The use of case histories in geo-engineering education

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The use of case histories to encourage reflection by civil engineering design students

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ABSTRACT: The paper considers the use of case histories to promote reflective learning in a final year Geotechnical Engineering elective module. Reflection in action is promoted as a means of simulating the working environment and of encouraging student engagement with advanced topics. An example is presented in which students were provided with a site investigation report and were required to estimate the bearing capacity and in-service settlement of three shallow footings on sand. The student's predictions were compared to the measured footing response and the effects of mean stress level and non-linear soil stiffness were investigated in the context of a real-world design problem.

1 INTRODUCTION

The paper describes the design and implementation of a master's level elective module in civil engineering entitled Soil-Structure Interaction. The course was designed to incorporate the best features of Enquiry Based Learning (EBL), Boud (1985) and Kolmos et al. (2007) with the background technical content delivered through formal lectures. The class is scheduled 50% in a formal lecture space and 50% in the civil engineering project rooms located in the University College Dublin (UCD) Newstead building. The learning outcomes state that students should (i) be proficient in the design of foundation systems for unusual structures, (ii) choose suitable models and input parameters and (iii) be capable of incorporating improved models developed in the latest state of the art research in order to improve predictive reliability. It develops on theories of soil mechanics learned in core modules of 3rd year soil mechanics and the general design skills developed for civil engineers in 4th year design in Soils.

A key element is the use of worked examples to illustrate the use of design approaches and case studies (workshops) to verify the accuracy and identify the critical parameters to be chosen by the designer. The problems are based on full-scale experiments and case histories and after grading student predictions, a review session is held in which the students can compare the answers they predicted to the actual results. In each workshop the students begin by applying some of the conventional design approaches used in industry. The input parameters for these models are somewhat subjective and they gain experience in both choosing these and then seeing what effect their choice had on the accuracy of their predictions. By comparing predicted and actual responses the use of improved models of soil behavior being developed by current research are introduced in context.

2 ENCOURAGING REFLECTION

2.1 *Defining reflection*

Refection in education can be defined in many ways. In this paper the design of a module which aims to provide students with a means of reflecting on the practice of geotechnical engineering is described. The philosophical basis for this notion was first suggested by Dewey (1922) who contrasted the inertia associated with education, wherein the knowledge transmitted is the known orthodoxy, to the dynamic developments taking place at the time in the development of steel cantilevered bridges. He suggested that custom (orthodoxy) unmodified by thought, would not have produced these developments in practice. Schon (1983, 1987) suggests that in practice, Engineers reflect in action, using skills which cannot be taught in the classroom or laboratory but in the design studio. This support of social constructivist theory is dependent on some core principles being available to the student, and strongly suggests that a mixture of pragmatism (state of the art) and constructivism present appropriate models for engineering education.

2.2 *Enquiry Based Learning*

Enquiry Based Learning (EBL) is becoming a very popular form of undergraduate teaching (Boud 1985, Savin-Baden 2000, Kolmos et al. 2007). EBL provides an opportunity to develop many of the graduate attributes (outcomes) required by employers and accreditation bodies, these include; teamwork, problem-solving and leadership skills, within a framework where the student accepts control of what needs to be learned and how it should be learned. EBL provides opportunities for deep learning and introduces the students to resources and skills necessary for lifelong learning. Well designed courses satisfy many of the objectives (learning outcomes) specified by accreditation bodies. However, in engineering, where the accumulation of core principles is hierarchical, missing essential concepts may result in a failure to learn. Whilst the development of meta-cognitive skills will result from EBL, the risk of missing vital concepts and theories suggests that EBL should be used as partial solution to develop professional problem solving skills through the application rather than the acquisition of knowledge.

2.3 *Issues affecting geotechnical engineering*

Atkinson (2002) notes that in the relatively recent past civil engineering graduates learned the theories of soil mechanics at University and joined firms as trainees. Working under licensed agreement, this on the job training prepared the graduate for chartered membership. However, in recent years there has been a move from industry to try to move this training into the University, such that graduates have the capability to earn money from their first day of employment. He argues (somewhat compellingly) that Universities should teach theories and that practice is learned in the work place. However, experience of using real-life design problems in the class room undoubtedly raise student interest. Because of the recent expansion of undergraduate courses in Ireland from four to five years, an opportunity exists to integrate some design work which reinforces the core theories. We must however recognise that the primary role of the University is to produce critical thinkers and any such move should to ensure that relevant theories are embedded in student learning through appropriate teaching methods spread across the curriculum. Any move to move towards vocational training would be a shift away from the principles of Dewey (1922) who considered the issue of education as a means of training faculties or acquiring skills. Whilst recognising the importance of training in certain professions, he cautions that the method of achieving any such training should be through the growth and development of the individual, rather than by the training of some specific reflex action akin to the physical training undertaken by a gymnast or swimmer. Instead he argues that the purpose should be that the process of education will develop the capacity for further education.

3 MODULE ON SOIL-STRUCTURE INTERACTION

3.1 *Background*

As an example of an attempt to promote reflection-in-action in a traditional classroom setting a module in Soil-Structure Interaction (SSI) was developed for the new Masters programme in Civil Engineering at University College Dublin (Gavin 2011). The course which ran for the first time in January 2010, considers the interaction of structures with the ground. It is an optional module with a current enrolment of 35, 4th and 5th year students.

Each week there is one 3 hour class. The first 1 to 1.5 hours is a formal lecture. The remainder of the class is a workshop session. The majority of these sessions involve the students (working in groups of 2–3) undertaking a design assignment (for example estimating the load at which a foundation will fail, or the settlement of a structure). The problems are largely based on full-scale experiments from the literature.

The problems are chosen to demonstrate some weakness in the current theories (that are conventionally taught at undergraduate level and contained in most reference texts), for example the use of conventional earth-pressure approaches to estimate the shaft capacity of driven piles. Having demonstrated potential deficiencies or problems with the application of these methods, the use of improved models developed as a result of up to the minute research is presented. Whilst these address some of the deficits evident in existing theories, the limitations of the new models are also illustrated and discussed. The real objective in introducing these techniques is not as new improved models per-se rather to illustrate that the state of the art is constantly evolving. An important outcome is to encourage students to develop a scientific scepticism of some of the accepted knowledge. In this way it is hoped that they might be more open to question this and develop alternative, hopefully improved solutions.

3.2 *Example problem*

An example problem aimed at promoting reflection-in-action is described in this section. The students who will have learned traditional bearing capacity approaches for shallow foundation design and simple settlement analyses in basic soil mechanics courses are given a problem on the design of shallow foundations on sand. They are presented with an overview of the soil stratigraphy for a site, which comprises a 7.5 m layer of sand overlying clay. The water table is at 4.9 m below ground level (bgl.). field and laboratory test data including Standard Penetration Test (SPT) N values, Cone Penetration Test (CPT) q_c values (see Figures 1 and 2) and laboratory test data is provided.

The students, working in pairs are asked to:

(i) Calculate the ultimate bearing resistance of a 1.5 m, 2.5 m and 3 m wide foundation founded at 0.75 m bgl.
(ii) Estimate the settlement of the footings at the working load, and
(iii) Estimate the mobilised resistance when the footing settlement is 25 mm.

The students submit their predictions and in the class the following week, their predictions are

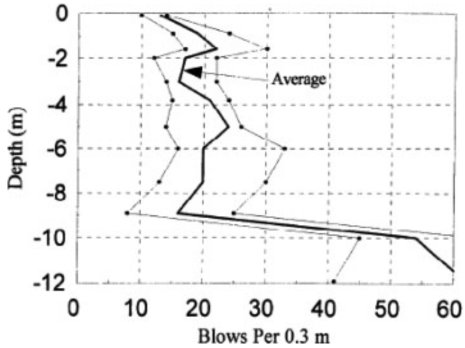

Figure 1. SPT Profile at site (after Briaud and Gibbens 1999).

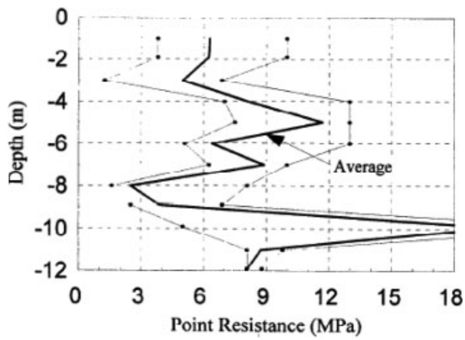

Figure 2. CPT q_c profile at site (after Briaud and Gibbens 1999).

compared to the actual foundation response thus providing the opportunity for meaningful reflection.

3.3 *Predicted response*

As noted, in introductory soil mechanics courses the students will have performed text book problems on applying the traditional bearing capacity approaches for estimating the ultimate bearing resistance of foundations and simple linear elastic approaches for estimating footing settlement, including the widely used equation:

$$\text{Settlement} = s = (\pi/4)qB\,(1-\upsilon^2)/E'_s \qquad (1)$$

The main input parameters needed for them to apply these familiar models to this problem are therefore the soils friction angle (ϕ') for the bearing capacity equation and the secant elastic stiffness (E'_s) for settlement estimation. The first lecture on the soil-structure interaction course concentrates on how to choose soil properties from site investigation data. Using this knowledge students estimate constant volume and peak friction angles based on material properties, relative density and the mean stress level applicable to the bearing capacity problem. They usually estimate the secant stiffness using some correlation with in-situ test data e.g. SPT N of CPT q_c. One of the first challenges they face in choosing design values for their parameters is considering the zone of influence of the foundations and dealing with the inherent variability in the measured data. To help in this process graduate demonstrators are provided to give guidance when requested.

Eighteen groups undertook predictions in the first year the module was offered. The range of predictions of the ultimate bearing capacity for the three foundation widths considered is shown in Figure 3.

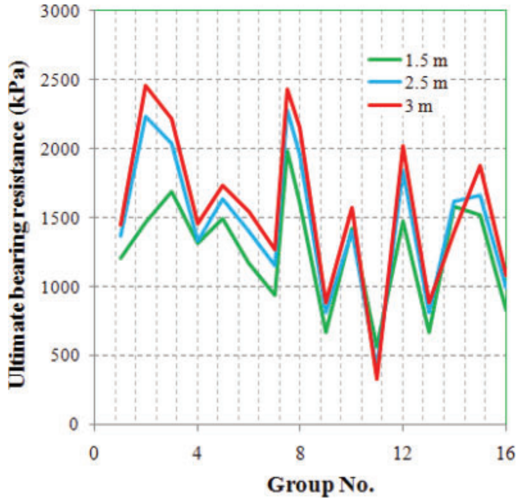

Figure 3. Estimates of the ultimate bearing resistance of shallow foundations on sand.

The following points are noteworthy:

(i) Although all groups used the same bearing capacity, shape factors etc, provided in a review sheet, their predictions for the ultimate bearing resistance (q_{ult}) were characterised by large scatter. In the absence of error in the calculations, this scatter is largely due to variability in the choice of ϕ' used in the calculation. This is as a result of assumptions made in the zone of influence (i.e. some groups used the same ϕ' value in all calculations) or variations in the level of dilation induced increase in ϕ' which were included. For example the predicted q_{ult} ranged from 380 kPa to 2475 kPa for the 3 m wide footing.

(ii) The predicted ultimate resistance increased as the footing width increased – one exception being the estimate by Group No. 11 of the q_{ult} value of the 3 m wide footing. This calculated value contained an error.

The estimates of settlement at working stress level are shown in Figure 4. All groups estimated the footing settlement using Eqn. 1 with some also using Burland and Burbridge's (1985) method as an alternative. The predictions are again characterised by large scatter with estimates of the initial settlement of the 1 m wide footing ranging from 5 mm to 25 mm, and for the 3 m wide footing from 10 mm to 62 mm. Part

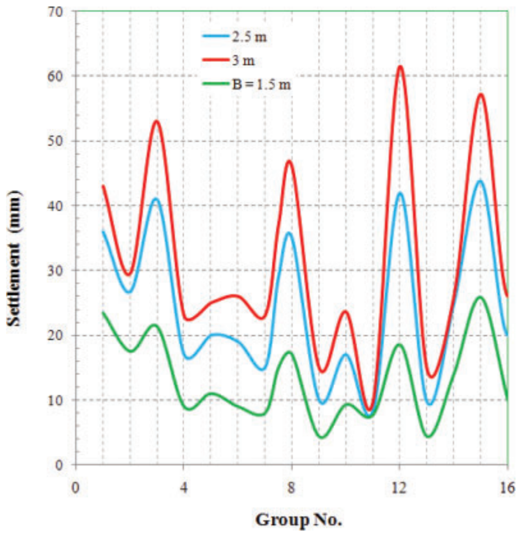

Figure 4. Estimates of settlement at working stress level.

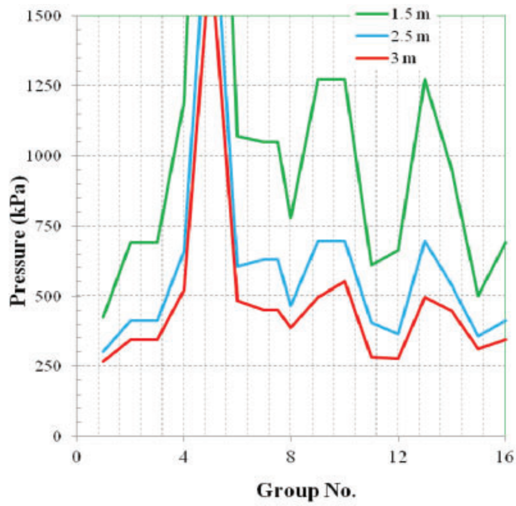

Figure 5. Estimates of mobilised pressure at a footing settlement of 25 mm.

of the reason for this scatter was a result of the definition of working stress, which groups took to be their q_{ult} value reduced by a factor of 3. Of the other input parameters used in the settlement model used by all groups, the same Poisson's ratio and shape factor were adopted by most groups. In practice the most uncertain parameter in this expression is the secant modulus, E'_s all groups used correlations between E'_s and SPT N or CPT q_c (of the form shown in Eqn 2), however, these simple correlations vary with the stress history of the deposit. Some groups assumed that the sand layer was over-consolidated and therefore assigned a much higher E'_s for the sand.

$$E'_s \approx 2500\, N_{60} \text{ or } 5\, q_c \text{ (kPa)} \tag{2a}$$
(in aged over-consolidated natural cohesionless soils)

$$E'_s \approx 750\, N_{60} \text{ or } 2\, q_c \text{ (kPa)} \tag{2b}$$
(normally consolidated, unaged soils)

In the final part of the problem, the students were asked to estimate the applied pressure mobilised for the three footing when the settlement was 25 mm. These estimates were readily obtained by rewriting Eqn. 1 for a fixed footing settlement of 25 mm. The estimates shown in Figure 5 exhibit the lowest variability between groups. With the exception of Group 5 who made an error in their calculations as their predicted mobilised pressure exceeded their estimate of q_{ult}, the ratio between the lowest and highest predictions was $\approx$2.5.

As the only variable input parameter in this calculation was E'_s and groups tended to favour the use of CPT data, is clear that groups who assumed the material to be over-consolidated assumed $E'_s = 5q_c$, whilst other used $E'_s = 2q_c$, thus explaining the relatively narrow range of predictions.

3.4 *Comparison of measured and predicted response*

The pressure-settlement response measured during load tests on the three foundations are shown in Figure 6a. The bearing resistance mobilised by footings was in the range 1100 kPa to 1400 kPa. The smallest footing (1.5 m diameter) developed the highest resistance and stiffest pressure-settlement response. Briaud (2007) compared measurements made at this site with a database of other footing tests and noted that when the footing settlement was normalised by the footing width, and the applied pressure was normalised by strength measurements from in-situ tests (i.e. the limit pressure measured in a pressuremeter test) a unique load settlement curve resulted.

Gavin et al. (2009) used the CPT q_c as the in-situ test for normalisation and produced the normalised pressure-settlement response for the test site shown in Figure 6b. They proposed the use of a definition of ultimate resistance which corresponds to the mobilised resistance at a normalised settlement of 10% of the footing width. They compared the footing tests shown in Figure 6b with a wider database of tests performed on model and full-scale foundation tested in a range of sand densities and found that the resistance mobilised at 10% settlement ($q_{0.1}$) could be conservatively estimated using the expression:

$$q_{0.1} = 0.2\, q_c \tag{3}$$

Using Eqn. 3 to provide an estimate of the *measured* ultimate resistance based on average CPT q_c within a zone of influence of the foundation results in q_{ult} values of 1400 kPa for the 1.5 m footing (which is in agreement with the measured values in Figure 5), 1375 kPa for the 2.5 m and 1560 kPa for the 3 m wide footing.

Comparing these to the values predicted using the traditional bearing capacity approach in Figure 3

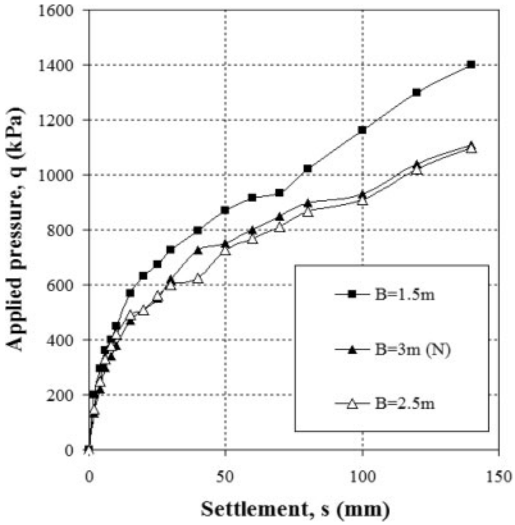

Figure 6a. Measured pressure-settlement response of footings.

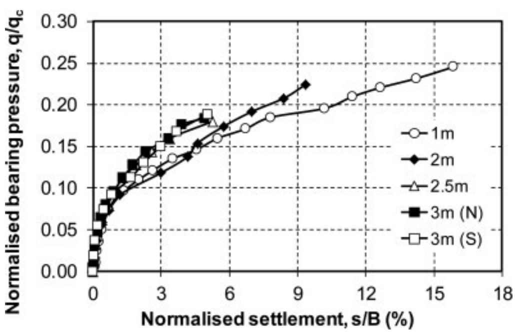

Figure 6b. Normalised pressure-settlement response of footings.

shows the *measured* values to be broadly compatible with the average values predicted, with ratios of predicted to measured q_{ult} being 0.93, 1.09 and 1.03 for the 1.5 m, 2,5 m and 3.0 m wide footings respectively. The traditional bearing capacity approach slightly underestiated the resistance of the smallest footing and slightly over-estimated the resistance of the larger footings. This trend arises because the mean stress level in the lightly over-consolidated sand deposit considered is relatively constant over the zone of influence considered for the three footings. The trend for the bearing capacity equation to predict increasing resistance for increased vertical effective stress, footing width and footing depth is of concern in deposits where the soil strength does not vary with depth.

The close agreement between the normalised footing response (at a footing displacement of 10% at this and other sites) and the bearing pressure which is predicted using Eqn. 3, suggests a simple correlation between in-situ test results is a good alternative to traditional bearing capacity approaches in the design

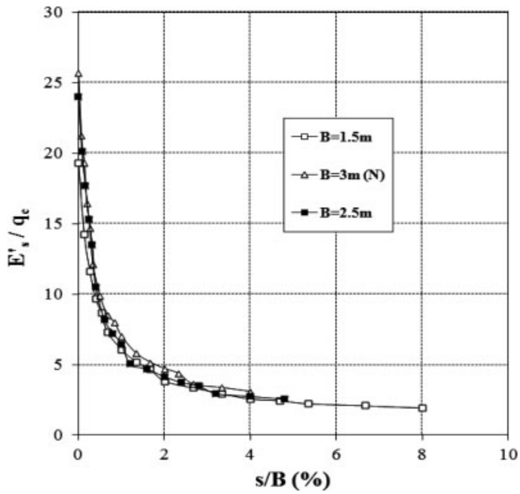

Figure 7. Normalised stiffness response of footings.

of shallow foundation. During the review session reference is made to the work of Briaud (2007) which questions the applicability of bearing capacity theory for soils where the soil strength does not increase with depth.

It was already noted that variability evident in the students' predictions for part (ii) of the problem, the footing settlement at working stress level (See Figure 3) were affected in part by their by their estimates of the ultimate bearing resistance. The groups used Eqn. 2 to derive stiffness values of between $2q_c$ and $5q_c$. These constant stiffness values were then used in part (iii) to calculate the bearing pressure when the footing settlement was 25 mm (See Figure 5). The bearing pressure mobilised at this displacement was between 550 kPa (for the 2.5 m wide footing) and 650 kPa for the (1.5 m wide footing). Predictions for the 2.5 m wide footing varied from 300 to 700 kPa, with an average of 518 kPa being just slightly lower than the measured value. For the 1.5 m wide footing, the predicted bearing pressure varied from 425 to 1275 kPa with an average of 890 kPa, i.e. a 37% over-estimate. This indicates that the soil stiffness was over-estimated for the smallest footing.

The adoption of a constant stiffness value results in a family of pressure-settlement prediction profiles (for varying footing widths) which are linear. This obviously does not agree with the highly non-linear measured footing response evident in Figure 5. The actual variation of stiffness normalised by the CPT q_c value is shown in Figure 7. From this figure it is clear that the E'_s value of $5q_c$ is applicable for one unique normalised settlement (strain) level of approximately s/B = 1.5%, while the E'_s value of $2q_c$ applies only at very large normalised settlement levels (>6%). For a fixed footing settlement of 25 mm and varying footing widths of 1.5 m, 2.5 m and 3 m, a variable stiffness must be chosen if using a simple settlement model such as Eqn 1. For the 3 m wide footing, the normalised settlement is 0.83% (i.e. 25 mm/3 m) and from Figure 6 an E_s' value of $7.5q_c$ could be adopted. For the 1.5 m wide footing the normalised settlement is 1.66% (25 mm/1.5 m) and from Figure 6 it is clear that the mobilised E′s is $<5q_c$. This simple exercise highlights the importance of considering the non-linear stiffness response of soils, and illustrates how, through the judicious choice of stiffness values, complex soil behaviour can be modelled using relatively simple techniques including Eqns 1 and 3.

4 CONCLUSIONS

The paper presents an example of the use of a case study from the literature in an effort to promote reflective learning in a final year course in geotechnical engineering. Simple design problems are presented to the students in a format similar to how they would be encountered in industry. In the first session students chose soil parameters from site investigation reports and applied standard design models to estimate footing resistance and settlement. In a follow-up session predictions were compared to actual footing response and trends such as (i) the effect of mean stress level on the mobilized bearing resistance and (ii) the non-linear stiffness response of soils are introduced in the context of real world design problems. In later problems the students used the non-linear stiffness models in preference to simple linear-elastic approaches as they recognised their advantage.

The introduction of weekly case study problems encouraged student engagement with the topics covered and promoted self-learning. As a result the workshop and tutorial sessions provided an enjoyable educational environmental where detailed discussion on the practical application of soil mechanics principles tool place, promoting learning for students, post-grad demonstrators and staff members alike.

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