Book Section:

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The development of a small-scale geotechnical teaching centrifuge

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Abstract

Geotechnical engineering is a core discipline within civil engineering that supports the infrastructure development which underpins modern society. The simulation of realistic geotechnical design at undergraduate level is often restricted to routine calculation-based methods reinforced by simple element laboratory tests which fail to provide a holistic learning experience. Using the latest research techniques, laboratory teaching can now offer the opportunity for students to test small-scale physical models which are representative of larger real world full-scale engineering problems. To provide greater connectivity between geotechnical theory and design, a small-scale 1.1m diameter teaching centrifuge has been developed. This enables observation of the behaviour of small-scale models tested under increased gravity to be directly related to full-scale field conditions. Accompanying educational resources have also been developed. An additional core objective was to promote widening participation amongst other higher education institutions and this has been achieved by ensuring that the centrifuge is highly cost-effective, built from standard off-the-shelf parts and features supporting documentation in the form of a "*how-to*" guide which details the centrifuge design, engineering drawings and the manufacture and installation process for technology transfer.

Keywords: experiential learning, geotechnical design, civil engineering, activity-led learning

Background

Figure 1. 18m diameter centrifuge at the University of California, Davis (image courtesy of Dan Wilson)

Laboratory-based demonstrations are a valuable learning tool within the engineering curriculum as they provide an opportunity to challenge and reinforce theoretical content taught in lectures. Typically, these demonstrations are limited to element tests used to assess soil behaviour, such as compressibility and strength. While beneficial, these tests fail to provide observations of how actual geotechnical structures perform in practice in routine stability problems such as slopes, retaining structures and foundations. These real life design problems are taught via analytical design calculation methods for a given set of input soil parameters. Although this delivery style may be sufficient as a diagnostic assessment to check that students have basic comprehension of the key design principles, it fails to provide a holistic learning experience. Kolb (1984) described a learning cycle often referred to as the *theory of experiential learning*, which emphasises the important roles of "observation and reflection" and "active experimentation". This complements Bloom's *taxonomy of learning* (Bloom et al., 1956) which evaluates the student's level of understanding in the learning process, starting with the lowest level (knowledge) and building to the highest (evaluation). For this purpose, physical models are widely adopted in engineering research, practice and education; however, in geotechnical engineering it is exceedingly difficult to demonstrate designs for real world applications (e.g. slope stability) as the full-scale stresses of self-weight cannot be reproduced in small bench-scale models. The key limitation is that the stress-dependent behaviour of soil is not properly accounted for in a 1g environment, thereby making it difficult for quantitative interpretations of the experimental data to be made (Dewoolkar et al., 2003). While reduced-scale physical models at 1g can provide a basic overview of these problems, models tested at elevated accelerations can demonstrate the subtleties of soil behaviour, produce realistic failure mechanisms and provide simple data for post test analysis (Newson et al., 2002).

Realistic self-weight-induced stresses in a small-scale model can be achieved in the high gravitational acceleration field produced by a centrifuge and thus the stress and strain distributions in the model will be similar to that of a field situation. The geotechnical engineering centrifuge has become an important tool in research activities in many universities and has led to significant breakthroughs in geotechnical engineering understanding in pile foundation, tunnelling and offshore foundation engineering. Whilst most researchers and educators are aware of the teaching potential of centrifuge technology for demonstrating geotechnical design problems within the undergraduate curriculum, the cost of servicing this teaching tends to be prohibitive, as many research centrifuge platforms are large in diameter (Figure 1).

Craig (1989) was one of the first to formally discuss physical modelling for geotechnical engineering education. He described a modelling initiative that began in the mid-1970s at the University of Manchester where experiments were performed using an inexpensive “teaching centrifuge”. Mitchell (1994, 1998), Collins et al. (1997), Newson et al. (2002) and Dewoolar et al. (2003) also demonstrated the applicability of centrifuge modelling for instructional purposes to illustrate concepts of slope stability, retaining walls, foundations, tunnel stability and lateral earth pressure theory (Wartman, 2006). Many of these small-scale centrifuge developments have been undertaken in isolation and established in-house, with no unified approach within the geotechnical community for developing the required technology for teaching purposes (Figure 2).

Figure 2. 0.6m diameter teaching centrifuge at Dundee University (Newson et al., 2002)

The University of Sheffield has recently purchased a large 4m diameter centrifuge to establish a leading centrifuge research centre, thus providing an opportunity to embed this technology at the heart of the undergraduate curriculum. It was therefore necessary to develop a complementary cost-effective small-scale instructional centrifuge for teaching geotechnical design and centrifuge principles to undergraduate students.

The centrifuge has been developed specifically to support a new level 7 MEng module *Advanced* Geotechnics: CIV4501, for which Dr Black is the module leader (due to commence in September 2012). This module seeks to enhance students’ understanding of geotechnical design through enquiry and problem-based learning to promote critical/lateral thinking and reflective practice. This will be achieved through the integration of advanced geotechnical theory relating to constitutive models to describe soil behaviour, small-scale physical model centrifuge tests, self-learning laboratories and complementary analytical and numerical analysis methods.

Rationale

The overarching aim of this project was to facilitate greater understanding of the applications of geotechnical design. Specific objectives to address the project aim were:

1. development of a small-scale, cost-effective geotechnical centrifuge for the purpose of providing advanced under/postgraduate understanding of key geotechnical theory and design

2. development of supporting instructional material for routine experimental testing procedures and practical design examples to promote problem-based learning, reflective practices and learner autonomy.

An additional core objective was to promote wider use within other higher education institutions (HEIs). This has been achieved by ensuring that the centrifuge is highly cost-effective, built from standard off-the-shelf parts and features supporting documentation in the form of a "*how-to*" guide detailing the centrifuge design, engineering drawings and the manufacture and installation processes for technology transfer.

The approach

The work presented in this report has been undertaken in the context of the above aims/objectives with a view to establishing a small-scale geotechnical teaching centrifuge to enhance the student learning experience. The project was delivered in the Department of Civil and Structural Engineering at the University of Sheffield. A small-scale state-of-the-art beam centrifuge 1.1m in diameter has been developed which is capable of rotating a payload up to 20kg at 100 gravities (100g), referred to as UOS C2GT/1.1 (Figure 3). The maximum sample size that can be tested is 160mm (L) x 100mm (H) x 80mm (W), which relates to full-scale or "prototype" dimensions of 16m x 10m x 8m at 100g. This is sufficient to test a diverse range of reduced-scale engineering structures (such as failure mechanisms in slopes, retaining walls and foundations), while providing stress conditions that realistically duplicate prototype behaviour. The centrifuge is equipped with four 240V 10A power slip rings, dual port 10bar hydraulic rotating fluid union (enabling the delivery of air and water in-flight), digital image capture, load/displacement measurement, signal acquisition, an on-board PC and real-time wireless data communication/transfer. Images are captured through the viewing window in the payload which enables observations of displacement and failure mechanisms.

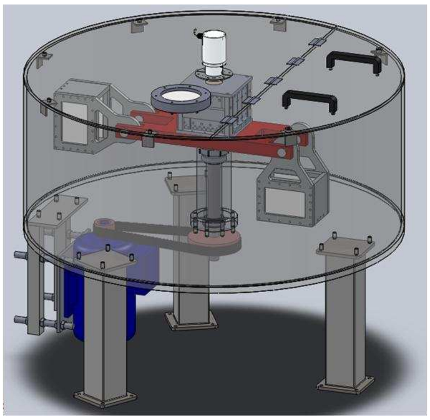


Figure 3. UOS C2GT/1.1 teaching centrifuge

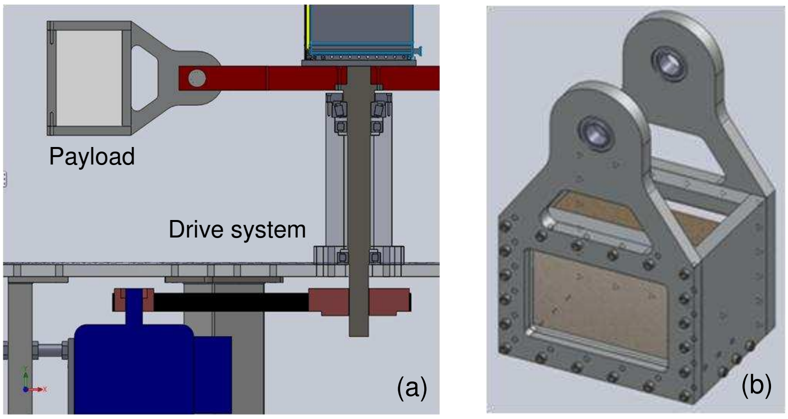
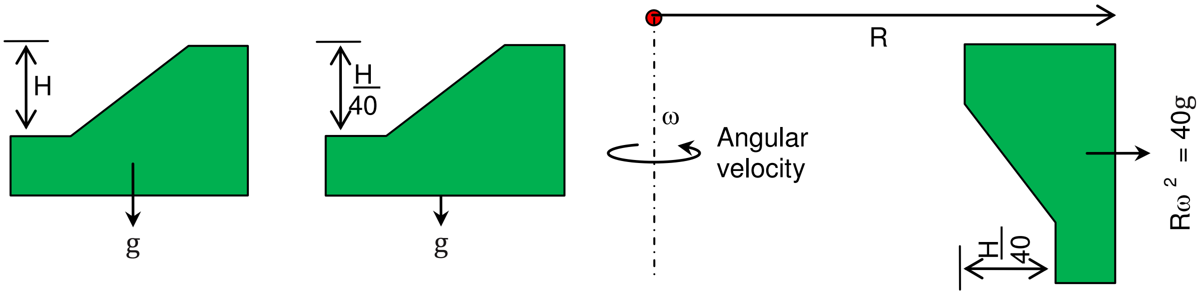


Figure 4. (a) Centrifuge detail and (b) sample payload with soil

The delivery plan for the *Advanced Geotechnics* module will incorporate the relevant underlying theory of soil mechanics and design elements. Physical laboratory experiments will be undertaken to evaluate soil properties (such as strength) which will be used to generate predictions of expected design behaviour. Centrifuge model tests on slope stability and shallow foundation problems will consider a range of design geometries (for example, slope angle or foundation width respectively). This will enable comparative analysis between laboratory predictions and real tests and will also generate a suitable database for complementary analytical and numerical validation. To demonstrate the delivery of the module, an example of the student learning cycle in relation to a slope stability problem is documented below.

Slope stability design: theory and principal of centrifuge modelling

Consider the case of a saturated clay slope of height H having a slope angle α as shown in Figure 5a. The stability of the slope is dependent on the un-drained shear strength of the soil, c_u, the slope height, H, and the unit weight $\gamma = \rho g$ and can be related to a dimensionless group referred to as the stability coefficient N_s (after Taylor, 1937). At failure, where the factor of safety is 1, the stability number N_s is given by Equation 1. Reduced-scale physical models for laboratory testing relate to prototype conditions by a linear scale factor, n. If the slope were at a scale n = 40 and tested at 1g (Figure 5b), it would be necessary to produce a model material having $c_u / \gamma = 1/40$. This is virtually impossible to achieve; however, similitude can be provided by testing the model slope in a centrifuge at n times the earth's gravitational field (Figure 5c), such that the slope stability number can be written as Equation 2. Equations 1 and 2 produce the same stability number; hence it is evident that the model slope in a centrifuge will behave similarly to that in the field.



(a) (b) (c)

Figure 5. (a) Prototype clay slope, (b) model clay slope and (c) model slope in the centrifuge.

$$N_s = \frac{c_u}{\rho H} = \frac{c_u}{\gamma g H} \quad [1]$$

$$N_s = \frac{c_u}{\rho(40g)\frac{H}{40}} \quad [2]$$

Slope stability design: experimental methods

The slope stability experiment is probably the most appealing among all centrifuge experiments because students can visually confirm the development of a failure surface. Students will prepare samples for testing by consolidating kaolin slurry, prepared at 1.5 times the liquid limit, to a known vertical effective stress to produce samples of uniform soil strength. A prefabricated former will be used to cut the consolidated block sample of clay to the desired slope geometry. Students will work in groups to conduct a series of tests considering various soil strengths and slope angles to provide multiple data sets for follow-up analysis. The payload bucket containing the model slope will be placed into the centrifuge, ensuring that all required safety protocol is strictly adhered to prior to starting the system. Full details of the centrifuge operational safety features are described in the accompanying "*how-to*" guide. The speed of centrifuge rotation is slowly ramped up to provide increasing gravitational acceleration until failure occurs. A miniature camera fixed to the payload swing bucket is used to capture images of the progressive slope movement and failure mechanism where a distinctive slip plane is formed (Figure 6.). The recorded images will be used to assess the slope displacement and failure characteristics using image-tracking methods developed for geotechnical applications, GeoPIV (White et al., 2002). As part of the experimental activities, students will also be required to conduct complementary self-directed laboratories to evaluate the sample soil properties such as un-drained shear strength, unit weight and moisture content, etc. This data will provide design input parameters for analytical and numerical studies.

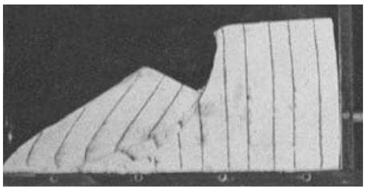


Figure 6. Model slope failure (Dewoolkar et al., 2003)

Slope stability design: analytical and numerical modelling

The results of soil strength determined by unconfined compressive strength tests in the self-directed laboratory and by *in-situ* vane shear tests will be used in conjunction with relevant theory of stability numbers (Taylor, 1943). In the slope stability laboratory, students will be required to predict the failure *g*-level for the slope and estimate the un-drained strength of the clay (using inverse relationships of Equations 1 and 2). These performance predictions will be compared with the actual test observations for the range of parameters investigated and collated data sets will be compared against routinely adopted slope stability design charts. Students will be required to interrogate the data set and justify their observations and any discrepancies that exist.

The image data collected is highly valuable as it enables students to visualise and confirm the slope displacement behaviour and failure plane that develops. Numerical modelling will be undertaken to predict the location of the failure surface, centre of rotation and slope factor of safety. The images will be processed using GeoPIV to enable detailed analysis of the slope movement and failure plane. The geometry of the cross-sectional area contained by the failure surface will be compared to numerical and analytical solutions for the slope collapse. Students will be required to assess the "fit" between the predicted and actual results, exploring aspects such as error assessment, sensitivity analysis and statistical methods. The numerical simulations will also extend to a full parametric design evaluation of wider aspects affecting slope behaviour and methods of enhancing slope resistance against collapse.

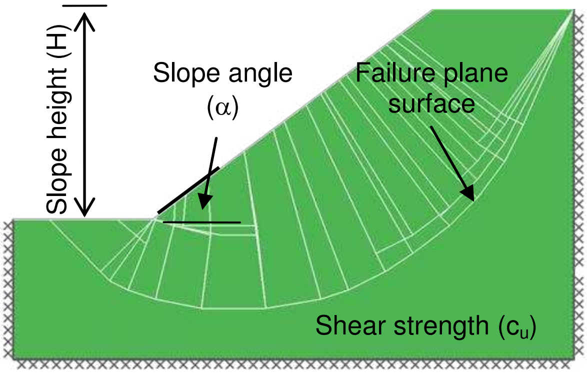


Figure 7. Numerical model of slope failure plane

Impact on student learning experience

The centrifuge will have a significant impact on the student learning cycle by providing a deeper understanding and appreciation of routine geotechnical design problems. Furthermore, it will pose challenges and make a positive contribution in terms of developing learning autonomy, critical thinking and reflective practice. Educational pedagogy is embedded at the heart of the module learning practice and it embraces theory such as Kolb's learning cycle and Bloom's taxonomy of learning. Due to the higher level of aptitude expected from final year MEng students, the latter is considered a valid benchmark and educational framework for assessment of this module. Table 1 briefly summarises the taxonomy and its six levels and how these are achieved within the module content.

Table 1. Bloom's *taxonomy of learning* and its relationship to module content

Level	Tasks addressing different levels of cognitive learning of Bloom's taxonomy
Knowledge	1. Recall analytical methods/theory to analyse stability problems 2. Recall soil properties needed to inform development of self-directed laboratory
Comprehension	3. Predict centrifuge model performance using relevant theory 4. Describe centrifuge modelling principles in a technical paper 5. Engage and discuss original literature (journal papers) via seminar sessions
Application	6. Conduct sample preparation, test set-up and complete centrifuge tests 7. Grasp the concept of increased g-level; predict g-level at failure for slope
Analysis	8. Correlate experimental observations to validate analysis/numerical methods 9. Analyse the performance of the problem against design methods 10. Eliminate erroneous data from data sets; carryout statistical analysis and compare data
Synthesis	11. Compare/contrast expected and actual results and synthesise findings 12. Evaluate the hypothesis and discuss the outcomes of lab tests
Evaluation	13. Centrifuge data interpretation and reflection 14. Parametric considerations and recommendations on design theory 15. Evaluate the success of the research project as a reflection exercise 16. Peer and self-assessment of performance

Assessment

On completion of the module, it is anticipated that students will demonstrate greater awareness and appreciation of geotechnical design and demonstrate the ability to:

1. Describe the constitutive behaviour of soil and implement appropriate soil models in routine design analysis
2. Develop suitable methodologies to evaluate design parameters through self-developed element test laboratories and *in-situ* sample investigation
3. Develop an appreciation of broader aspects associated with advanced laboratory testing and physical modelling principles such as (i) scaling laws, (ii) dimensionless analysis, (iii) soil model preparation and (iv) instrumentation/electronics
4. Develop suitable experimental methodologies for physical modelling of routine geotechnical problems (slope, retaining wall, foundation) and undertake data measurement/collection
5. Deploy appropriate research methods for analysing data sets, including particle image velocimetry (PIV) for soil displacement analysis
6. Undertake analytical predictions and conduct finite element analysis to calibrate/validate physical model test observations
7. Review and evaluate physical model behaviour with analytical, numerical and classical plasticity methods and discuss the implications for design
8. Develop and deploy scientific research methodologies.

The above expected learning outcomes will be appraised using a variety of assessment methods. The main output will be in the form of an individual scientific technical paper that will present details of the laboratory investigations and results obtained. It should also describe the analytical and numerical evaluation methods employed and discuss/review the correlation of the physical model tests with design theory. The use of a scientific paper is twofold: (i) to instil research methodology within the undergraduate taught programme and (ii) to develop technical writing ability by presenting content in a concise and focused report. Successful completion of this piece of work, which integrates much of the lecture content and practical classes, will require students not only to engage with the directed content, but also to undertake their own background literature review so that they can contextualise the work they have undertaken in the laboratory. They will need to be able to demonstrate technical competence as well as critical and evaluative skills.

Assessment by examination will also be utilised. This will be a blend of discursive and numerical questions to enable students to exhibit their comprehension of design aspects. Successful completion will require students to write lucid prose and demonstrate their understanding of the relevant concepts/equations and ability to critique and evaluate design solutions.

Credit in the module will also be awarded for active contribution and discussion in the reading seminars. Students will also be required to develop an instructional laboratory video on centrifuge testing that will be used as a peer-to-peer learning resource by new students undertaking the module in subsequent years. The physical modelling centrifuge tests, self-directed element test laboratories and learning video will be undertaken in small groups, thus peer and self-review will also form part of these assessments. All other assessments (technical paper, seminar and exam) are individual.

Evaluation

The centrifuge and learning material developed are to be implemented during the 2012/13 academic year; thus at the time of writing formal assessment of student learning has not been evaluated. Nevertheless, the centrifuge development will play a pivotal role in the new module and will provide a platform for linking geotechnical theory and design for many years. During the first year of use the project impact will be assessed through student focus groups, questionnaires and general qualitative assessment of student comprehension by the module leader.

The direct impact of the new pedagogy will be determined by comparing historical student feedback regarding their experiences and overall satisfaction in similar design-based modules. While not a measure of student learning, student satisfaction plays a significant role in the level to which they engage with the subject matter; hence this criteria will serve as an indication of the positive contribution of the new centrifuge activities to their learning experience.

The results of the module evaluation will be published on the project website which has been set up to support the dissemination and sustainability of the project and facilitate exchange of learning resources between participating HEIs (http://www.geotech.group.shef.ac.uk/teaching/centrifuge).

Discussion and summary

The project thus far has been heavily involved with the sustainable development of the "*how-to*" guide for a small-scale teaching centrifuge. One of the major difficulties encountered was in sourcing off-the-shelf components which were compatible with one another and could be seamlessly integrated into the design of the centrifuge platform. Furthermore, safety was a major concern and thus considerable effort was expended in conducting rigorous structural integrity calculations and checks on all components operating in the high gravity environment.

Further development

The project materials, "*how-to*" guide and evaluation data are available via the University of Sheffield Geotechnical Engineering Group website (see above). The project team will actively encourage other HEIs to develop this system, thus developing a support network for the exchange of learning resources and knowledge.

References

Bloom, B. S., Englehart, M. D., Furst, E. J., Hill, W. H. and Krathwohl, D. (1956) *Taxonomy of educational objectives: the classification of educational goals. Handbook I: cognitive domain*, David McKay, New York.

Collins, B., Znidarcic, D. and Goddery, T. (1997) 'A new instructional geotechnical centrifuge', *Geotechnical News*, vol. 15, no. 3, pp. 10–12.

Craig, W. H. (1989) 'The use of a centrifuge in geotechnical engineering education', *Geotechnical Testing Journal*, vol. 12, no. 4, pp. 288–291.

Dewoolkar, M. M, Goddery, T. and Znidarcic, D. (2003) 'Centrifuge modeling for undergraduate geotechnical engineering instruction', *Geotechnical Testing Journal*, vol. 26, no. 2, pp. 201–209.

Kolb, D. A. (1984) *Experiential learning: experience as the source of learning and development*, Englewood Cliffs, N.J., Prentice-Hall.

Mitchell, R. J. (1994) 'Centrifuge modeling as a teaching tool', *Geotechnical News*, vol. 12, no. 3, pp. 30–31.

Mitchell, R. J. (1998) 'The Eleventh Annual R. M. Hardy Keynote Address, 1997: centrifugation in geoenvironmental practice and education', *Canadian Geotechnical Journal*, vol. 35, no. 4, pp. 630–640.

Newson, T. A., Bransby, M. F. and Kainourgiaki, G. (2002) 'The use of small centrifuges for geotechnical education', *Proceedings of Physical Modelling in Geotechnics: ICPMG '02*, 10-12 July 2002, St. Johns, Newfoundland, Balkema, Rotterdam, pp. 215–220.

Taylor, D. W. (1937) 'Stability of earth slopes', *Journal of the Boston Society of Civil Engineers*, vol. 24, no. 3, pp. 337–386.

Wartman, J. (2006) 'Geotechnical physical modelling for education: learning theory approach', *Journal of Professional Issues in Engineering Education and Practice*, vol. 132, no. 4, pp. 288-296.

White, D. J., Take, W. A. and Bolton, M. D (2003) 'Soil deformation measurement using particle image velocimetry (PIV) and photogrammetry', *Géotechnique*, vol. 53, no. 7, pp. 619-632.

Further reading/bibliography

Further information and relevant documents are available for download and are provided on the dedicated project webpage accessed at http://www.geotech.group.shef.ac.uk/teaching/centrifuge or by contacting the project leader, Dr Jonathan A. Black j.a.black@sheffield.ac.uk.

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