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Holistic analysis methods used to support education in geotechnical engineering: tunnel stability

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ABSTRACT: An educational framework for understanding tunnel stability through physical modelling, numerical analysis and plasticity solutions is presented along with the planning, preparation and assessment of a module where students investigate the stability of a tunnel via these three important methodologies. The physical modelling is conducted using the centrifuge at City St George's, University of London. Students are tasked with examining the critical support pressure required to prevent tunnel collapse in over-consolidated clay. The experimental setup, designed to be reproducible in teaching laboratories, demonstrates the construction process through gradual reduction of air pressure support. Comprehensive measurements of ground surface and subsurface movements provide students with rich datasets for understanding soil-structure interaction. The experimental results are complemented by plasticity solutions and finite element analyses using Abaqus, offering students exposure to physical, analytical and numerical modelling techniques. The comparison between these methods emphasises the value of using holistic approaches in geotechnical engineering. This case study serves as a valuable teaching resource for undergraduate and postgraduate courses in geotechnical engineering and soil mechanics. Observations on module delivery and student performance highlight the importance of authentic assessment in the AI age.

KEYWORDS: centrifuge modelling, plasticity solution, finite element method, AI, authentic assessment.

1 INTRODUCTION

Holistic methods are employed in the module "Analysis of Geotechnical Infrastructure" within the MEng Civil Engineering and Infrastructure programme at City St George's, University of London. The module is designed to provide students with a comprehensive understanding of tunnel stability through the integration of three core methodologies: physical modelling using centrifuge tests, numerical analysis via Finite Element Analysis (FEA), and theoretical approaches using plasticity solutions. Furthermore, the paper reflects on the implications of Artificial Intelligence (AI) in engineering education, particularly in the context of authentic assessment, and discusses how the module design ensures academic integrity in the AI age.

1.1 *The Learning Outcomes*

The module is designed to support the students in achieving four Learning Outcomes (LO) namely M1, M2, M3 and M12 in the Accreditation of Higher Education Programmes 4 (AHEP4). These AHEP4's LOs are embedded in nine LOs of the modules described below.

1.1.1 *Knowledge and understanding:*

- Formulate the behaviour of soil within the framework of the theory of plasticity (LO1);
- Design soil structures using both upper and lower bound theories (LO2).
- Create an application of numerical analysis and centrifuge testing techniques to geotechnical design (LO3).

1.1.2 *Skills:*

- Create a finite element analysis using an industry standard geotechnical program (LO4);
- Formulate plasticity theorems to understand the stability of a novel geotechnical structure (LO5);
- Create a centrifuge model test to investigate a novel geotechnical structure (LO6);
- Propose methods of assessing design methodologies for geotechnical infrastructure (LO7);
- Recognise and evaluate the limitations of different methods for analysing geotechnical problems (LO8).

1.1.3 *Values and Attitudes:*

- Formulate a view of the process of analysing soil structures that acknowledges the limitations of different approaches and the need to assess the significance of any approximations required (LO9).

1.2 *The assessments*

The module includes Coursework components, which assess LO3, LO4, LO5, LO6, LO8, and LO9. To achieve the LOs, the students are tasked to assess the stability of a tunnel in over-consolidated clay in one of the three different scenarios as shown in Figure 1 (Divall et al., 2018). The variables in the three scenarios are the structure next to the tunnel, including either a shallow foundation (Scenario 1), an L-shape retaining wall (Scenario 2), a cantilever vertical retaining wall (Scenario 3). These scenarios are chosen due to their complexities, as often encountered in practice, which are not readily solvable only by using standard formulations. Instead, to achieve a substantiated solution for such problems, a set knowledge and skills are needed, which are expected for a Level 7 module.

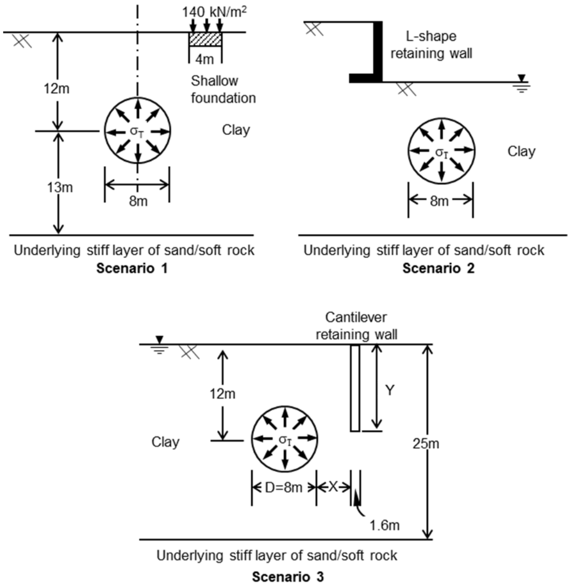


Figure 1. Typical prototype model geometries (Divall et al., 2018).

The students need to conduct a successful centrifuge test (groupwork), develop a plausible Finite Element Analysis (FEA) (individual work), and produce plasticity solutions (individual work). Results for Scenario 3 are presented which is a plane strain situation consisting of a tunnel and a cantilever retaining wall. The tunnel has a diameter $D = 8$m and axis level 12m below the ground surface. The cantilever retaining wall has a thickness of 1.6m, height of Y, and is of a distance X from the tunnel (Figure 1).

For the centrifuge test, the model geometries X, distance between the wall and the tunnel, and Y, the wall's height (Figure 1) are the same for all students. For FEA and upper bound solutions, each student is assigned with a unique set of X and Y which are slightly different to those from the centrifuge test. This variation helps ensure academic integrity and encourages independent problem-solving, while still allowing students to draw on shared experimental data.

As a means of assessment for learning, the marking criteria signposts the students to design centrifuge and FEA models for tunnel stability assessment, develop the collapse mechanism using upper bound solutions, prove that their analyses have produced believable results by comparing the results from three different methods. Ultimately, the students are required to discuss the assumptions made in each method and comment on how they would affect the results.

The following sections describe the methods used, the students' achievements, and some observations on the use of Artificial Intelligence (AI) from the students in addressing this coursework.

2 CENTRIFUGE TEST

The centrifuge test has advantageous capabilities in reproducing realistic soil behaviour and serves as a case study and benchmark for the other two methods in assessing tunnel stability. The students' engagement in the centrifuge test and their achievements for LO3 and LO6 are described. Further details on the centrifuge test can be found in Divall et al. (2018).

2.1 *Determination of the model dimensions*

To simulate Scenario 3 (see above), the students first need to suggest and justify the key dimensions of the model for a feasible and reliable centrifuge test. By doing this exercise, the students can practice designing an experiment scheme which requires critical considerations including i) boundary conditions, ii) capabilities of the centrifuge, and iii) the availability of the model making tools, such as the strong-box (the model container), and the model tunnel.

For boundary effects, key references such as Kimura & Mair (1981) and Taylor (1995) were suggested to the students so that they can determine the distance from the model tunnel and wall to the boundary of the model container to minimise any potential boundary effects. At City St George's, University of London, the Acutronic 661 beam centrifuge is a $40g$-tonne machine which can accommodate a model with weight of 200kg at up to $200g$. The internal dimensions of the strong-box are 550mm$(L) \times 200$mm$(W) \times 375$mm(H). These dimensions put another constraint on the dimensions of the model tunnel and wall. Once the students have designed a satisfactory centrifuge model, they proceed to prepare the model for testing.

2.2 *Preparation of centrifuge model*

The clay sample is created using Speswhite kaolin clay powder and distilled water to form a slurry with a water content of 120%. The students are tasked to calculate the required volume of the slurry so that after consolidation, the height of the clay sample is at least $150mm$.

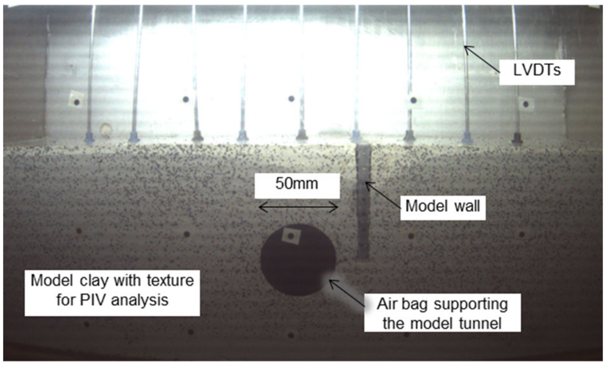


Figure 2. The complete model with instrumentations.

Once the required volume of slurry is determined, the slurry is poured into a strong-box, previously greased, for one-dimensional consolidation in a hydraulic press. The stress path is to increase the maximum consolidation pressure to 350kPa followed by swelling to 250kPa. That provides an over-consolidated clay sample in the strong-box.

On the test day, the students take the strong-box out of the hydraulic press and move it to a model preparation area. They then remove front side of the strong-box to gain access to the clay sample for model making. The students are instructed to use necessary tools to create the model tunnel and cantilever wall (Divall et al., 2018). The process involves trimming the clay model to the correct height, creating a cavity for the model tunnel and inserting the wall into the clay model. The cantilever wall is modelled by an aluminium plate with ridges machined in the vertical faces to provide roughness. The tunnel cavity is fitted with a rubber bag which will be pressurised to provide support to the surrounding soil as the centrifuge acceleration is increased during the test.

2.3 *Calibrations and installation of instrumentations*

The model is instrumented with a pressure transducer to measure the support pressure inside the tunnel, 9 Linear Variable Differential Transformers (LVDTs) to measure the ground surface settlement. In addition, the front of the sample was sprayed with dyed fine sand to create texture for Particulate Image Velocimetry (PIV) analysis for subsurface ground displacement measurements (Stanier et al., 2016). The photo of the complete model before the test is presented in Figure 2.

The students were in charge of the calibration for the pressure transducer and LVDTs. Therefore, they appreciate the precision of the measurements which are important to the later analyses.

2.4 *The students' engagement in the centrifuge test*

To prepare for spinning up of the model to the acceleration of $160g$ and to achieve correct stress level in the model, the students determine the effective radius R_e and the rotational speed, w, of the centrifuge by using the following equations.

$$R_e = R_t + \frac{H_m}{3} \quad (1)$$

$$\omega = \sqrt{ng/R_e} \quad (2)$$

where R_t is the radius from the centroid of rotation to the top of the model; H_m is the height of the model; g is Earth's gravity; and n is the acceleration factor, in this case $n = 160$.

Through these calculations, the students gain a better understanding on the variation of acceleration within the model depth, and potential errors, though insignificant, in a centrifuge test.

As the centrifuge acceleration is increased, the air bag is pressurised to support the tunnel cavity to balance the self-weight of the soil. The students were asked to calculate the support pressure required to match with the g level. When the model is at $160g$, the tunnel pressure is gradually reduced to simulate the tunnelling process which in turn induces ground displacements.

Readings from the LVDTs, pressure transducer, and images of the subsurface of the soil model were recorded at one second intervals for further analysis on tunnel stability by examining the relationship between the tunnel support pressure with ground displacements.

Once the tunnel has collapsed, the centrifuge is stopped and the students use a hand shear vane to measure the undrained shear strength, S_u, of the clay model. The undrained shear strength normally ranges from $41kPa$ to $49kPa$, from the top to the bottom of the model. The undrained shear strength is used in the subsequent FEA and upper bound solutions.

2.5 *Centrifuge test results*

Regarding ground displacements, it was interesting to note that, before the centrifuge test, some students expected less displacements on the side with the retaining wall. They thought any retaining wall would reduce the soil displacements while ignoring the importance of the wall dimensions and position in relation to the tunnel. In addition, in this case, the self-weight of the model wall, made of aluminium which is ≈ 1.5 times heavier than the clay. The results from the centrifuge test show larger displacements in the area with the retaining wall (Figure 3). From this marked difference, the students gain a better understanding on the tunnelling induced ground displacements in greenfield area and area with structures, such as the wall, and their effects.

The students process the data from the LVDTs to plot the ground surface settlement with the tunnel support pressure to determine the tunnel support pressure at collapse. A typical relationship between ground surface settlement above the tunnel centreline and tunnel support pressure is presented in Figure 4.

The students need to estimate the collapse pressure by either draw lines which are asymptotic to the two gradients of the curve settlement, or specify a magnitude of settlement that they consider the tunnel has collapsed (Divall et al., 2018). The tunnel support pressure at collapse from the centrifuge test will be compared with that determined from the upper bound solutions and FEA.

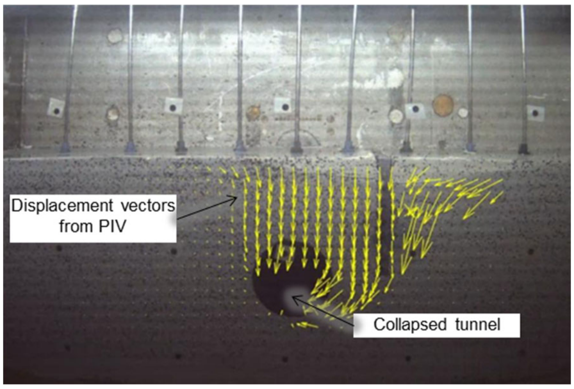


Figure 3. Soil displacements mechanism observed in the centrifuge test from PIV analysis.

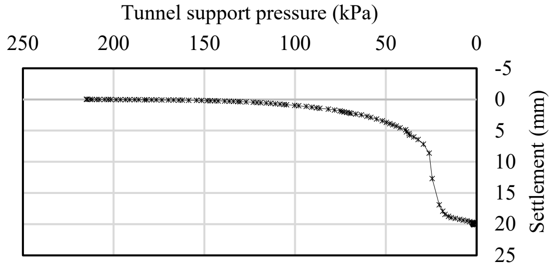


Figure 4. Tunnel support pressure vs ground surface settlement above the tunnel centreline.

3 UPPER BOUND SOLUTIONS

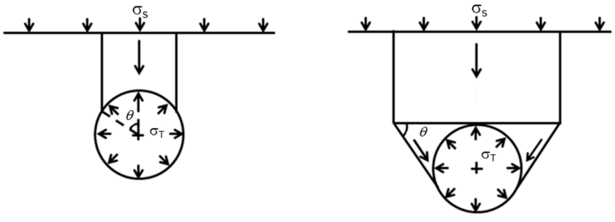
The inclusion of upper bound solution is to help the students achieve LO1, LO5, and LO9. Despite the availability of advanced numerical tools, upper bound solutions remain valuable for providing quick, conservative estimates and for validating more complex analyses. The students are taught the fundamentals of upper bound solutions of plasticity theorems. The lecturers also provide relevant examples such as four standard upper bound mechanisms (Figure 5) describing the collapse around a plane strain tunnel (Davis et al., 1980).

It is encouraging for the students to see the similarity between the collapse mechanisms A/B with that in the greenfield area in the centrifuge test shown in Figure 3. This confirms the repeatability and reliability of the centrifuge test when compared with the established upper bound mechanisms. However, these standard mechanisms do not consider the retaining wall which requires the students to come up with a specific upper bound mechanism for the centrifuge test.

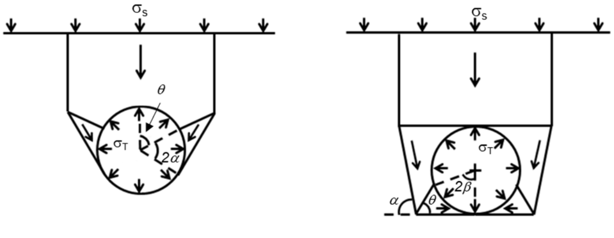
For the relationship between tunnel stability and tunnel support pressure, the students can refer to equation (3) (Davis et al., 1980).

$$N = \frac{\sigma_s - \sigma_T}{S_u} + \frac{\gamma D\left(\frac{C}{D} + \frac{1}{2}\right)}{S_u} \qquad (3)$$

where N is the stability ratio; σ_s is surcharge at the ground surface; σ_T is the tunnel support pressure; γ is the unit weight of the soil; C is the cover depth from the ground surface to the tunnel crown.



a) Upper bound mechanism A
b) Upper bound mechanism B



c) Upper bound mechanism C
d) Upper bound mechanism D

Figure 5. Upper bound mechanisms for plane strain tunnel (after Davis et al., 1980).

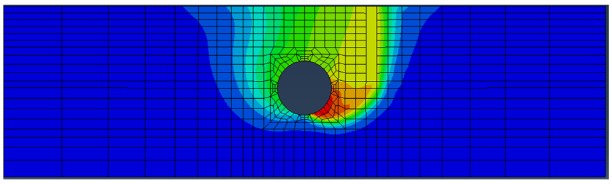


Figure 6. Ground displacement contour from FEA.

To estimate the tunnel support pressure at collapse, σ_{TC}, Equation (3) requires stability ratio at collapse N_C . This can be obtained from relevant research such as Davis et al. (1980) and Kimura & Mair (1981). It is expected this value of σ_{TC} will be different with that from the centrifuge test. The students are asked to explain not only why σ_{TC} are different from the two methods but also why σ_{TC} from one method is higher than the other.

4 FINITE ELEMENT ANALYSIS

The inclusion of FEA is to help the students achieve LO3, LO4, and LO9. The students use ABAQUS finite element programme to conduct the FEA. As the analysis concerns the stability of the tunnel, the soil is modelled as elastic perfectly plastic with a Tresca failure criterion to be consistent with the Upper Bound solution.

The soil is Speswhite Kaolin with a bulk unit weight $\gamma = 17.5\text{kN/m}^3$. The properties of the soil are "Cohesion" $= S_u = 40kPa$ and "Friction angle" $= 0°$. The undrained Young's modulus $E_u = 180 \times 100\text{kN/m}^2$, Poisson's ratio $\mu = 0.485$ (no volume change when elastic). The strength of the soil is assumed to be constant with depth. The initial lateral earth pressure coefficient at rest $K_0 = 1$. The wall has properties that link to the centrifuge test where it is modelled using aluminium with the properties $E = 70 \times 100\text{kN/m}^2$, $\mu = 0.33$, $\gamma = 28\text{kN/m}^3$.

Figure 6 presents ground displacement contour from a typical student's FEA. Most students are able to create a successful FEA that produces deformation mechanisms comparable with that in the centrifuge test (Figure 3). The students find these similarities encouraging that help them have more confidence in their simulation and calculations. The students are asked to explain the observed differences by considering the effect of any assumptions, such as soil-structure interfaces, undrained shear strength profile, K_0.

5 THE IMPORTANCE OF AUTHENTIC ASSESSMENT IN THE AI AGE

Since the 2024–2025 academic year, the use of AI in student coursework has become increasingly apparent. While AI can support learning, its uncritical use has raised concerns about whether students genuinely achieve the intended learning outcomes. This is particularly relevant in modules like "Analysis of Geotechnical Infrastructure," where understanding is demonstrated through the application of theory to complex, real-world problems.

Authentic assessments, which mirror professional practice and require the application of knowledge in context, have proven essential in maintaining academic standards (Race, 2019). In this module, students must engage with physical experiments, interpret real data, and apply engineering judgment, all of which are difficult to replicate using AI alone. From trial use of several AI agents (such as ChatGPT, Claude), as a quality control measure, conducted by the author and some students' output, several limitations of AI-generated work were observed below:

- AI tools often produced upper bound mechanisms that were physically incompatible with the problem.
- Even with decent prompts containing insightful information, AI tools could not comprehend the nature of centrifuge tests and the implications of the results. Therefore, the failure mechanisms could not be adequately captured or interpreted by AI. These aspects are critical for informing subsequent analysis.
- Without access to backend finite element modelling software, AI could not conduct or validate numerical simulations.
- The coursework requires the students to integrate findings from literature review, physical, numerical, and theoretical methods. This involves data processing in different formats, graphical interpretations, and critical comparison. These tasks demand multiple manual data inputs and manipulations, human insight, and engineering reasoning which at the time of writing, AI was not yet sufficiently mature.

These observations reinforce the value of authentic assessment in the AI age. By designing tasks that combine hands-on experimentation, critical thinking, and synthesis of diverse data sources, educators can ensure that students develop the competencies expected of professional engineers. Moreover, such assessments promote deeper learning and discourage over-reliance on generative AI tools.

6 CONCLUSIONS

This paper has presented holistic methods for teaching a Level 7 Geotechnical Engineering module. By integrating physical modelling, plasticity theory, and FEA, students gain a comprehensive understanding and enhance their capabilities in using a combination of methods in solving complex, real-world like geotechnical problems.

The case study demonstrated how students engage with each method, develop critical engineering skills, and validate their findings through cross-method comparison. The module, aligned with AHEP4 LOs, ensures that students not only acquire technical knowledge but also develop the ability to evaluate and justify engineering decisions.

While AI can support learning, it cannot replace the experiential and analytical depth required in authentic assessments. The module's emphasis on physical testing, numerical modelling, and critical synthesis ensures that students achieve meaningful LOs.

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