To Embrace Scientific Performance-based Design

Interview with Prof. Malcolm Bolton

by Ms. Reika Kua Kee Eng

THE scientific research of soil along with its practical applications, specifically known as soil mechanics, is considered as a relatively recent discipline as compared to other major branches of engineering. In 1936, this new discipline has made a significant progress into some of the major fields of engineering. Many theories and methods of soil mechanics were developed during the beginning of the twentieth century, for instance by profound researchers such as Atterberg, Terzaghi, Casagrande, Gilboy and so forth. Subsequently, these theories and methods have become an integral part of the engineering fraternity. Today, soil mechanics has progressively become a more diverse and comprehensive field. In order to take an in-depth look at the influence of soil mechanics in the contemporary engineering industry, *JURUTERA* has taken the opportunity to interview Prof. Malcolm Bolton, a world renowned expert in soil mechanics and also the present Director of the Schofield Centre for Geotechnical Process and Construction Modelling, and Head of the Geotechnical and Environmental Group in the Department of Engineering, University of Cambridge, United Kingdom.

THE NEED FOR SOIL MECHANICS

"Buildings need foundation, slopes need careful design, and dams even more so. Advanced society needs all such facilities to be properly designed and properly constructed, so that they work and that they would not be a hazard. Hence, the need for soil mechanics," said Prof. Bolton when asked about the importance of soil mechanics. He elaborated that soil mechanics refers to the mechanical behaviour of soil under different conditions and circumstances such as its deformation, failure, and the leakage of water through soil on the ground.

"The earth is a very useful material. You can press it into a compact form, and make embankments. Dirt is full of void where water can seep or travel through it, and soil mechanics deal with all the aspects of the grains of soils deforming, moving around, causing the earth to maybe crack or deform or even fail completely as well as cover things like pollution migration through the ground. It's a very wide ranging topic," added Prof. Bolton.

"Bearing in mind that soil is a very natural material, as we look out the window, we can see hillsides, which may be completely natural. To consider the blocks of flats or residences are using the soil underneath and using the hillside is perhaps an unusual way of putting it, but if the hillside failed and the blocks collapsed, then there will be an investigation of the mechanics – why that happened?" explained Prof. Bolton. "Was water pressure involved? Was there an earthquake? Were the blocks of flats too heavy to be supported by the earth? All these issues are the issues of soil mechanics. And the question of soil mechanics is to discover what the earth or ground comprises, what its properties are, and then what you can reasonably ask it to do in the way of supporting foundations and slopes, and so forth".

"Practitioners have developed ways of coming up with rules for the design of foundations, slopes and tunnels, for example. Some of which are unexpressed necessarily in a rational form and possibly because the ground is a natural material. And because geotechnical engineers or ground engineers have to work closely with structural engineers, who design the bridges and buildings that we can see above ground, there has always been a natural anxiety in that relationship" commented Prof. Bolton.

According to Prof. Bolton, more often than not, soil mechanics and geotechnical engineering are regarded as slightly mysterious by most structural engineers. "A sort of 'black art' because they can't themselves completely understand how practitioners come to the judgement they do," quipped Prof. Bolton.

VENTURING INTO CENTRIFUGE MODELLING IN GEOTECHNICAL ENGINEERING

Prof. Bolton obtained his first graduate degree in structural engineering. In the subsequent years, he became very interested in soil mechanics, and in a particular experimental research technique, which is to make small models of the sort of structure of grounds that one is interested in, and centrifuge them. "My interest was kindled by Prof. Andrew Schofield. He came to Manchester when I was a research student in structures, and listening to him talk about the excitement of discovering scientific laws and the true behaviour of soil and the ground, I was entirely convinced that this was a good way for me to go. So I joined him and we worked on the UK's first geotechnical centrifuge centre and that was in Manchester University as it is now," recalled Prof. Bolton.

"He came back to Cambridge, and about six years later, I returned to Cambridge as well. And I'm now very pleased to be the Director of what we called the Schofield Centre. We got money for a research centre to dedicate to physical modelling and especially to centrifuge modelling in geotechnical engineering. And we named it after our old boss, Schofield".

"The centrifuge models that I refer to have revealed many of the mechanisms, many of the ways that soil can respond in different circumstances. And that, plus the improved understanding in general about soil of different types, have led me to the position that we can now improve design methods, by including in our thoughts the soil deformations and ground movements. Whereas, until fairly recently, design really consisted of injecting so-called factors of safety which were really rather arbitrary, in the way they were design and applied," said Prof. Bolton.

He further explained, "For example, my lecture here, later today is called, Performance-based design in geotechnical engineering, and I contrast basing decisions on the actual performance, in this case, of the ground, with decisions based on rather arbitrary calculation of safety factors".

THE CHALLENGES AND CONTRIBUTIONS OF CENTRIFUGE MODELLING

"The ground is a natural material. Geological processes have meant that it is very variable, especially when you go downwards. Soils in most parts of the world have been deposited in lakes or in the sea as sediments, and as the continent move around, and climate changes, those sediments which were accumulating very slowly in thin layers, change very frequently. And when we drill a shaft for a pile to make a foundation of a building for example, we might encounter tens of millions of years of accumulated and differentiated sediments. And we have ways of probing the ground and of describing, especially its nature, for instances, whether it is sandy, or it has clay in it, and we have ways of taking samples, such as sampling tubes so we can extract samples from them," explained Prof. Bolton.

According to Prof. Bolton, the properties within these sediments can change centimetre by centimetre. He also highlighted, "It doesn't mean that just because the soil is in the same location it will have the same properties. That has made our jobs very difficult. What is its representative? The soil could be sand, clay, residual soils (a lot in Malaysia, that is maybe granite) which is weathered, and the tropical climate which has chemically rotted it down to something like the soil. All these complicate the processes that are going on".

He further elaborated, "Engineers have to cope not only with the mannerism of soils, but the ratio in size. The ratio in size between a flake of clay and a piece of gravel could be the same ratio as between a postage stamp and a block of flats. So the spaces between the particles equally have such enormous ratio. Clays sometimes are described as impermeable to water. But it isn't true. It's just that water flows through them so slowly that you can hardly measure it". He added, "In any type of soil, regardless of its properties, water can actually flow through but the difference will be its speed, whether the water seep through it slowly or rapidly".

To further demonstrate the above mentioned challenges, Prof. Bolton quoted an example, "There is a water table in the ground, in Malaysia, because of the rainfall. The water table tends to be rather high. And below the water table, the grain of soils, whether they are clay or sand are bathed in water. And so the little pore channels between the grains are full of water. All of that make it very difficult to characterise the material, decide which piece of material is the representative, and decide what calculation that you need to do, to make sure that the material will be strong enough and stiff enough to support loads such as a building's foundation".

"I supposed we have in our mind, two simple stereotypes, one would be clay, saturated clay would be a common stereotype, and because water travels through clay very slowly, the first deformation of clay would have to be at a constant volume. So if you suddenly apply a load on clay it will flow plastically at constant volume. And that is a rather simplifying idea. The so-called undrained behaviour of clay," explained Prof. Bolton. He continued his explanation with another example. "Another stereotype would be sand, through which water travels very easily. So when you apply loads to sand, the particles can be immediately re-packed, they either compact or dilate or balloon up when you apply load to them".

"So it takes years of undergraduate education in university and then years of professional training and experience before somebody could have absorbed enough of the individual stereotypes that I was talking about. And enough experience to know how to apply the stereotypes to particular design questions that may help geotechnical engineers. It really is quite a difficult profession to follow. But of course, it's fascinating, because every piece of ground is different. So you never encounter the same problem twice," commented Prof. Bolton.

According to Prof. Bolton, there have been accounts of various ways in which simple ideas can be used to come up with reasonably reliable estimates of soil strength and stiffness. That particular attitude of generating simplified rules that should work on a particular condition. "That has been what I have been doing this last 10 or 20 years, mostly, and so I come up with some simplified calculations that initially I showed work very well with clays and then I've been extending that work, and now I have got students to look at the deformation of sand which hundreds or thousands of people have looked at, but I think maybe I've got a way of deducing simple design rules, that would more effectively predict the details of what's going to happen when load is put on the sand," said Prof. Bolton.

"Over the years I studied clays, for example, in modelling the excavation in centrifuges with piled foundation through them, clay slopes e.g. tunnels in clay. But I've also studied sands in most of the same sort of scenarios. So excavations in sand, foundations on sand and so on. I've studied earthquake effects on various soils or grounds too. All these with the help of centrifuge modelling," said Prof. Bolton.

He added, "By raising the acceleration of a small model, you can recreate full scale stresses in a small model, so you can expect how the soil would behave in a similar fashion to the way it would have behaved if it has been part of the full scale structure. With the help of more than 40 research students, for over 40 years, I observed how the ground responds in various situations and with the variety of soils, and it is in that way that I've been trying to come up with general rules of their behaviour".

"In order to get engineers to believe me when I say that they can apply the general rules, I have been recently making very strong use of the measurements that practising engineers have made on movements of the grounds while they have been constructing various facilities. So research students have been hunting for full scale measurements made by, as it were, real engineers, in real circumstances. I also had students looking for published accounts by others, of how a variety of soils behave in simple laboratory test. And these databases have given me a lot more confidence, that the theories that I have been working on can be applied," asserted Prof. Bolton.

"As the ground is so variable and complicated, we will never be able to make a little model equivalent to the real ground. And so we just have to take one step back from there. The way engineers work as I was saying before, is that they take if they can, samples of soils, bring them back to a laboratory, and squash them, test them very carefully," said Prof. Bolton.

He continued to explain, "For example, one of my research student, Dr Sidney Lam, who is also one of my most recent PhD graduates, now working in Advanced Geomechanics, Australia, have found papers written in previous years by famous engineers and academics based on two things, (1) the observation of real excavations in real ground in this particular case (2) evidence from the samples that were taken at the time, of how those soils responded in laboratory test. And with those two pieces of information, Dr Lam was able to match the historic observations of ground movements surrounding deep holes in the ground in 9 famous cities around the world as if they were predictions he might have been able to make himself based on our new theories if he had been around at that time".

Prof. Bolton said that Dr Lam was able to find historical records of constructions and ground movements, and at the same time, historical records of soils behaviour in laboratory tests. "And with the new design methods that he has got now, he can put those two things together and say if I had been an engineer then, I could have predicted quite closely, what would have happened when they made this hole in the ground. He did centrifuge models in simple ground, he made a theory working with me on how those behave. He found historical records of how small soils elements behaved and historical record of how ground moved around big excavations such as the subway station and put all that together to support the theories that we have been working on," said Prof. Bolton.

BRIDGING THE GAP BETWEEN ACADEMICIANS AND PRACTISING ENGINEERS

According to Prof. Bolton, the understanding of soil mechanics by academicians in top class research universities which can be found all around the world is far in advance of where it was when he was still a student, more than 40 years ago, and it is still improving and advancing.

Prof. Bolton also expressed his resolution to bridge the gap between his findings and the current understanding of practising engineers. "Of course, there are some things that are simply not yet known. So there's a need for further research. However, there is a gap in understanding, that perhaps you might expect, between the top research universities and the rest, but especially a large gap, and I think in every country in the world, between what is generally understood in universities and the understanding that practising engineers have, has been part of my interest, to try to bridge that gap, by making theories that can be applied in practice, by talking to practising engineers, to encourage them to use some of these ideas".

He also pointed out his concern pertaining to the application of new ideas or theories by practising engineers. "As academicians in universities, they spend their time thinking deeply about all these things. On the other hand, within the world of practising engineers, there is a tendency to apply existing ideas in their practice. I suppose in every profession, there is a tension between discovering more knowledge and applying the existing knowledge in a good way." However, Prof. Bolton also highlighted that most of these practising engineers are only good at applying engineering knowledge which has already existed for more than 20 or 30 years ago into today's engineering practice. "But I'm worried about the rate of diffusion of new ideas into the profession. I think that it is slower than it needs be. And I'm keen to see practitioners pick up relevant new ideas more quickly," commented Prof. Bolton.

Pertaining to the understanding of soil mechanics by the fraternity of geotechnical professions, both in academicians and practising engineers, particularly in Europe and Asia, Prof. Bolton expressed his interest in the Asia region for his research. "There certainly is a gap in the rate of creation of infrastructures. Europe infrastructures were largely in place 20 to 30 years ago. Asia is at the epicentre of infrastructure construction. All the countries in the ASEAN region have a very rapid rate in construction of infrastructure demanded by different societies. That's why I'm particularly interested in coming over to this part of the world to see if I can get across any of these new ideas."

"The right place to expand them because it's over here in Malaysia, China and Taipei, Taiwan, for example, is where the world's construction is centred. So it's a challenge to me to see if I can say anything which engineers in these countries find useful," said Prof. Bolton.

REPLACING THE USE OF SAFETY FACTORS WITH PERFORMANCE CRITERIA

"I have been advocating replacing the use of safety factors with performance criteria. A safety factor is the ratio between an estimated material resistance or estimated resistance of the structure and the ground in some way where the load is placed upon it. As these two estimated things are somewhat imaginary and because the ratio of them has no particular physical meaning, safety factors cannot be related to observed behaviour. So that's the first problem, and through my research, I am aware that there are ways of setting performance requirements, for instance, if I were to say that the foundations of a structure should not move more than 20 millimetres. Hence, there would be a way of designing foundations at least within the intention of delivering that performance requirement".

Prof. Bolton further elaborated about the use of safety factors by performance criteria with another example. "If you lived in one of those blocks of flats, you might wish that the foundation engineers had ensured that the foundation wouldn't move more than 20 millimetres when the building was constructed. That would mean that it shouldn't be tilting, the walls shouldn't be cracked, it should be okay and furthermore you can go back and check it. That's what I mean by performance-based design. You now got a rule based on a sort of scientific calculation and if it's wrong, you should be able to find where the mistakes were and improve things".

In comparison to just safety factors per se, Prof. Bolton said: "Whereas, if you just said that I want the factors of safety, I wonder if you could get what the factors of safety of the foundations underneath one of those buildings are, that is, how much heavier a building would have to be before the foundations failed. To make it clearer, let us take the example of the multi-storey building. It shouldn't tilt so as to jam the lift in the lift shaft, and that's quite a tight criteria. One part in a thousand might be enough to jam a lift. But one part in a thousand isn't very much at all."

He continued: "So it shouldn't tilt too much, it shouldn't deform too much. Thus, if the foundations go down different distances, and because building materials are quite brittle, you would probably get cracks and if you could see those cracks, you wouldn't be very happy. But you might be able to cement over them. If you could put your hands into the cracks, you would probably come out of the building, pull it down and sue everybody in the court of law. Therefore, there are these more rational criteria about the movement of foundations which relate closely to the function of the building and people's perception of it."

"I ought to say at this point, there are some good things in the Euro Code 7 such as some clarifications of responsibilities, some clarifications about the nature of the tasks faced by the designers. I like many aspects of the new Euro Code, but where I'm particularly critical is that there is a rather pedestrian and somewhat impenetrable set of partial safety factors and equations which separate the good design engineers from the performance of the structure that they are designing, even more than the old single value safety factor did. It's rather arbitrary, so few buildings ever failed that we don't have a database, of what the safety factors could mean," said Prof. Bolton.

"It's just playing with numbers instead of addressing what the owners of the infrastructures would be interested in. It's making it seem like an arithmetic exercise instead of focusing on the real behaviour of the ground and of the structures on the ground. It's exactly like a 'tick box' situation. We end up with lots of equations and factors and so the designer checking his design finds that he's got lots of tables and numbers to apply to different parameters in different circumstances. An engineer at a workshop told me that all these numbers make him feel as though he was not well in contact with what was actually going to happen with this structure as he was before".

According to Prof. Bolton, all those old safety factors such as 2.5 on foundations, which were advocated since the 1940s to 1960s, they were effectively still with us because the Euro Code governing foundations was just merely splitting the old safety factors into smaller fractions. "So there are safety factors on loads, safety factors on materials, sometimes safety factors on components, and if you multiply all these safety factors together, miraculously, they very often would have given you the safety factors that our grandfathers would have designed with, back in the 1950s or 1960s," said Prof. Bolton.

FUTURE RESEARCH DIRECTION OF SCHOFIELD CENTRE

Prof. Bolton pointed out that the most wonderful thing about academicians in universities is that they often refresh themselves at frequent intervals, by defining new research goals. He observed that there has been more emphasis placed on geotechnical engineering for alternative energy and power generation. Apart from renewable energy, Prof. Bolton also emphasized that re-development of major cities including the management and maintenance of existing infrastructures and buildings would be the main focuses. "All major cities will face the same problems such as issues about the very congested underground which is full of pipes, channels, tunnels, and foundations. In future, as the cities are re-developed, we need new transport tunnels and new foundations. So how are we going to introduce those into the grounds without disrupting what is already down there? Hence, urban infrastructures will still be our research in the next few years," concluded Prof. Bolton. ■