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Learning through physical modelling observations in the Undergraduate Curriculum

Apprentissage par l'observation de modélisation physique dans le programme d'études universitaires

I.U. Khan
University of Sheffield, Sheffield, United Kingdom

S.M. Bayton
University of Sheffield, Sheffield, United Kingdom

ABSTRACT: Element tests are routinely conducted as part of geotechnical courses to evaluate soil properties such as compressibility and strength. Although beneficial to build comprehension of geotechnical theory, these tests fail to provide observations of real geotechnical structures performance *i.e.* failure of slopes, retaining structures and foundations. While complementary design problems can be taught using analytical/numerical methods for a set of laboratory-derived input soil parameters, these only serve as a diagnostic assessment of comprehension and fail to provide a holistic learning experience incorporating observation and reflection. Since 2012, a small-scale educational centrifuge has been in operation at The University of Sheffield contributing in excess of 500 tests to support educational delivery and demonstration of geotechnical design within the undergraduate (UG) curriculum. This paper summarises the centrifuge capabilities, focusing on a bespoke educational experiential learning module that has been established to investigate slope stability; and reports on the positive impact to the student learning experience that has been achieved through experimental inquiry-based pedagogy.

RÉSUMÉ: Des tests d'éléments sont régulièrement effectués dans le cadre de cours de géotechnique afin d'évaluer les propriétés du sol, telles que la compressibilité et la résistance. Bien que bénéfiques pour renforcer la compréhension de la théorie géotechnique, ces tests ne permettent pas d’observer la performance réelle des structures géotechniques, c’est-à-dire la défaillance des pentes, des structures de retenue et des fondations. Bien que des problèmes de conception complémentaires puissent être enseignés à l’aide de méthodes analytiques / numériques pour un ensemble de paramètres de sol d’intrants dérivés du laboratoire, ceux-ci servent uniquement d’évaluation diagnostique de la compréhension et ne fournissent pas une expérience d’apprentissage holistique intégrant l’observation et la réflexion. Depuis 2012, l'Université de Sheffield utilise une centrifugeuse éducative à petite échelle, contribuant à plus de 500 tests destinés à soutenir la prestation pédagogique et la démonstration de la conception géotechnique dans le programme de formation de l'UG. Ce document résume les capacités de la centrifugeuse, en se concentrant sur des modules éducatifs d’apprentissage par l’expérience pédagogiques conçus pour étudier les la stabilité des pentes; et rend compte de l'impact positif sur l'expérience d'apprentissage des étudiants, obtenu grâce à une pédagogie expérimentale basée sur l'investigation.

Keywords: centrifuge; small-scale testing; geotechnical; slope failure

1 INTRODUCTION

Physical modelling is seen as an important tool in predicting the behaviour of full-scale engineering problems and is usually carried out by making small-scale models of a prototype. These are tested in a laboratory under controlled conditions. The controlled conditions provide a starting point for validating theoretical and numerical analysis carried out on a geotechnical problem, which is very important to for the connection between theory and real-world problems (Wartman, 2006).

In most of the undergraduate (UG) curriculum, this is achieved through laboratory demonstrations. Laboratories attempting to capture the performance of a realistic prototype have limitations particularly in the field of civil and structural engineering due to low self-weight contributions which often govern and dominate the system stability. To overcome these limitations and to provide a better understanding of geotechnical design problems, a 1.1 m diameter centrifuge was built at the University of Sheffield, in 2012. It has been in operation for almost 6 years with more than 500 tests completed. The focus of this paper is to analyse the role of this centrifuge in enveloping the learning curve of UG students.

Centrifuge testing comes under the category of small-scale modeling, which has several benefits beyond the fact that it is considerably cheaper than full-scale physical modelling (Craig, 1989). From a theoretical perspective, the benefit of centrifuge testing in comparison to alternative techniques is that the stresses at different points in the model are approximately the same as that of the prototype. In addition to this, small-scale tests allow for full control over the details of the model, allowing the pre-conditioning of the characteristics of the soil in question. Furthermore, loading conditions are known so that the exact stress state and boundary conditions of the setup can be determined.

The educational centrifuge at the University of Sheffield, shown in Figure 1, has the capability of achieving accelerations of 100 times Earth's gravitational field (100*g*) with a payload of 20 kg. The maximum dimensions of the test sample are 160 mm (length) x 100 mm (height) x 80 mm (width). By being able to apply elevated gravity, one can increase confining stresses, which is ultimately advantageous as it increases the similitude of the model to the prototype condition since stress states become almost the same (ignoring radial stress errors). Model studies using the centrifuge, if done correctly, demonstrate behaviour that is close to prototype behaviour; this ability to provide realistic results and allows for the verification/development of theoretical models (Mitchell, 1994).

To demonstrate the capability of the centrifuge, a slope stability boundary value problem is performed as part of the learning syllabus by the students. The motivation of this exercise is to evaluate the performance under an induced stress as well as predicting the undrained shear strength of the soil at collapse. Forensic analysis of the experimental model is complemented by classic analytical solutions and numerical simulation.

2 SLOPE FAILURE BACKGROUND

Natural disasters are ever-occurring and one of the most common of these is the failure of natural slopes (Take, 2004). Perhaps equally as important is the failure of man-made slopes. Failure can be caused by a variety of occurrences, but it is an engineer's responsibility to assess stability, with two categories of failure typically considered - rotational and wedge failure.

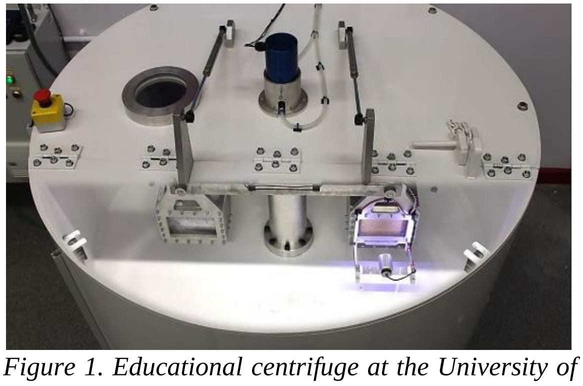

Figure 1. Educational centrifuge at the University of Sheffield (Black, 2014)

There are several different methods used to estimate the stability of slopes. A brief summary of these is outined herein:

(*i*) The *infinite slope* method involves identifying what conditions will result in the layer of soil slipping along a surface beneath it. This is achieved by identifying forces acting on the soil block element and calculating equilibrium conditions. The largest deficiency with this method is that no consideration is given to the rheological properties of the soils;

(*ii*) Perhaps more simple is *Taylor's chart method* for rotational instability (Taylor, 1937). Taylor produced charts that are for idealised situations of failure based on the base boundary condition, slope height and angle which produced the now well established chart for Stability Number. Due to the fact the iteration has already been performed, the lowest factor of safety can be identified and thus no analysis is needed on different slip circles.

(*iii*) Failure of slopes through *rotational mechanisms* is performed through the summation of mobilising and resistive moments, and requires an iterative process to reach a solution. By assuming an initial failure surface and calculating a factor of safety for this scenario, and then repeating for a new assumed surface, it is possible to identify the lowest factor of safety and hence the overall safety of the slope.

(*iv*) *Wedge failure method* is generally identified as a method of slices. This method assumes possible slip surfaces as segments of a circle. The driving and resisting moments are calculated allowing for the calculation of a factor of safety.

(*v*) With the continued advancement of computer software, the use of *numerical modelling* of slopes has accelerated. Uncertainties surrounding input parameters need to be addressed to ensure confidence of the output results. Generally, simplifications are made and just three parameters are considered in design: soil strength, geometry, and pore-water pressure.

The methods outlined above are important due to their ability to assess slope stability under current and foreseen conditions. If a slope is currently stable due to a low water table for example, it may not be after heavy rainfall results in an increase in the pore water pressure. It is for this reason that it is no longer acceptable to give general comments regarding a slope's stability - a far more rigorous approach is expected and required - and methods of analysis have therefore developed significantly over the years.

As part of the UG module the slope boundary problem exercise serves two main purposes: (*i*) to enable the students to gain confidence in the theoretical elements of centrifuge modelling; and (*ii*) to bring alive theoretical elements in tests of their own design to verify and benchmark the observed performance against established design methods.

3 SAMPLE PREPARATION

The experiment undertaken was designed to validate a model slope subjected to vertical loading. The slope was tested to failure by increasing the gravitational acceleration, thereby increasing the loads 'felt' by the undrained clay. The slope was set up as shown in Figure 2.

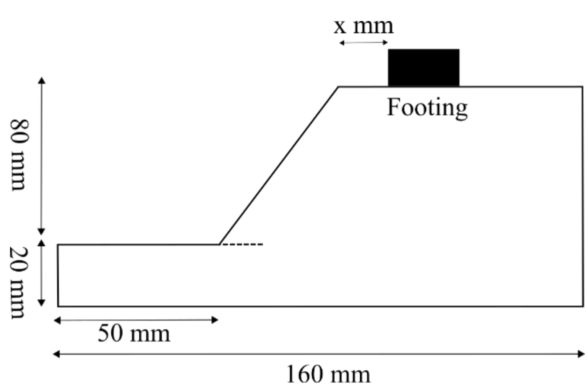

Figure 2. Slope setup

The slope itself was formed by saturating a sample of clay and consolidating it to 800 kN/m^2 in a large 1-dimensional press to create a stiff homogeneous block of clay. Cutting templates were used to sculpt the geometry of a number of slopes to a range in angle between 70° to 80°. On the sides of the sample, reference lines were sprayed onto the exposed surface to make the failure easier to observe during testing. A metal footing of mass 1.2 kg was placed at the top of the slope at different distances from the crest, between 0 and 20 mm, such that each group would have a slightly different failure surface to analyse.

4 SLOPE TEST

The soil sample with strip footing was loaded into the centrifuge payload box to carry out the test. Having determined the mass of the payload, the required counterweight was calculated and applied to ensure that the centrifuge was balanced correctly. Once this was achieved, the centrifuge slowly accelerated the package, increasing the gravitational acceleration in the soil. The model was rotated from standstill with a constant increase in rotational velocity of 100 RPM per minute until failure occured. Throughout the test flight images captured at 1 frame per second (fps) and continuous video at 30 fps were recorded which was displayed live to the students during the test.

In addition to recording visual data, the true rotational velocity of the payload was continuously calculated using the inverter drive output power. This information was then communicated to the control PC and displayed as a live plot of RPM against time. Using this RPM data and the known geometry of the centrifuge beam and payload assembly, a second plot of the variation in gravity over time was generated and displayed alongside the original in National Instruments LabView®. Taking a readout directly from this at the point at which failure was observed on the overhead video monitor allowed for a preliminary estimation of the centrifugal acceleration experienced by the model at failure. Following the failure of the model, which can be seen in Figure 3, the payload was decelerated to a standstill and the recorded data exported for processing by the students.

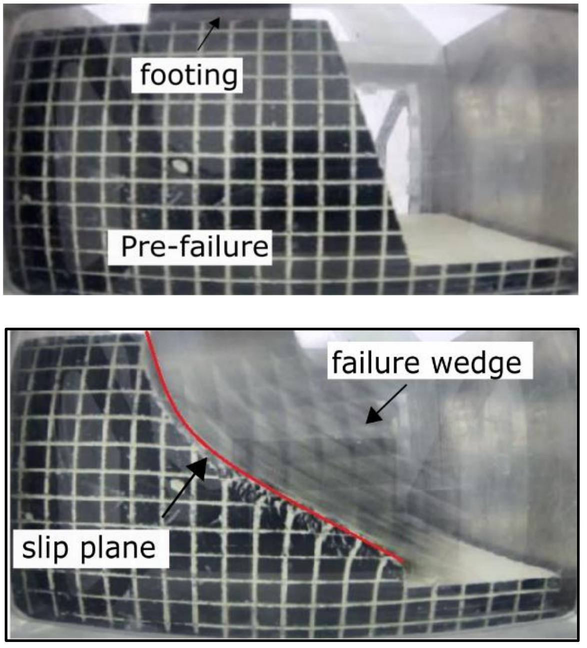

Figure 3. Slope – pre and post failure

5 SOIL STRENGTH ANALYSIS

At least three different analytical and numerical techniques have been used by each student group to analyse the soil strength. In total five techniques are used by seven groups. These are outlined below:

Method 1: Taylor Stability Method
Method 2: Kinematics Method
Method 3: Total Stress Analysis
Method 4: Bishop Simplified Method of Slices
Method 5: Limit Analysis

5.1 Taylor stability method

Taylor's stability method uses a design chart derived from circular failure planes in homogenous finite slopes and is based on the relationship between the angle and height of the slope in question. The chart was originally intended for effective stress analysis only but can also be used for an undrained case by assuming the shear strength is constant with depth. This method also assumes no surface loading and no tension cracks form during failure.

To manage the placed footing on the crest, its reversed weight (mass x centrifugal acceleration) at failure was converted into a hypothetical additional surcharge stress, and subsequently to an equivalent extra slope height. This was then fed into the Taylor design chart. Given the strip load nature of the footing, an equivalent UDL surcharge over the full crest of the slope had to be assumed by the students, adding uncertainty to the strength predictions.

5.2 Kinematics method

The kinematic method produces an upper bound solution for plane modes of failure which usually occur in slopes formed by stratified sedimentary and meta-sedimentary rock formations. The conservation of energy principles are observed and the internal work done (the energy dissipated along the length of the slip plane) is equated to the work done by gravity, or the mobilising force. It doesn't consider the effects of layered soils nor the frictional interface with the boundaries, though is well suited to this case because of the homogeneity of the soil.

5.3 Total stress analysis

Total stress analysis balances the moment of applied forces and resisting forces along the slip surface. The method is applicable to loading scenarios where the load rate is great enough to prevent excess pore pressure dissipation, or for the case of overconsolidated cohesive soils, whereby the effective internal angle of friction can be assumed to be zero.

5.4 Bishop simplified method of slices

Bishop's simplified method of slices (Bishop, 1955) is a limit equilibrium method in which failure along a circular arc is assessed by considering the static equilibrium of a series of vertical slices. The summation of mobilisation and resistance equations are most commonly solved iteratively to find the factor of safety of a slope, and a failure plane can be identified, as shown in Figure 4, where the factor of safety at failure is known to be 1. This method can be used to calculate the undrained shear strength directly.

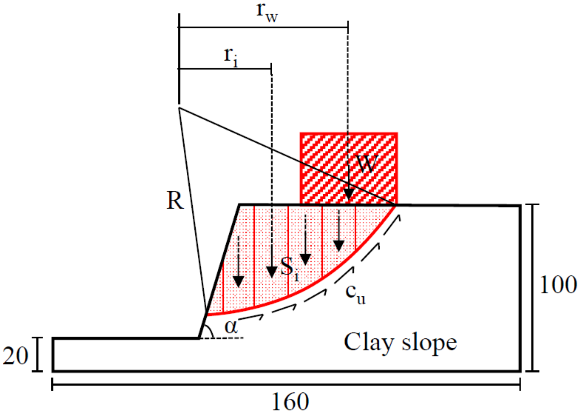

Figure 4. Slope failure geometry

5.5 Limit analysis

LimitState:GEO (LSG) has been used to both verify the aforementioned calculation methods as well as provide an additional method of determining the soil strength. LSG also provides a visual representation of the final failure mechanism and an animation of its propagation as shown in Figure 5. This allows a critical comparison to be made between the true failure mode observed in the experiment and the mode considered by LSG to evaluate the accuracy of the analysis.

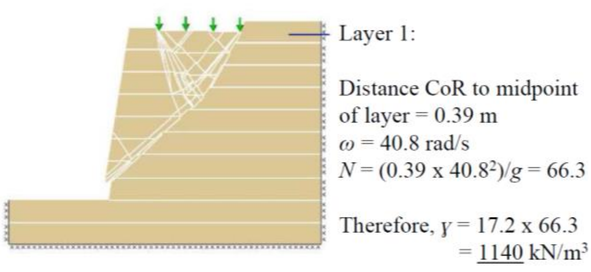

Figure 5. LimitState:GEO model and example calculation of discretised layer unit weight due to gravity variation with depth

5.6 Student slope failure prediction success

The success of the student's design prediction of slope failure is ultimately determined by the precision of their predicted soil shear strength in comparison to the actual value (determined by triaxial testing). The estimated undrained shear strength determined by each group and the analysis method(s) selected are presented in Table 1. Note, while the slopes were cut from the same larger block of clay, thus in theory should have the same strength for each case, slight variation arose due to the precise point each group considered failure in their data, and also the refinements in the analytical methods used.

It is evident that there is some spread in the assessment of the strength depending on the method used. Of particular interest is that Methods 4 and 5, undertaken by every group, provided a very large range of predicted strength despite the underlying design methods requiring the least number of geometrical assumptions. The greatest range of predicted shear strength was by using the Taylor design chart (from a very low 56.6 kN/m^2 to 127 kN/m^2), which highlights the challenges and uncertainties when adopting this method for a strip loading design case.

Table 1. Soil strength prediction by student groups.

	Predicted c_u (kN/m^2) with method				
Groups	**1**	**2**	**3**	**4**	**5**
1	127	-	-	132	132
2	-	-	102	117	110
3	-	114	-	115	135
4	-	-	-	91	91
5	80	94	-	104	104
6	56.5	101	106	107	109
7	96	-	-	119	124

The actual shear strength of the soil, determined by undrained triaxial test, was 109 kN/m^2. The predicted values in Table 1 show that most of student's estimations are reasonably close to the actual shear strength value.

6 SURVEY QUESTIONS

At the end of the module, a questionnaire was distibuted to the students. The questions in the survey were designed in a way to capture the impact of this module on students learning and understanding. Nine questions in total were asked as given below and the students responses are presented in Figure 6.

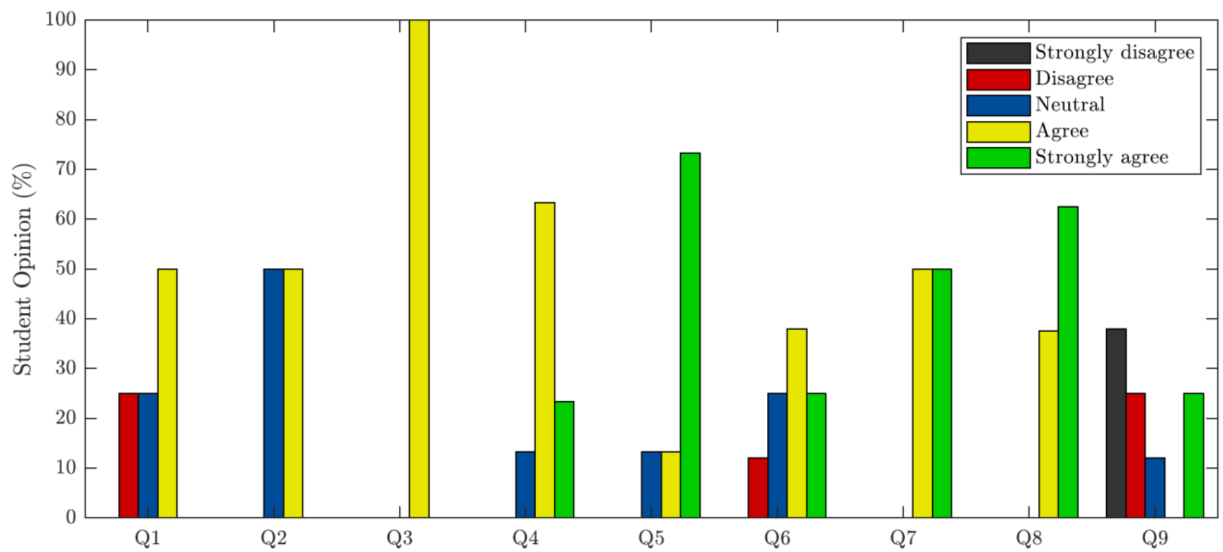

Figure 6. Results of student questionnaire

It can be seen from Questions 1 and 7 that the module has improved student understanding of slope stability. Questions 2-6 and 8 reinforced that the laboratory demonstration has given the student a better way to visually understand the magnitude of the problem. From Question 9, after this module, 25 % of the students started thinking about PhD research, and 12.5 % are undecided, which is an good accomplishment for this module.

The questions asked to the students were as follows:

1- I had a strong understanding of slope stability before the module;
2- The use of centrifuge modelling was an effective approach to learn about the stability of slopes;
3- The centrifuge experiment was an effective way to visualise the failure mechanism of slopes;
4- The centrifuge experiment was an effective way to connect traditional theory and numerical analysis;
5- The hands-on laboratory sessions were beneficial to my learning;
6- Engaging with existing literature (journals) was beneficial to my learning;
7- My knowledge of geotechnical slope theory was improved by the forensic investigation;
8- Learning from observations and data I collected in laboratories was valuable to my learning;
9- Participation in the module has made me think about possible PhD research studies.

7 CONCLUSIONS

This paper demonstrates the role of observational learning with undergraduate students in their formative years of study. The educational geotechnical centrifuge has been used in order to recreate the full scale equivalent prototype stress conditions for a slope stability design scenario.

The student project demonstrates the capabilities of the centrifuge and how data can be analysed using different techniques. At the end, a student survey is presented, capturing the importance of this module in overall student understanding.

8 ACKNOWLEDGMENTS

The success of this module is a collective effort and relies heavily on the support and dedication of the technical staff and PDRA. Their contribution is deeply appreciated and acknowledged. This module would not be possible without the student's involvement, so a big thanks to all the students of CIV4501 from the year 2012 to 2018 who were part of this journey of discovery. Elements of their work are reported within this paper.

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