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Activities to enhance students' understanding of pore water pressure, seepage and total head

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ABSTRACT: When students start an undergraduate engineering course, many have a limited comprehension of water pressure, and find that understanding first hydrostatics and later the concepts of total head and seepage is extremely challenging. Yet this topic is very important in engineering practice, and misconceptions about the water regime often contribute to major failures in excavations and tunnels. This paper describes attempts at the University of Bristol to develop undergraduate civil engineering students' understanding of pore water pressure through classroom exercises and in the laboratory. In class students are encouraged to explore problems of one-dimensional seepage. Later, working in small groups, students observe flow through a dam built from sand in a seepage tank and compare their empirical flow-net with predictions using a finite element seepage analysis run for them in the laboratory. They measure the permeability of the same sand using a permeameter, which also demonstrates the link between seepage and non-hydrostatic pressure. Using this permeability they compare the predicted and measured discharge from the dam, before they observe failure of the downstream slope of the dam induced when the exit from the underlying drainage blanket is blocked. These activities develop their understanding of pore water pressure, seepage and total head so that many have confidence in their ability to predict and interpret groundwater observations by the time they graduate.

1 INTRODUCTION

Pore water pressure is central to soil behaviour, and a good understanding of it is essential for geotechnical professionals. On starting a civil engineering course, many undergraduate students have a limited comprehension of water pressure, probably because it does not form a significant part of the school physics syllabus. Most students can state that water pressure at a depth z in a water tank is equal to $\rho_w gz$ but then find that understanding and applying the laws of hydrostatics in a geotechnical context is tricky. Despite studying Bernoulli's equation in hydraulics courses, it gradually becomes clear that the concepts of total head and seepage are extremely challenging. The late Professor Peter Wroth identified groundwater and pore pressure as key concepts in civil engineering education, but despite the best efforts of educators, many students still graduate with a poor understanding of water in the ground.

This topic is of course very important in engineering practice. Many geotechnical professionals are uncertain how to interpret readings from piezometers in non-hydrostatic conditions. This becomes very important when interpreting conditions in an unstable slope or comparing assumed or predicted conditions in finite element analyses (e.g. using Plaxis) with the field conditions they are supposed to represent. Misconceptions about the water regime often contribute to major failures in slopes, excavations and tunnels.

Students learn in a variety of ways and at Bristol we have attempted to stimulate their curiosity both in class and in the laboratory. This paper describes some activities we use to challenge first and second year undergraduate civil engineers in large cohorts.

2 CLASSROOM EXERCISES

Students can generally calculate the water pressure at the bottom of a bucket full of water but they may be uncertain whether this is altered by filling the bucket with coarse gravel thereby displacing some of the water. Most can envisage threading a small tube (a simple piezometer) through the pore space down to the base of the bucket, and can then understand that the water pressure at the base of the tube is unchanged by the presence of the gravel. Students initially say that water flows along a pipe in response to a pressure difference but know intuitively that it is total head rather than pressure that drives seepage. When asked which way the water will move through a tube connecting two tanks and containing soil as shown in Figure 1, they are clear that it will flow from right to left, despite the pressure being greater at the left end. Similarly, calculation of the instantaneous pressure just beneath a porous bung in a U-tube as shown in Figure 2 is often difficult at first sight. The key to improving student's understanding of total head appears to develop their

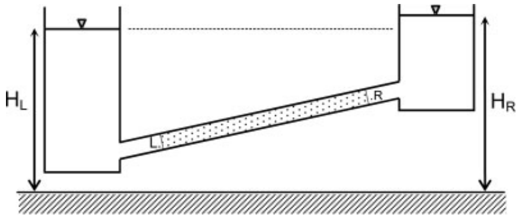


Figure 1. Simple demonstration of how it is total head rather than pressure that drives seepage through soils.

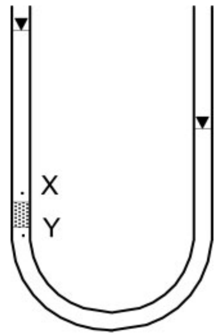


Figure 2. Problem to calculate the instantaneous pressures at points X and Y above and below a porous bung in a U-tube.

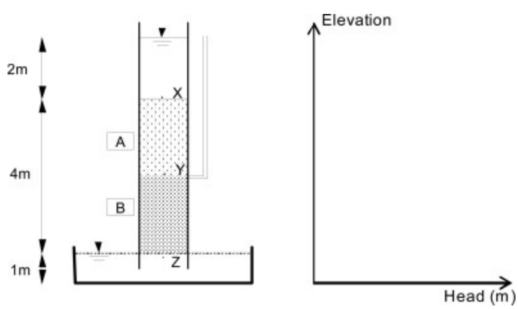
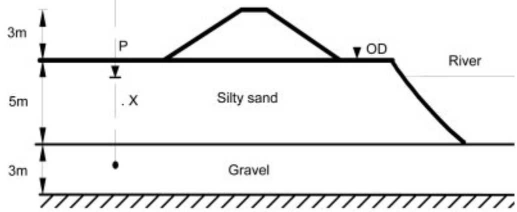


Figure 3. Problem to calculate and draw the variation of total head, pressure head and elevation head down the centre-line of a large tube containing two layers of sand A and B when i) $k_A = k_B$ and ii) $k_A = 2^*k_B$.

experience incrementally and to specifically challenge false preconceptions.

Many soil mechanics text books gloss over the conceptual difficulties of understanding total head, but the writer has found the chapter entitled *One-dimensional fluid flow* by Lambe and Whitman (1969) particularly helpful. A similar one-dimensional approach has been developed at Bristol and is described by Muir Wood (2009). Students may be encouraged to draw diagrams showing the variation of total head, pressure head and elevation head against elevation for problems such as that shown in Figure 3.

Students (and practising engineers) often have difficulty knowing how to start to analyse a full scale problem, and they need practice in recognising the parallels with simple conceptual models that they can



Note: Normal river level is 1 metre below ground level (i.e. at -1.0m OD) as shown. The gravel is hydraulically connected to the river so that the piezometer level at P always equals river level. Predict the conditions at point X when the river level is a) at -1m OD, b) at +0m OD, c) just below +3m OD, d) just above +3m OD and P is flooded to 3m depth, and e) when the river has dropped back to -1m OD leaving P still flooded.

Figure 4. Problem to predict the pore water pressure at point X halfway down the sand layer behind a flood embankment.

already analyse. A one-dimensional seepage problem that has proved useful in this respect is shown in Figure 4. Here the student is asked to predict the pore pressures in the ground behind the flood embankment as the river level fluctuates, before and after the ground is inundated by flooding. Recognising that this problem is analogous to those in Figures 2 and 3 is often the key to solving it.

3 LABORATORY EXERCISES

3.1 *Introduction*

Hands-on experiments in the laboratory are one of the best ways by which students may develop their understanding of total head. The writer has evolved a linked set of experiments that are carried out in a single three-hour laboratory class. Two groups of four or five second-year students undertake permeability measurement of a medium to coarse sand using a constant head permeameter, observe the seepage though a dam made from the same sand, compare the flow-net determined experimentally with that drawn with the aid of finite element software, and compare the observed seepage rate with that computed from the flow net. By the end of the class each group has undertaken similar tests and may then share the results.

3.2 *One-dimensional seepage*

Darcy's law may readily be demonstrated using a constant head permeameter (Figure 5). By arranging the apparatus so that seepage is upward, the transition to boiling may be observed and the hydraulic gradient at the onset of boiling determined. Knowing the dimensions of the sand column in the permeameter and its dry mass, the average void ratio may be found and the theoretical critical hydraulic gradient calculated. One student group measures the permeability of loose sand, the other of dense sand, so that the variation

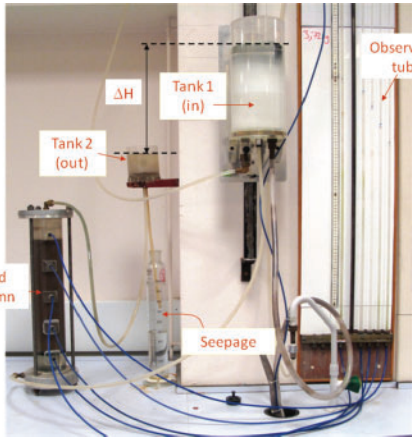


Figure 5. Constant head permeameter showing movable inlet and fixed outlet constant level tanks, and tapping points linked to observation tubes.

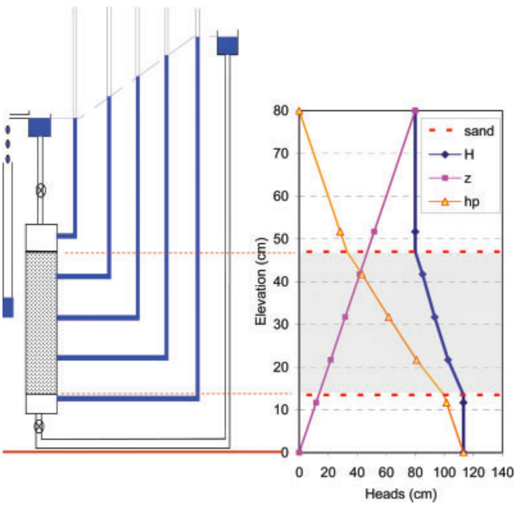


Figure 6. Diagram of permeameter showing the variation of total, pressure and elevation heads for one flow rate.

of coefficient of permeability with void ratio may be explored.

The permeameter is fitted with several tapping points which are used to observe the total head (or piezometric level). Students are asked to plot a graph showing the variation of total, pressure and elevation heads through the sand like that shown in Figure 6. For many students this is challenging and is a good opportunity to revisit the ideas developed in similar exercises undertaken in class (for example Figure 3).

When the sand has been boiled it is of course in a very loose state but it can be densified by vibration (using an electric engraving tool). Students are shown how even small vibrations result in the liquefaction of the sand as its surface settles and the sand densifies, and the parallels are drawn with liquefaction in earthquakes.

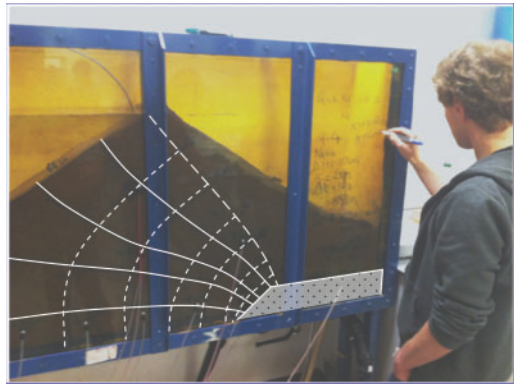


Figure 7. Flow through a model dam.

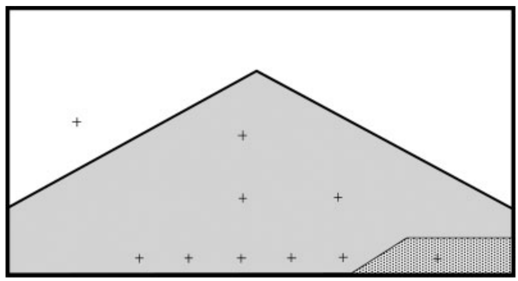


Figure 8. Scaled cross-section handout showing positions of tapping points.

3.3 *Two-dimensional seepage*

Most students are mystified when they have to sketch a flow net for the first time. The process appears to be completely subjective and the solution to be rather arbitrary. It does not help that the examples in many text books are poorly explained and frequently contain errors (as noted by Bromhead 2007).

One of the exercises that Bristol students undertake in class is to sketch a flow net for unconfined seepage through a dam, a problem that is also examined in the laboratory. Originally inspired by the description in *Two-dimensional fluid flow* in Lambe and Whitman (1969), the model dam is built in a tank 165 cm long by 25 cm wide. The perspex forming the front of the tank has been fitted with a number of tapping points, and the tank has an overflow at one end to control the upstream water level, and a basal drain at the other. Die is injected at several points just beneath the upstream slope, enabling the flow lines to be visualized and traced onto the side of the tank (see Figure 7 in which the photograph has been traced over). The seepage rate is measured by discharging water into a bucket for a known time, and the levels in the observation tubes are recorded. Each student is given a pre-drawn scaled cross-section (Figure 8) onto which the positions of the flow lines are carefully plotted. The piezometric levels at the tapping points (shown with +) are noted, marked on and are used to contour the total head to

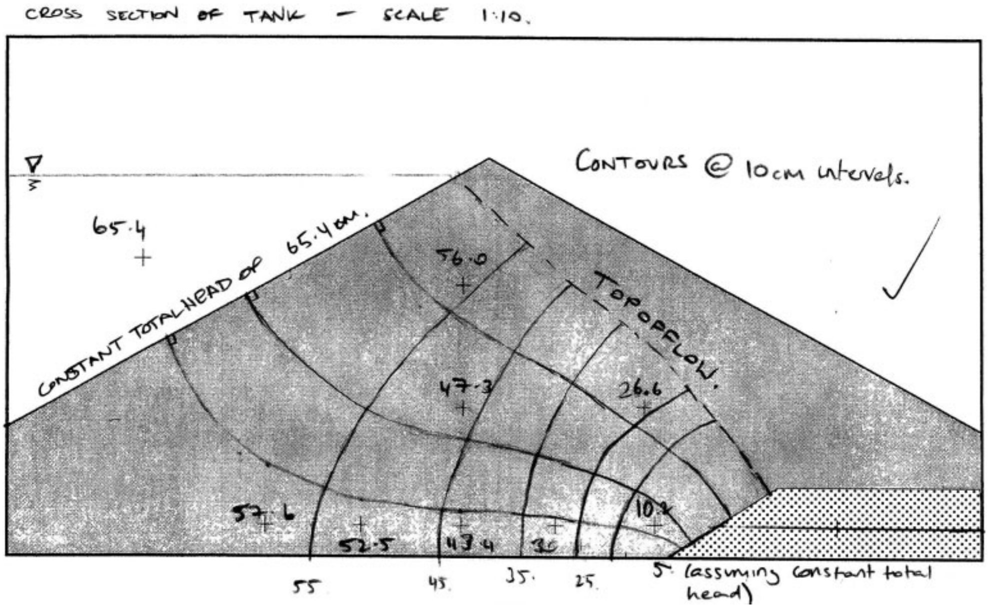


Figure 9. Flow net determined experimentally by students with total head contours at 10 cm intervals interpolated from values at tapping points plotted onto the scaled cross-section handout.

complete a flow net as shown in Figure 9. It is necessary to add a top flow line by inspection, along which the pore pressure is zero. Although there is some seepage through the zone above the top flow line it does not appear to influence the flow net.

The experimental flow net illustrates the concepts of orthogonal flow lines and equipotentials very well. Originally the chosen die injection points were equally spaced down the upstream slope of the dam and this tended to result in some flow fields being slightly rectangular rather than square (see Figure 9). The shape of the fields is also affected by variations of permeability resulting from uneven sand density obtained during construction of the dam. Currently we are experimenting with the die injection points to optimize the precise positions of the flow lines.

Students are also asked to generate a theoretical flow net for the same dam and to discuss the similarities and differences. In the past an electrical analogue model was used, but more recently the groundwater seepage analysis in the Plaxis 2D finite element package is demonstrated during the laboratory class – with the model prepared beforehand it takes only a few seconds to run (see Figure 10). Students are then provided with a handout of the same cross-section with the appropriate number of equipotentials, onto which they individually sketch flow-lines to complete the flow net (see imperfect example in Figure 11).

Using their theoretical flow net and experimentally determined coefficient of permeability students then compute the seepage rate from standard theory using:

$$q = k.\Delta H.\frac{N_f}{N_d}x$$

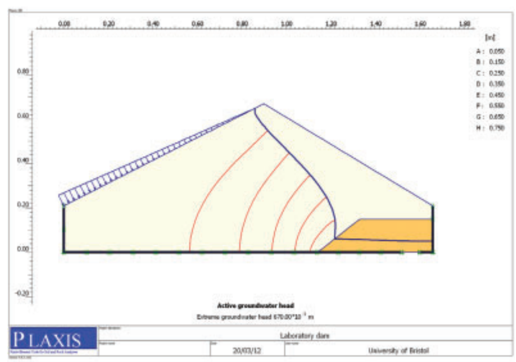


Figure 10. Output from demonstration of finite element seepage analysis.

Initially, when the experiments were first introduced there was not a very good agreement between the experimental and predicted seepage rates. This was thought to be because the sand in the dam was not homogeneous, and that the sand in the permeameter was of a slightly different grading. Taking care to ensure comparability, it is now found that predicted seepage rates using the two values of coefficient of permeability (loose and dense sand) bracket the experimental data satisfactorily, a finding that gives confidence in the validity of the analysis.

3.4 *Failure of dam*

It is found that the model dam is stable for long periods of time even if it has only minimal freeboard, although a gradual migration of sand into the gravel under-drain

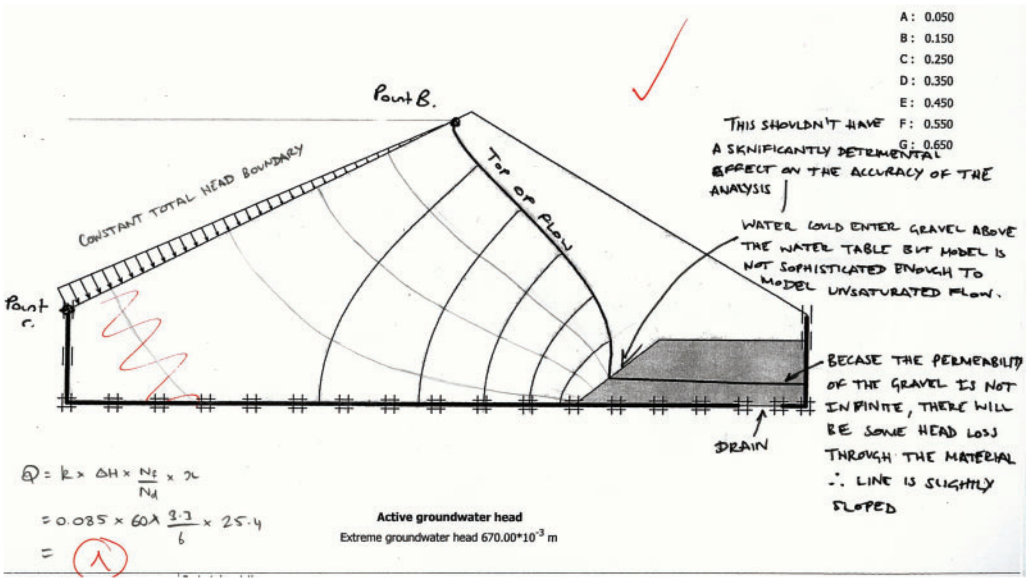


Figure 11. Handout from finite element seepage analysis with the theoretical flow net completed and annotated by a student.

may be observed. The detailed design of the filter could be improved, but the present arrangement is serendipitous as it prompts a discussion of internal erosion and the importance of careful filter design, and the possible consequences if the drainage system were to become blocked.

At the very end of the laboratory class the exit from the base of the tank is closed, and seepage is forced to exit from the downstream slope of the dam. Within a couple of minutes there is a shear failure of the downstream slope and the dam overtops in a dramatic manner. It may be remarked that such a failure results from the unsatisfactory design of the soil filter, and could not be predicted with any finite element analysis.

3.5 *Analysis and write-up*

Students routinely record experimental data and plot graphs in laboratory notebooks, and in this instance the completed flow net handouts are also glued in. The experimental work and most of the data analysis and flow net sketching are completed within the three hour laboratory class. Students are then asked to draw brief conclusions and to present their notebooks for marking three days later. If resources permitted, this group of exercises would be very suitable for writing up as a fuller report or technical note, an activity that would help to develop the student's writing skills.

4 DISCUSSION AND CONCLUSIONS

The study of soil mechanics requires commitment from the student with focused support from academic staff. Despite the considerable emphasis placed on developing students' understanding of pore water pressure, seepage and total head at Bristol, some students remain puzzled. For others the integrated approach described here is a helpful introduction to a difficult aspect of geotechnics on which they build further in later years, when for example they come to interpret piezometric data from a site with under-drainage as part of a design project.

Although demonstration of flow lines using a seepage tank is not uncommon (for example Marsland, 1953, Lambe and Whitman, 1969, Poulos, 1994, Jaksa, 2009, Marques, 2011), the writer believes there is great merit in the active learning involved in students undertaking this laboratory study for themselves. A similar but somewhat more extended project is reported by Marchese et al. (1999).

It is sometimes argued that skill in sketching a flownet is unnecessary. In the introduction to an interesting project on flow nets, Marstella (2010) considered that "*flow net analysis is a relatively disjointed and incomprehensive engineering tool that is not used extensively in industry*". The writer sympathises but disagrees. Whilst at university, students should be exposed to fundamental concepts that underpin engineering practice. Geotechnical specialists need to be fully confident in their understanding of pore water pressure, seepage and total head. While they are unlikely to solve many practical problems using hand-drawn flow nets alone, a flow net should always be sketched before the computer is switched on so that the boundary conditions and seepage pattern may be fully understood. The specialist is then in a position to check the output from a finite element analysis of seepage through a dam or into an excavation. Similarly before undertaking a limit equilibrium analysis of an unstable slope, the specialist needs to interpret the piezometric data so as to understand the hydrogeology.

A good understanding of pore water pressure, seepage and total head should be one of the *anchor points* for geotechnical engineers at all stages of their career (Burland, 1987). The educational approach described here is very traditional and requires good interaction between staff and students – something that is not easy to maintain as student-staff ratios increase inexorably.

Evaluating the success of this approach is difficult. In a recent survey of 19 final year students the majority said they were confident in their general understanding of total head although when faced with a problem like that in Figure 3, only one third could calculate the values correctly. Asked which activities most helped to develop their understanding of this topic the responses included "*Lectures and example classes have helped the core understanding, but experiments have helped to cement the learning".* and "*I believe that the only way to really get confident with the concepts has been to do numerous example sheets and exam questions. I also feel I have benefitted from the lab experiments, referring to my 2nd year lab book on a number of occasions. Having said this, the lecture notes (including worked examples) are also vital. In short, a combination of material and activities is necessary. In particular, I feel that the multiple exposures one gets to the same concepts are key – the ideas are new and take time to 'marinate'. My understanding was not a sudden eureka event, but more a gradual development as the material was revisited in different contexts".* and*"Laboratory experiments were essential. I still picture them in my mind every time I solve a problem about seepage. Flow net drawing sessions help a lot as well. Example sheets are also useful".*

Asked how students' understanding of these topics might be improved, the responses included "*Seepage and total head started to make sense for me when I was messing about with a siphon when making beer!"* and*"I would reiterate the need to cover the material multiple times".* and "*Simple: do a site visit. I have learned that site visits are real eye openers. If you took students to say an embankment dam or a cofferdam it would help visualise future questions they might be challenged with. On the site visit, make them calculate seepage through the dam, draw flow nets, point out the head difference between one side of the dam and the other".*

Clearly this is a topic that students learn incrementally in a variety of different ways. Students regularly give feedback that they like the integration between class and laboratory exercises, but it is clear from the survey and examination performance that many students still find the topic very challenging. For others, their curiosity about geotechnics has been engaged for ever.

ACKNOWLEDGEMENTS

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