

## INTRODUCING ADVANCED TOPICS IN GEOTECHNICAL ENGINEERING TEACHING – TUNNEL MODELLING

Jim Shiau, Mathew Sams and Brian Lamb  
School of Civil Engineering and Surveying, University of Southern Queensland, Australia

### ABSTRACT

This paper demonstrates a strategy to integrate research into teaching at a postgraduate level. It involves the use of simple small-scale physical models of a tunnel heading, the introduction of particle image velocimetry, an advanced computing technique used to further visualize the movement of soil, and a numerical model of a tunnel heading. Based on staff experience and student feedback, it is concluded that this is an effective and satisfying way to engage students with the subject matter. It is also hoped that discussing and displaying some of these advanced topics will encourage further student interest in geotechnical engineering research.

*Keywords: Tunnel, Heading, Modelling, Particle Image Velocimetry, Education*

### INTRODUCTION

The complex nature of geotechnical engineering in general leads to a heavy reliance on computer modelling both in research and development as well as in practice, and this makes it difficult to teach using conventional ‘chalk, book and talk’ methods.

With the limited time allocated to geotechnical engineering by some universities, finding efficient ways of teaching is critical [1]. The benefits of hands-on teaching and using laboratory work have been widely published. Both teaching staff and students can benefit from such an approach [2], as it is more enjoyable for the staff and more engaging for the student.

Physical modelling has long been used by geotechnical engineering researchers with success for a number of years. It is an effective way of simplifying and visualizing a particular problem [3] and will likely always be necessary at some level to validate increasingly popular numerical modelling. The models referred to in this paper were developed for this very reason, during research activities by the USQ tunnel group.

In particular, tunnelling has undergone significant research using physical modelling; a comprehensive review has been done by [4]. Physical modelling of tunnels is generally split based on whether it has been done in a centrifuge ( $ng$ ) or under normal  $1g$  conditions. The former can more accurately model realistically larger structures; the model can be scaled up by a factor of  $n$ . It is, however, expensive and time-consuming. The latter are easy to develop and cost-effective, more suited to qualitative and educational purposes [5 and 6].

Numerical modelling is more cost and time efficient however, and is more capable of modelling complex geometry. These reasons have made it a primary tool for geotechnical engineers, both in

practice and in research. Thus, it is important that students gain some experience with the software.

With modern cities and highly developed regions around the world struggling to cope with increased motor vehicle traffic, alternative transport solutions have to be found. There is still a strong need for inner city roads. However, space for expansion and/or upgrading of such infrastructure is generally limited and can cause significant public disruption when undertaken. Because of this, tunnelling is increasingly becoming a preferred solution.

The critical geotechnical aspects for tunnel design as discussed by [7]-[10] are: stability during construction, ground movements, and the determination of structural forces for the lining design. These simple models can give valuable insight into the stability and settlement problems. In particular, the stability and settlement problems have researched previously in [11].

The ultimate aim of this paper is simply to demonstrate a way in which physical modelling can be used to enrich a technical course in geotechnical engineering. It is believed that showing some aspects of an advanced topic such as tunnelling, *PIV* and numerical modelling may help to reinforce earlier learnings such as the concept of a soil model, and show the possibilities and breadth of the geotechnical area.

### TUNNEL HEADING - PHYSICAL MODEL

The purpose of this model is to investigate tunnel heading stability and soil movement upon collapse in cohesionless soil over a range of cover to diameter ratios ( $C/D$ ) as defined in Fig. 1. In this case,  $C/D$ 's from 1-7 can be investigated. To do this, the following methods will be used: physical modelling using scale models with a transparent face, and particle image velocimetry (*PIV*) to demonstrate

the movement of the soil in these models. The sand used was kept constant and the properties of this sand were used in future numerical modelling.

The modelling was only two-dimensional (2D) in this project, as the increased complexity, time and cost of doing three-dimensional was considered unnecessary in this particular case. It should be noted that modelling this particular problem in 2D is considered conservative, as the effects of the soil structure in the other axis are being disregarded.

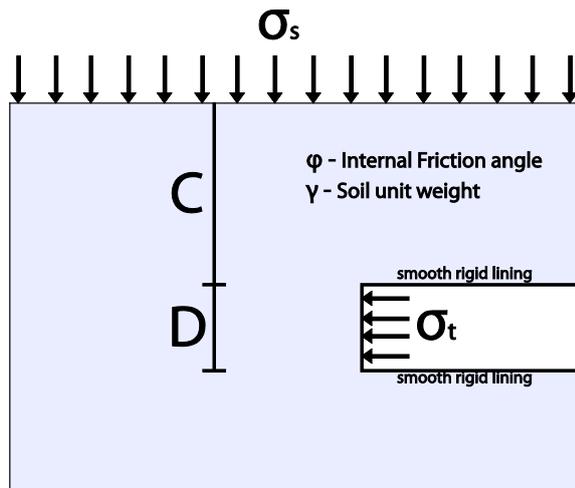


Fig. 1 Statement of the tunnel heading problem

Geotechnical problems in reality are very difficult to model with 100% accuracy because of the number of variables involved. Although numerical modelling has significantly improved in quality and quantity over the past few decades, it is still somewhat bound by these restrictions. This combined with the need for numerical modelling to be verified means that physical modelling is still a large part of geotechnical research.

Physical modelling has been used widely in geotechnical research for quite some time. Large scale tests and centrifuge testing are expensive, time consuming, and often don't deliver sufficient return, in terms of results, for the investment. The use of much smaller scale models is therefore much more preferred.

There are two main types of small scale tests: those that are run under standard gravity conditions, that is 1g, and those that use a centrifuge, under *ng* conditions. Tests conducted under 1g conditions are easily reproduced, have minimal preparations required, and are easily controllable. The drawback is that the stresses in the soil compared to the soil properties are not realistic.

Centrifuge modelling can overcome some of these shortcomings. The small scale model can be subjected to higher gravity levels, *ng*. This then allows the self-weight of the soil and the stresses within it to become comparable to a large scale model which is *n* times larger [12]. However, the gravity level that each soil particle experiences is

relative to its distance from the centre of the centrifuge, which means that there is a distribution of gravity acceleration through the model. This problem requires adjustment and calibration to the model dimensions and instrumentation to overcome it which is quite complex. Thus, centrifuge modelling is very expensive and time consuming.

Physical models are used themselves to study the behaviour of soil and its impacts as well as to verify numerical models. If the soil of interest is sand, using 1g scale models is particularly attractive, as there is no need for a centrifuge as the soil fails under its own self weight. The models can be relatively simple and affordable to construct and operate, whilst still yielding good results. Therefore for this exercise, 1g scale models have been used to conduct the physical modelling.



Fig. 2 The tunnel heading model

The aim of the experimental tests in this project was to gain an understanding of the failure mechanisms in front of the tunnel face, and to examine the settlement characteristics of the soil with varying overburden (*C/D* ratios). To do this, the physical model tanks were designed and the sand material used was identified. The design of the models draws inspiration from other projects at USQ as well as other external research projects, namely from [5], [6], and [12]. A picture of the models used is shown in Fig. 2.

A total of five boxes were constructed to cater for the six *C/D* cases that were to be examined. They are 50 cm long and 5cm in breadth, with a totally transparent Perspex front panel. The crank handle rotates the screw which slowly withdraws the heading. For this project, the tunnel has been approximated to a rectangle to simplify construction. The sand used was blended with coloured sand (for the PIV), and was constant for all experiments. The density was determined to be 1800 kg/m<sup>3</sup>, and the friction angle to be 35 degrees.

The procedure for the physical modelling was kept as similar as possible through the six cases. Firstly, sand was poured uniformly into the model to the correct overburden level (e.g. 100mm for *C/D*=2) while avoiding any compacting or settling

action. Then the heading is slowly withdrawn using the crank handle. The screw that has been used is calibrated for 1mm/revolution. Thus, the handle was rotated at approximately 1 revolution every two seconds, which therefore leads to the heading being retracted at 0.5mm/sec. This is stopped when the sand is no longer touching the heading, and this was considered as the total failure of the tunnel heading. After this, measurements were taken of settlement parameters:  $S_{max}$ ,  $L$ , and  $B$  as shown in Fig. 3.

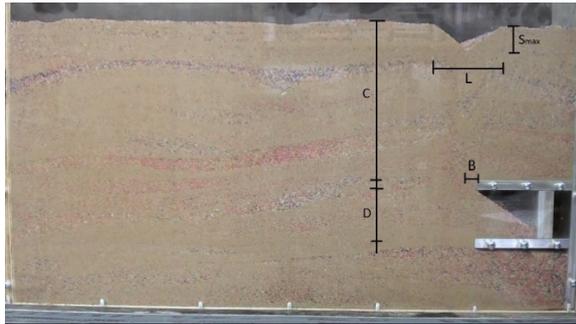


Fig. 3 Definition of Settlement Parameters

It can be seen that the maximum settlement,  $S_{max}$ , decreases with increasing  $C/D$  as the distribution of stress is spread over a wider area. The parameter  $B$ , representing distance of maximum settlement from initial tunnel face position, seems to increase and then plateau out with increasing  $C/D$ . This is due to soil arching effects becoming a more dominant factor of the soil's movement. It's entirely possible with  $C/D$  of greater than 7 that the  $B$  parameter may in fact start to decrease. The  $L$  parameter, indicative of the observable settlement trough width, seems to increase exponentially with  $C/D$ .

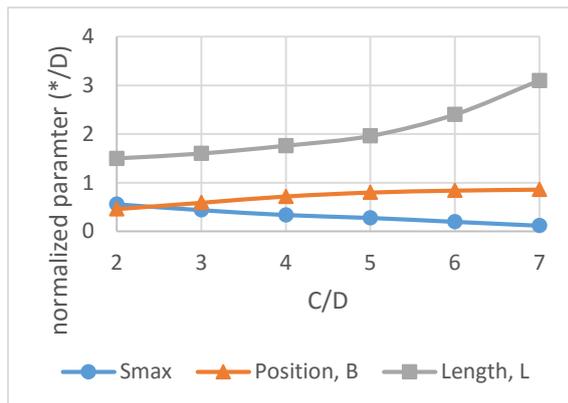


Fig. 4 Settlement results from physical modelling

While the heading is being retracted, the soil movement from start to finish was recorded by a full HD camera. This footage is then used for the particle image velocimetry analysis.

## PARTICLE IMAGE VELOCIMETRY

Particle Image Velocimetry (*PIV*) is a technique that allows investigation of plane displacement patterns [13]. It was first used in fluid dynamics to demonstrate flow fields, but it has since become widely used in various applications, from aerospace, thermodynamics, and also geotechnical research. It is non-invasive, requires relatively minimal setup, and can analyse a soil sample on a grain-scale level [14]. This combined with rapid technological advances in computing during the last few decades, has meant that *PIV* has become very widely used in the geotechnical area.

There are many possible software alternatives that can do *PIV* analysis, but the program that was selected was *GeoPIV*, created by [15]. The theoretical background *GeoPIV* uses means that its performance is better compared to others results, and is relatively easy to use. The authors also provide the software and manuals free of charge for educational purposes. *PIV* is also easier and less time consuming to setup and can demonstrate movement of the entire soil sample rather than just layers, and is more precise.

In this research project, a qualitative investigation using *PIV* of the tunnel face collapse is used to identify displacement patterns and demonstrate failure behaviour. Layers of coloured sand were used in the physical models to better allow *PIV* to track the soil particles.

During the first operations of the software, it became clear that it was very sensitive to the lighting conditions and movement of the camera and the model. The effects of this are shown in Fig. 5.



Fig. 5 A *PIV* analysis with wild vectors

Therefore, careful positioning of the model and camera was needed to ensure that we had minimal reflections on the transparent panel but also ample light so that the footage is clear. There was also the issue of the operating personnel moving, and creating shadows as well, this had to be managed such that the model was somewhere where the personnel could operate the crank handle but not negatively impact the lighting on the model. Fig. 5

still shows some reflections, but the objects causing them are stationary and unlikely to cause issue. Another problem was the vibrations caused by the operating of the crank and the inherent resistance in the system. This problem proved somewhat difficult to fully eradicate, but was minimised by having stabilisers on the bottom of the model, placing the model on a fixed bench, and using the relatively slow handle rotating speed.

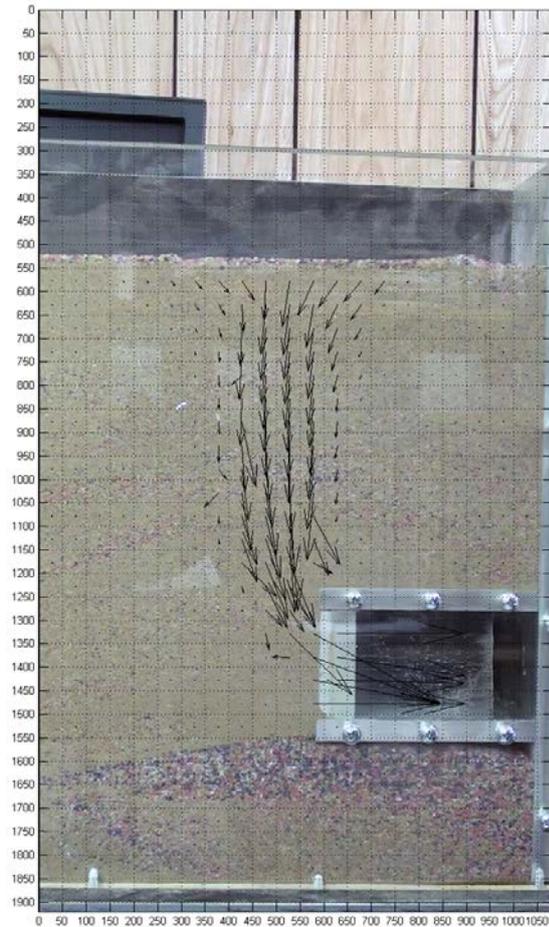


Fig. 6 A PIV analysis of the  $C/D=3$  case

Figs. 6 and 7 are the PIV analyses of cases  $C/D=3$  and 7 respectively. As the analysis software requires images rather than a video file, the first step once the testing is completed is to export images out of the video. A freeware program named “VirtualDub” has been used for this purpose. As the raw footage has been recorded at 50 frames per second (fps), only every 100th frame is exported, this corresponds to one image every two seconds. More frames may increase accuracy but there will be diminishing returns, and this will also dramatically increase the computing time. Then Adobe Photoshop was used for a slight adjustment to the levels to increase spatial variation in brightness and contrast across the image.

From the physical modelling results, it was measured that maximum settlement ( $S_{max}$ ) decreases

with increasing  $C/D$ , the position ( $B$ ) of this maximum settlement from the initial tunnel face increases but seems to plateau out at higher values of  $C/D$ , and the observable length ( $L$ ) of the settlement appeared to increase exponentially with  $C/D$ . These PIV plots of the physical modelling appear to somewhat confirm these observations.

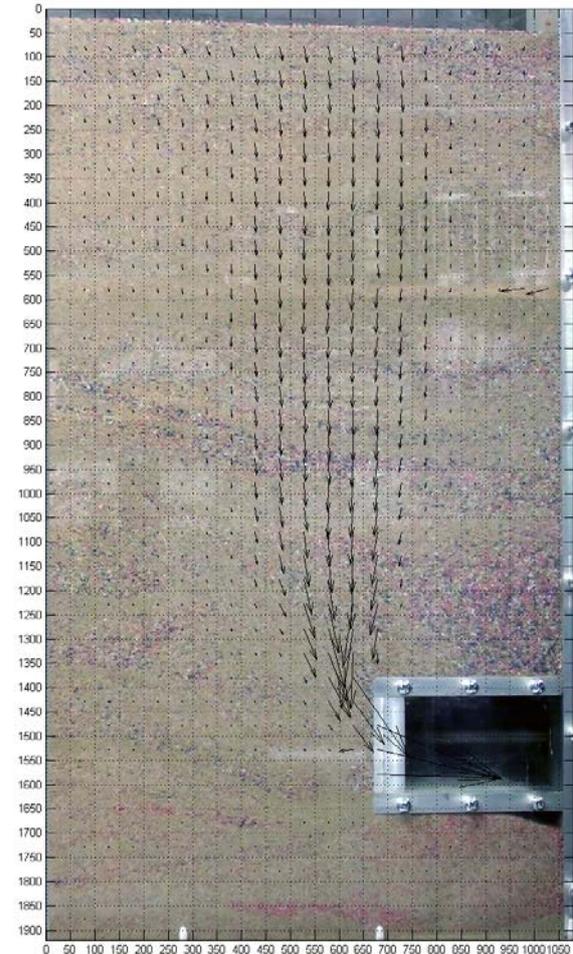


Fig. 7 A PIV analysis of the  $C/D=7$  case

Using the PIV analyses in such a qualitative manner means other observations can be made regarding the failure behaviour. For instance, the failure mechanism observed using an animation of all the frames analysed using PIV is consistent with what is described in [13] and [14], of a staged failure.

#### TUNNEL HEADING – NUMERICAL MODEL

A numerical model has been developed for simulating a tunnel heading [11]. The developed FLAC model uses the built-in FISH language [16] that automatically generates grid dimensions, solution commands and outputs relevant plots for prescribed condition. The developed model is user friendly with only limited soil parameters and dimension inputs required by the designer to achieve relatively accurate and meaningful results for

preliminary design and construction purposes. A typical mesh generated by *FLAC* using the developed script is shown in Fig. 8.

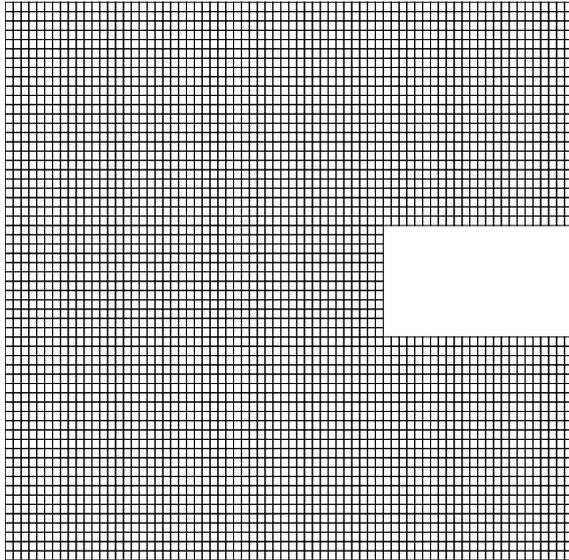


Fig. 8 A typical mesh of a tunnel heading ( $C/D=2$ )

The model assumes a Mohr-Coulomb material, and 2D plane strain conditions. While the real soil conditions and tunnel/soil interactions are three-dimensional, the model uses these assumptions for simplicity, such that the tool could be used in the preliminary stages.

The tunnel lining is assumed to be rigid and soil conditions homogenous having uniform properties with increasing depth. The problem is similarly defined using Fig. 1:  $C$  is the overburden height,  $D$  is the tunnel diameter,  $\sigma_s$  is the surface surcharge,  $\sigma_t$  is the tunnel support pressure,  $\gamma$  the unit weight and  $\phi$  is the angle of internal friction.

The tunnel heading problem can be approached by making use of a pressure relaxation technique whereby the internal pressure ( $\sigma_t$ ) is gradually reduced until a point of failure is detected. During the operation of a tunnelling machine, it is the slurry or earth pressures at the tunnel heading that is controlled. Therefore, the use of a pressure relaxation technique would provide a more realistic result when compared to other methods such as the displacement method, as the relaxation method better reflects the conditions at the cutter head.

When the heading pressure is relaxed, the heading stability decreases until yielding occurs at the point of instability. This point is also where a sudden change in tunnel face movement takes place. While reaching this point of collapse would be avoided in practice, it does provide a meaningful bound to designers in understanding the sensitivity of the soils response to changes in face pressures during construction.

The overall heading stability is commonly

presented using the dimensionless quantities  $\gamma D/S_u$  and  $(\sigma_s - \sigma_t)/S_u$  and in conjunction with the geometry ratio  $C/D$  [17]. These dimensionless quantities, which are also adopted in this paper, would help to define the point of instability, providing designers and TBM operators with minimum heading pressures to prevent collapse and to estimate the sensitivity of the soil response to the tunnel boring and changes to face pressures.

The aforementioned point of collapse is identified by examining the force history plot, which describes how convergent the solution is, in that particular stage. A convergent solution indicates that the retaining soil forces (shear strength and internal pressure) have reached equilibrium with the destabilising forces (weight). As this numerical method gradually reduces the internal pressure, there is eventually a stage where it is reduced enough for an equilibrium to be unattainable. A typical history plot is shown in Fig. 9. After approximately 80,000 steps, an equilibrium can't be found, this is identified as the collapse stage.

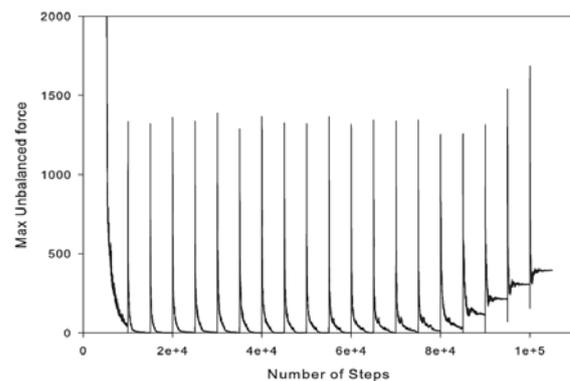


Fig. 9 Typical unbalanced force history plot

Figs. 10-14 present typical plots of velocity vector, plasticity indicator, shear strain rate (SSR), vertical displacement contour, and principal stress tensor. These plots are useful for student learning in observing and comparing model responses. They also provide an increased understanding for soil behaviour and the failure mechanisms of a tunnel heading collapse

#### CLASSROOM INTEGRATION – FOUR WEEK ACTIVITY

The above developments were implemented into an advanced geotechnical engineering course over a four week period, where each week constitutes a three hour session. The contents of these four weeks are given below. Week 1 is an introductory lecture covering some of the required material; basics of tunnelling and a discussion about physical modelling in geotechnical engineering. In week 2, the physical models are actually used by the students, and a brief

demonstration of the *PIV* analysis as well as the computer modelling is conducted. Week 3 is for the *PIV* analysis and the computer simulations, while week 4 involves an activity to complete a group report which is due two weeks after.

**Week 1:** There is a short lecture of introduction to tunnelling: history, methods of construction, discussion of design criteria (stability, settlement, lining forces), and define the problems that engineers face. Discussions also include tunnel stability and settlement – how these are measured, and how are they managed in tunnel boring machines (TBM's). Finally, a brief explanation of the 1g model in the laboratory, *PIV* analysis and numerical modelling techniques using *FLAC* is presented. Students are shown what to expect in the following weeks. Also a number of journal and conference papers are given to students for reading activity at home.

**Week 2:** Class meets in the soil laboratory. Five groups are formed (one for each box), and they are each set the task of investigating a different *C/D* (between 1 and 7). Students are asked to draw diagrams showing deformed shapes and failure planes, and participate in a discussion with questions such as: what is the effect of *C/D*? What effect would the strength of sand have? What are the assumptions involved? A demonstration of the *PIV* process (series of images extracted from video, mesh generation, processing, post-processing, vector animation, and final picture) and the numerical model using *FLAC* is conducted. Detailed procedure of input parameters, program operation, analysis of outputs, and identify the collapse stage are explained. Both *PIV* and *FLAC* script are given to students for preparing Week 3 activities.

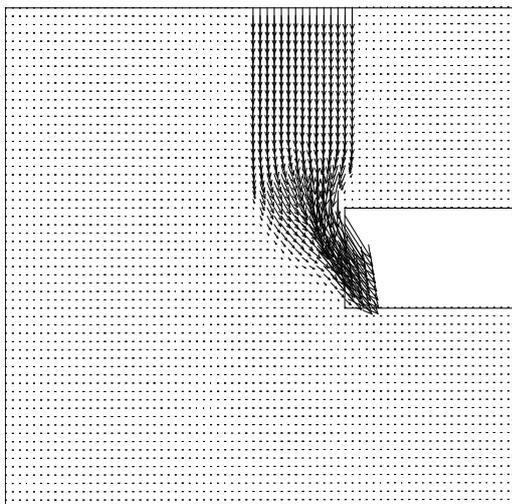


Fig. 10 Velocity vector plot at collapse for  $C/D=2$ ,  $\phi=40^\circ$

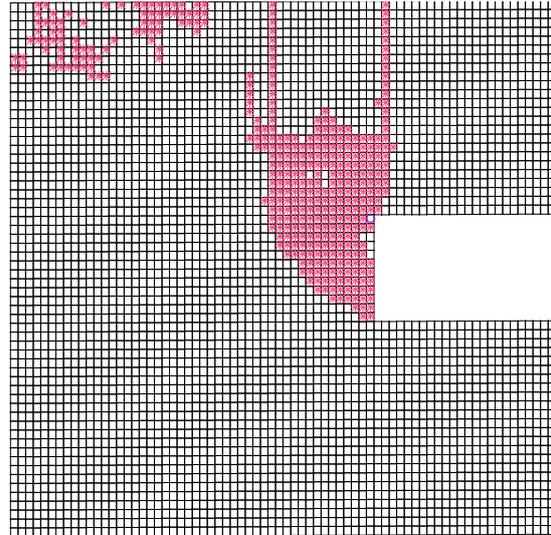


Fig. 11 Plasticity indicator plot at collapse for  $C/D=2$ ,  $\phi=40^\circ$

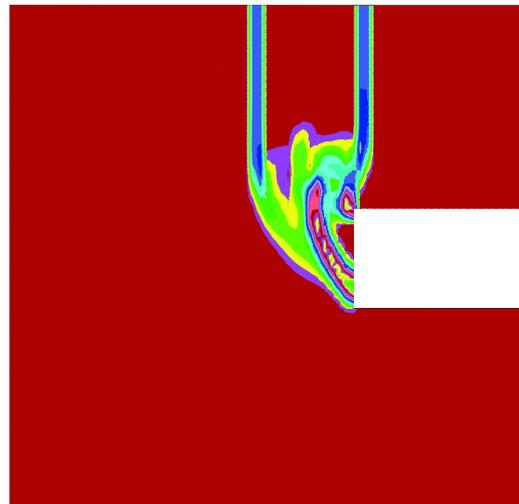


Fig. 12 Shear strain rate (SSR) plot at collapse for  $C/D=2$ ,  $\phi=40^\circ$

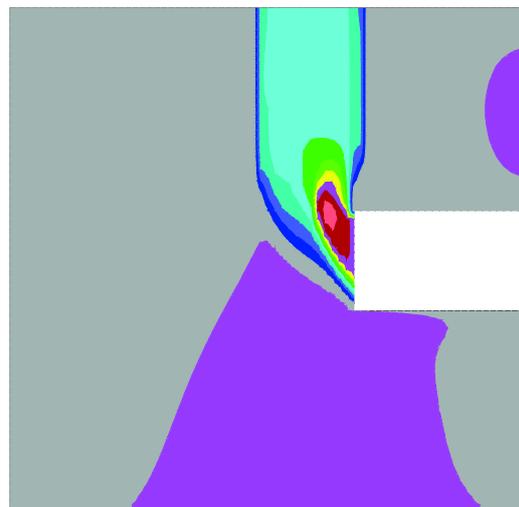


Fig. 13 Vertical displacement contour plot at collapse for  $C/D=2$ ,  $\phi=40^\circ$

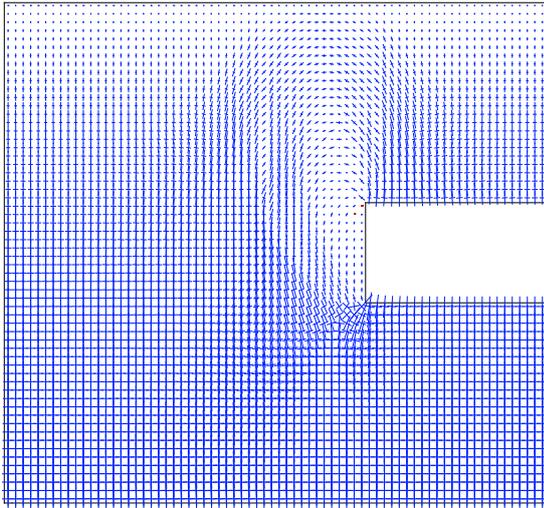


Fig. 14 Principal stress tensor plot at collapse for  $C/D=2$ ,  $\phi=40^\circ$

**Week 3:** Class meets in the computer laboratory. Students are required to complete *PIV* analysis using the images captured in Week 2. Students are also required to perform stability and settlement analysis using *FLAC* with the developed script provided by the lecturer. A series of parametric studies on the effects of depth ratio  $C/D$  and the frictional angle of sand  $\phi$  are required from student work, as well as a comparison with the *PIV* results and observations.

**Week 4:** Class meets in the tutorial room. Students begin a group technical report of approximately 15 pages summarising all their findings. There is no fixed structure of this report, it needs to demonstrate that they have learnt and understood from this subject matter.

## CONCLUSION

A four week teaching activity has been developed which introduces students to some advanced aspects of geotechnical engineering and tunnel design (stability and settlement). This activity involves physical modelling in geotechnical engineering, using advanced computing techniques (*PIV*), and employing a numerical model (*FLAC*). This development would suit a postgraduate course; it could also suit a short tunnel engineering course for practising engineers. It can also be tailored to fit undergraduate engineering.

According to some student feedback and general observation of the activity as it is in progress, outcomes from this activity seem to be quite positive. Using a more interactive class style such as this leads to better student engagement, when it is compared to a traditional classroom method.

These extra activities also introduce students to tunnelling and some of the methods of geotechnical research. It is hoped that this developments helps to increase awareness and interest in the field of geotechnical engineering.

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Corresponding Author: **Jim Shiau**

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