The Seven Ages of Centrifuge Modelling

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The paragraphs below arise from my contribution to a debate held at the Workshop at Monte Verita in which I was asked to present the case that

> *Centrifuge tests are a sufficient means of solution to geotechnical design problems.*

I have fought for a variety of lost causes in my time and this one was lost before we took the floor in the knowledge that the word '*sufficient*' would be interpreted in the mathematical sense as meaning necessary and sufficient for a particular purpose. I think there is not now, and never has been, an engineer to whom the centrifuge modelling technique has seemed so versatile and ubiquitous that no other tools or approaches to design are necessary. However there are some who consider that the centrifuge is one of the array of tools that can contribute directly to project-specific design and a rather wider group by whom the centrifuge is accepted in the development of more generic design approaches and as a means for determining the effects of parametric variations in design and in identifying mechanisms of behaviour in serviceability and limit states.

I took as a theme the speech of the 'melancholy' Jaques in William Shakespeare's play As You Like It (1599), that has become known as The Seven Ages of Man.

> *All the world's a stage,*
> *And all the men and women merely players.*

I tried to enliven and enlighten the debate by looking at seven individuals who had, or might have had, an influence on the development of centrifuge technology and its possible application to design over the last 150 years. In the note below I have expanded this a little but kept to the seven stages of my initial talk.

1 EDOUARD PHILLIPS

Born in Paris in 1821, the son of an English father and a French mother, Edouard Phillips became a naturalized French citizen during his period of study at the Ecole Polytechnique. Details of his life and work were reported briefly by Craig (1989) on the centenary of his death, drawing heavily on the obituary notice written by Sauvage (1891).

Phillips (Fig. 1) made his career principally in the railway and mining industries and he also held a number of teaching appointments. He published extensively from 1845 until his death, but in his obituary only a single paper is cited at length – the seminal work dealing with the possible use of centrifuge models in engineering that was published in full in the 1869 Memoires of the Academie des Sciences and summarized in the Comptes Rendus of 11 January of that year (Phillips 1869a). The paper recognized the limitations of contemporary elastic theory in the analysis of complex structures and considered the use of models. He introduced scaling relationships and examined several different scenarios, concluding with the case where self-weight body forces are significant. He proposed the exploitation of centrifugal acceleration to generate increased body forces on reduced size models, taking as examples the Britannia Bridge over the Menai Strait in Wales, designed 20 years earlier, the tubular bridge in Conway, also in Wales, and a possible bridge across the English Channel where he discussed briefly the foundation problems.

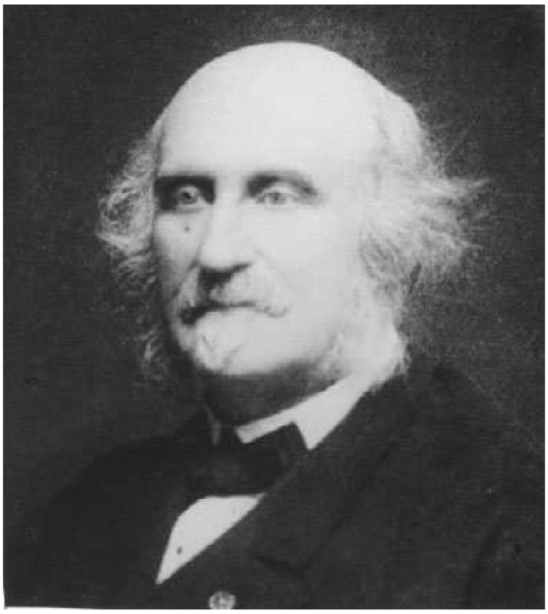

Figure 1. Edouard Phillips

In the first paper he considered only quasi-static problems, of analysis and design, but later in the same year (Phillips 1869b) he extended his thoughts to dynamic effects. His conclusion that, in the centrifuge, inertial time scaling is the same as linear scaling, is today commonly accepted by centrifuge modellers.

It appears that the idea was ahead of its time and there is no record of anyone in the nineteenth century using a centrifuge for modelling elastic or other structures.

2 PHILIP BUCKY

The first mention of applied centrifuge modelling in the literature appears to be that of Philip Bucky (1931), working at the University of Columbia in New York. Bucky (Fig. 2) worked on mining problems and first refers to the centrifuge after noting that

> *Models may be made the best means of designing works of great magnitude.*

It is not clear whether Bucky knew of Phillips' work, written in French, but as an educated American may well have read the lines of Walt Whitman (1855):

> *One of the centripetal and centrifugal gang*
> *I turn and talk like a man leaving charges before a journey.*

Figure 2. Philip Bucky

Little did he know of the journey ahead. Bucky's work in mining continued for several years and was applied specifically to design – see Bucky & Fentress (1934). It was followed later by that of Louis Panek at the US Bureau of Mines in College Park Maryland – see for example Panek (1952), also working on design problems and by others - see Clark (1988), before the explosive growth of the technique in North America in the 1980s and 1990s.

3 G. Y. POKROVSKY

At about the same time as a centrifuge was first used in the USA, two pioneers were developing the technique, apparently independently in the USSR. N. N. Davidenkov and Georgi Yosifovitch Pokrovsky both published papers in Russian in 1933 and the first paper was published in mainstream geotechnical literature, from the same source, at the First International Conference of Soil Mechanics and Foundation Engineering (ICSMFE) - Pokrovsky & Fedorov (1936).

Figure 3. G. Y. Pokrovsky

Pokrovsky came to dominate the field in the USSR and the scale and impact of his work only became apparent at the 8th ICSMFE, held in Moscow in 1973 when he appeared (Fig. 3) and indicated the scope of his work over 40 years at a special seminar. His valuable books were subsequently translated into English (Pokrovsky & Fedorov 1975) and enjoyed a limited circulation along with a volume of work by Malushitsky (1975), also translated from Russian.

Pokrovsky had a prime technical interest in explosives and their use for civilian and military purposes. He is described in a review of Soviet science that I bought and read as a schoolboy (Vassiliev & Gouschev 1961), as a man of culture who painted, composed music and wrote poetry – it is tempting to speculate whether he also might have read Whitman.

With changes in the political and economic situation in the former Soviet Union the visible output from centrifuge groups in this area has been limited in recent years. Nonetheless there can be little argument with the belief that Pokrovsky was a giant in the field and the significance of his work should not be underestimated. There is no doubt that his experiments were utilized within the design process on a grand scale.

4 KARL TERZAGHI

While Terzaghi (Fig. 4) is widely considered the founding father of Soil Mechanics his background was that of a geologist (Goodman 1998), whose early career was in Europe. In 1931, while writing a book on Foundation Engineering, which would be a step forward from *Erdbaumechanik*, he took a vacation in Ticino, at Lugano – only a short distance from Monte Verita. He sought the tranquility to concentrate.

Figure 4. Karl Terzaghi

Faced with political turmoil in Europe at this time, he was offered a post at Columbia University but chose not to pursue the opportunity. A later possibility of a sabbatical there in 1934-35 also failed to materialize. However he was aware of the activity of Bucky in that institution and acknowledged his work in the period 31-34 in Article 153 in Theoretical Soil Mechanics (Terzaghi 1943).

Not usually keen on physical models, though he did perform his own trap-door experiments, Terzaghi was well aware of their potential and corresponded in the 1950s with Peter Rowe in relation to the latter's classic work on large 1g models of anchored bulkheads and sheet-piled walls. In this context it is interesting to look at the presentation of Herle (2002) to this Workshop and to make the suggestion that someone armed with Rowe's flexibility method of analysis and little more than geometric data and stratification would have fared quite well in the prediction game.

Terzaghi was heavily involved in site-specific design problems throughout his working life. He sought peace to write by coming to Ticino and might well have worked in close proximity to Bucky had he so chosen. He did recognize the role of model testing in certain circumstances but elected not to become personally involved in any major way.

5 PETER ROWE

Peter Rowe worked in Manchester from the early 1950s and built his own centrifuge there in the Department of Engineering of the University of Manchester shortly after Andrew Schofield built one a kilometre or so away at UMIST – an associated institution at that time and now a separate University. It was my own good fortune to work there with Rowe on Schofield's new machine in 1969-70 and subsequently to become involved with the bigger machine built in 1970-71 in the laboratory that now bears Rowe's name.

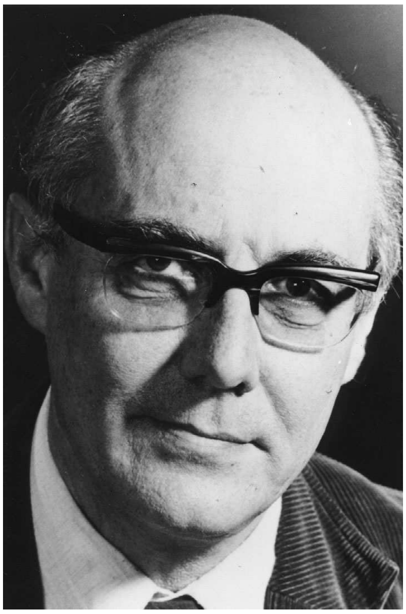

Figure 5. Peter Rowe

Rowe (Fig. 5) was an academic and a major geotechnical consultant. The machine he built was capable of carrying models 2.0 x 1.0 x 0.6 m deep to 120 g from the outset (and structurally capable of reaching 200 g, though the necessary drive power has never been installed). This specification was a direct result of his appreciation of the need for a major piece of hardware to assist the design studies for major projects. The first large models related to studies for two major (in UK terms) water retaining embankments up to 60 m high, incorporating quite elaborate geometrical details and, in one case, large undisturbed blocks of site clay with fabric that controlled foundation drainage. By chance, soon after machine installation, the development of oil and gas reservoirs beneath the North Sea began and the Manchester laboratory was kept busy with a series of modelling programmes related to huge offshore gravity platforms and later piled and jack-up structures. These have been followed, since Rowe's retirement, by studies of drag anchor behaviour and of upheaval buckling of pipelines when the combination of 100g+ accelerations and a 2 m model length have been particularly valuable.

Rowe's perception of the role of the centrifuge is best illustrated by major programmes in the 70s and 80s relating to the design of the Oosterschelde Storm Surge Barrier (Rowe & Craig 1976, 1978) and for the concrete gravity platform being developed by Norske Shell for the Troll field (Craig 1993). In both cases, model studies over several years were major contributors to the selection of overall structural form and subsequently to performance prediction studies for structures with no close antecedents. These instances may be among the closest that the centrifuge has come to being 'necessary' for design, though no claim is made for 'sufficiency'.

Like Terzaghi, Rowe spent vacations in the Swiss mountains, though his desire was to walk and his region of choice, as I recall, was the Bernese Oberland rather than Ticino.

6 ANDREW SCHOFIELD

In the debate at Monte Verita I singled out Professor Schofield to represent the sixth age. In truth I should have linked his name with that of Professor Mikasa in Japan. Both men developed centrifuge technology in their own countries in the mid 1960s starting from the twin considerations of consolidation of soil and slope stability problems.

Andrew Schofield (Fig. 6) was present at the Workshop and was surrounded there by his former students and colleagues. Neither he nor his work needed introduction at the debate and it was inappropriate to dwell there on his contribution. He introduced Peter Rowe to the idea of centrifuge modelling and he and Mikasa should be considered ahead of Rowe in strict chronological order. Departure from that order reflects the fact that Rowe and others above are now deceased while Schofield and those below continue to contribute in the twenty-first century. It was also tempting to link Rowe with Terzaghi and to bring Schofield closer to his former Cambridge student Springman.

Figure 6. Andrew Schofield

Schofield's range of work has been vast and much addresses directly or indirectly the broader concepts of identifying mechanisms of behaviour and developing strategies for avoiding problems – all of which are embraced by the broader concept of engineering design. I do not attempt to enlarge on Schofield the man and only make a personal selection of two examples of his work – others might choose differently.

London in the 1970s was threatened by flooding in the event of storm surges driving water down the North Sea and into the Thames estuary – essentially the same problem as that at Oosterschelde. The Thames Barrier was built, before the Dutch structure, and downstream riverside embankments were raised. Schofield worked with centrifuge models, during a period at UMIST in Manchester, probing the stress paths that might lead to the bursting of river waters into the marsh areas outside the embankments – as it were on the 'dry' side (Hird et al. 1978). He later worked at Cambridge on centrifuge model tests that elucidated the causes of collapse of some of the Mississippi flood levees towards the river – as it were on the 'wet' side (Schofield

1980). In both cases, by the time the centrifuge modelling was over, the problem identification and conceptual design needed to overcome those problems was complete and only detailed design and implementation of solutions remained.

It is appropriate to say more of Professor Mikasa. Working exclusively in Japan he developed theories of consolidation for soft clay and utilized the centrifuge in these studies. His paper (Mikasa et al. 1969) at the 7^{th} ICSMFE coincides with that of Avgherinos & Schofield (1969) at the same meeting – both were related to slope stability. His work continued for many years, though with a lower international profile than that of Schofield, who has travelled the world preaching the gospel of the centrifuge. Like Rowe, Mikasa had an involvement in site-specific design of large dams. The widespread use of the centrifuge today in the Japanese construction industry has its roots in the early work of Mikasa and his successors, notably Professor Kimura. The different national culture of Japan may be partly responsible for the substantially different centrifuge infrastructure that has developed there. Elsewhere in the world, centrifuges remain predominantly in academic and government agency hands. In Japan, a large part of the centrifuge activity lies much closer to the principal designers and constructors of new works.

7 SARAH SPRINGMAN

Reversing the order of Jaques' seven, the last Age is typified by the youngest of the men and women I have chosen. In the nineteenth century the seed of an idea for the centrifuge was sown and in the twentieth the technique was born and came of age. At the start of the twenty-first century there is a relatively mature technology in place, though nothing stands still. The giants above have brought many advances and the centrifuge has demonstrated capabilities that Phillips could never imagine. Sarah Springman (Fig. 7) has brought the centrifuge reality to Switzerland and in particular to ETH. She has told of the historical links of her own family with Monte Verita and all who attended the Workshop enjoyed the location and the atmosphere and the science that was discussed.

Figure 7. Sarah Springman

The ETH in Zurich, and its geotechnical group will develop solutions to problems that are peculiarly Swiss as well as those that are of more general concern. Sarah Springman is better known as an athlete than as an artist. All who attended the Workshop will wish her, and the group of young researchers she has assembled, well – their output as evidenced in the papers to the Workshop is increasing in volume and importance.

8 CONCLUSION

That the centrifuge will play a part in design in its broadest sense is not in doubt. This will not be sufficient for full design solutions, but will nonetheless be an integral part of many specific projects as well as of generic solutions presented is growing in volume and significance.

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