shown in Figure 10 which is a graph of the weight of the tower versus the change in inclination. This was important as it gave us a means of calibrating our computer models of the tower and underlying ground.

The Leaning Tower of Pisa

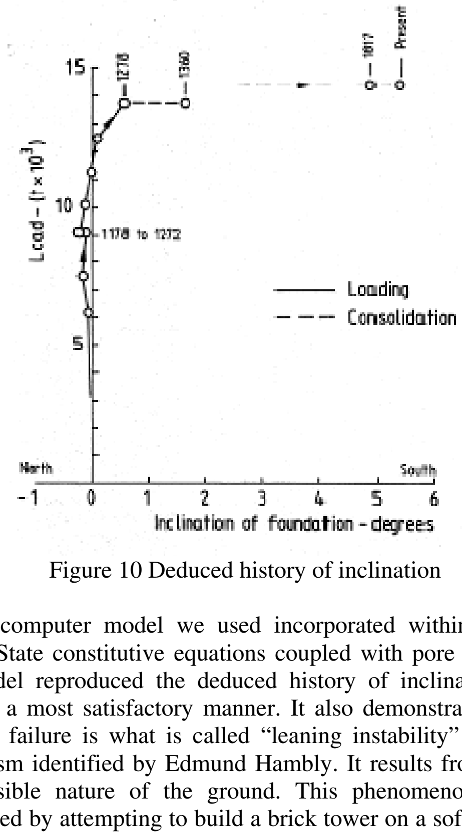

Figure 10 Deduced history of inclination

The computer model we used incorporated within it refined Critical State constitutive equations coupled with pore water flow. The model reproduced the deduced history of inclination of the tower in a most satisfactory manner. It also demonstrated that the mode of failure is what is called "leaning instability" which is a mechanism identified by Edmund Hambly. It results from the very compressible nature of the ground. This phenomenon is easily reproduced by attempting to build a brick tower on a soft carpet – at a certain height it begins to fall over no matter how careful you are. The Pisa Tower is at its critical height!

Having identified the mechanism of failure we were able to devise a temporary stabilisation measure involving the placing of 600t of lead weights on the north side of the foundations. In proving that this would be effective we had to incorporate in our Critical State model the effects of ageing which cause the development of some bonding between the clay particles giving the soil a small amount of cohesion. Without this refinement it would not have been possible to demonstrate that the lead weights would work – fortunately they did! The placing of the lead weights gave us some breathing space to develop the permanent solution.

We decided that the best permanent solution was to reduce the inclination of the tower by a small amount – about ten percent which is not enough to be seen. After considering many possible ways of doing this we chose a method we called *soil extraction* involving careful drilling outside and beneath the north side and leaving cavities which we hoped would close gently, thereby causing the north side to sink in a controlled manner – see Figure 11. The big question was: would it work or would it finish the tower off? Again the Critical State computer model was used to investigate the response of the tower. We found that, provided the cavities were formed north of a critical line, the response of the tower was always positive even though it was on the point of collapse. A very ingenious drill (which would have pleased Roscoe and Wroth) was designed by the Italian contractors that made it possible to bore beneath the north side of the tower without any disturbance. In early 1999, with our hearts in our mouths, soil extraction commenced. Slowly but surely over the months we began to move the tower back northwards and to remove the lead weights progressively. The work required daily monitoring of the tower's response followed by detailed instructions for the next day's work. By June 2001 we had reduced the inclination by one half of a degree and we stopped the soil extraction. Since that time a few additional measures have been taken to improve the stability of the tower. It was reopened to the public in December 2001 and is now showing negligible movement.

Without the assurance that the Critical State computer modelling gave us I would not have wanted to embark on the stabilisation measures. Moreover I doubt if we would have been able to persuade the other members of the Pisa Commission to go ahead with the work.

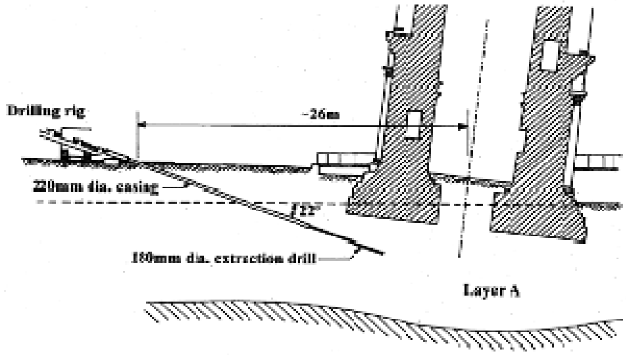

Figure 11 Soil extraction from beneath the north side of the Pisa Tower

Like Edmund Hambly, I believe that the demanding schooling I received under Roscoe has stood me in good stead. He insisted on rigour in the design of equipment, in experimental techniques, in the interpretation of results and in the development of theory. He required total commitment to the cause and built up a most lively and united research team. We were all influenced by his unlimited industry and tenacity in working towards the goals he had set. We had to learn to argue our corner, not just logically but with determination and patience. To this rigour and tenacity Wroth added elegance and relevance to engineering problems. It was a seminal time when Critical State Soil Mechanics was formulated and I am privileged to have participated and been a witness to it.