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Undergraduate teaching of ideal and real fluid flows: the value of real-world experimental projects

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This paper describes the pedagogical impact of real-world experimental projects undertaken as part of an advanced undergraduate fluid mechanics subject at an Australian university. The projects have been organized to complement traditional lectures and introduce students to the challenges of professional design, physical modelling, data collection and analysis. An overview of two projects is presented: wind tunnel testing of buildings and wave loading on piles. Both studies are undertaken as group work within the undergraduate subject. The pedagogy of the projects is discussed in terms of the classical educational psychology literature concerning project-based learning, collaborative and guided learning and reflection. In terms of learning outcomes, the primary aim is to enable students to deliver a professional report as the final product, where physical model data are compared to ideal-fluid flow calculations and real-fluid flow analyses. Thus the students are exposed to a professional design approach involving a high level of expertise in fluid mechanics, with sufficient academic guidance to achieve carefully defined learning goals, while retaining sufficient flexibility for students to construct their own learning goals. The overall pedagogy is a blend of problem-based and project-based learning, which reflects academic research and professional practice. The assessment is a mix of peer-assessed oral presentations and written reports that aims to maximize student reflection and development. Student feedback indicated a strong motivation for courses that include a well-designed project component.

Keywords: Project-based learning; Fluid mechanics; Real-world projects; Experimental projects; Collaborative learning; Group work

1. Introduction

Engineering is related to the application of science to real-world applications, and engineering graduates must be familiar with professional problems, practical applications and relevant solutions for the benefits of the society. During the last three decades, universities in developed countries have rationalized their engineering curricula, associated with cost cuts that have yielded a general trend in reduction of formal contact hours (e.g. Russell *et al.* 2000, Liggett and Ettema 2001). This tendency has been associated with the development of computer-based

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Table 1. Publications in engineering education journals on the teaching of ‘fluid mechanics’ (1999–2005).

Journal	Total number of published articles	Nb of articles on ‘fluid mechanics’	Nb of articles on practical projects in fluid mechanics
European Journal of Engineering Education	287	0	0
International Journal of Engineering Education	504	4	1
International Journal of Mechanical Engineering Education	189	7	0
Journal of Engineering Education	86	1	1
Journal of Professional issues in Engineering Education and Practice ASCE	301	0 (3 in Hydraulic Engrg.)	0 (1 in Hydraulic Engrg.)
Total	1367	12	2

courses and ‘virtual learning’, project-based subjects and management courses, often at the expenses of technical contents and practical studies (e.g. Chanson 2004).

The situation is illustrated by trends in engineering education journals. For example, between January 2000 and December 2001, *The International Journal of Engineering Education* published 139 articles with 57 papers on computer-based engineering courses including 12 on ‘virtual teaching’, plus 11 papers on quality assurance and over 32 papers on project-based courses. Not a single article described experimental projects to support basic teaching. This alarming trend is possibly more true in the teaching of fluid mechanics (table 1). For the period 1999–2005, it represented less than 0.3% of published articles in five leading journals in engineering education.

While project-based learning is widespread across the humanities, social sciences and sciences, the purpose and aims vary. Recent studies focused on engineering highlighted the challenges faced by the increasing use of information technology (IT) and the re-organization of curricula, and suggested that real-world projects can assist pedagogically in enhancing the student experience (Christodoulou 2004). In a recent review of project-based learning studies, Helle *et al.* (2006) noted that detailed course descriptors are required in fields other than educational psychology, but that the pedagogical framework needs clear explanation to enable both educational and non-educational academics to gain maximum benefit.

In the present paper, the authors attempt to achieve this balance and present innovative developments in the undergraduate teaching of advanced fluid mechanics in an engineering curriculum at the University of Queensland (Australia). Lectures and tutorials are complemented by detailed physical model studies that combine experimental, analytical and numerical work in order to develop students’ abilities to tackle real-world problems. A first study illustrates the differences between ideal and real-fluid flow force predictions based upon model tests of buildings in a large size wind tunnel used for research and professional testing. A second study introduces the complexity arising from unsteady non-uniform wave loading on a sheltered pile. The teaching initiative is supported by feedback from undergraduate students. The pedagogy of the course and projects is discussed with reference to experiential, project-based and collaborative learning.

2. Pedagogy of the course

At the University of Queensland, environmental fluid mechanics and hydraulic engineering are lectured in the Civil and Environmental Engineering curricula, which deliver respectively about 100–160 and 10–20 new graduates each year. The Advanced Fluid Mechanics course is a fourth-year elective and corresponds to two units within an engineering curriculum of 64 units over 4 years. The Advanced Fluid Mechanics course discussed herein attracts typically 15 to 35 students, and it is also available to mechanical engineering students.

2.1 *Advanced Fluid Mechanics*

The Advanced Fluid Mechanics course material is structured to guide the students from the basic principles of fluid mechanics to their application to engineering design. The focus is on the understanding of fundamental principles and their sound applications to real-world problems. The Advanced Fluid Mechanics elective subject is broadly divided into two themes: ideal and real-fluid flows, and these are drawn together through experimental projects. The ideal-fluid flow section deals with irrotational flow theory, streamlines and streamfunctions, superposition of potential flows, Rankine bodies, the basics of lift or transverse forces, and the fundamentals of linear wave theory and wave loading regimes. Where significant flow separation occurs, ideal-flow theory fails and a real-fluid flow analysis is required. For simple problems, students may apply standard textbook techniques to determine fluid loads, i.e. empirical drag or lift coefficients. However most real-life problems do not lend themselves to such an analysis. Frequently they require numerical and physical model studies to provide experimental data for design or validation. It is important that students recognize this issue and are aware of techniques to address the design problem. In addition, model testing requires some experience of experimental techniques, flow measurement equipment, data logging and data analysis. Therefore the experimental projects are designed to develop these generic skills in fluid mechanics.

Overall the subject includes 50 contact hours, roughly divided into 25–30 h of lectures, 10–12 h of tutorials and 14–17 h of experimental work. Assessment is a combination of end-of-semester examination and semester work. The total experimental component is about 45% of the overall assessment, of which the two projects discussed herein comprise 36% of the subject assessment. The remainder of the practical work component is a basic boundary layer experiment. A final important aim of the projects is to add some personal experience to the teaching and learning process, and the added challenge of working within a team to achieve a common goal. The latter is an essential part of professional practice but rarely part of the undergraduate experience.

3. Projects

The pedagogical rationale for introducing real-world projects is to provide new learning experiences and to develop competency in practical engineering problems, in addition to the development of fundamental concepts and abstract process skills (Tullis and Tullis 2001). Example descriptors of project-based learning (PBL) in civil engineering and other disciplines are given by Finnie (2001) and Frank *et al.* (2003) among others. Helle *et al.* (2006) and DeFillippi (2000) provided recent reviews of the theoretical practice and basis for project-based learning over a range of social and scientific disciplines. In terms of learning outcomes, the purpose of the present projects is to introduce undergraduate students to the complexity of turbulent flow studies, the complex interactions between fluid and structures, the difficulties associated with experimental work, and to link ideal and real-fluid flow calculations. The projects are carried out in groups of 5–8 students to develop skill and experience in teamwork, collaborative effort and communication. Occasionally these lead to tensions within the group and this is discussed later with regards to assessment methods.

The projects meet two of the three purposes of project-based learning (Helle *et al.* 2006). First the integration of material as a capstone; and secondly to provide a framework for guided learning. This is achieved with close interaction between the academics, students and technical staff during the project, and through the design of assessment with a strong verbal and written feedback component. In terms of engineering outcomes, the projects involve both accumulation of knowledge (vertical learning) and the development of generic skills (horizontal learning). The latter is built around the challenges faced by the students while working with advanced (research) facilities, state-of-the-art instrumentation and large data sets. The end product is a professional technical report, rather than the study process, which distinguishes project-based learning from problem-based learning (e.g. Blumenfeld *et al.* 1991). In terms of the main pedagogical concepts of experiential learning (e.g. Kolb 1984) and collaborative learning (e.g. Piaget 1963, Vygotsky 1978), the projects and their assessment encompass a mix of different aspects, i.e. the 'make' or 'do', the problem, and the acquisition of new skills. In the wave loading project, the reflective aspect of the Kolb cycle is enhanced by carrying out oral presentations prior to submission of the final reports. This enables students to reflect on their individual conceptual development and analysis, and to then include feedback from peers and academics. This reflective process forms a link between the learning cycle and Piaget's (1963) idea of cognitive conflict as being central to collaborative learning, such that individuals views differ, provoking some re-evaluation of their own concepts. This idea is at the heart of the professional scientific design and review process. This workshop and review approach fits with the Vygotsky view of collaborative learning. As teachers, the lecturers see the learner's state of development based on their own independent work and can increase their development through academic and peer collaboration. As researchers, they find this both useful and stimulating since the projects have a very strong research element and we do not know the results until the presentations occur. Consequently, the lecturer collaboration is real, rather than supervisory.

3.1 *Wind loading study*

The students investigate the flow field around buildings under cyclonic wind conditions in an atmospheric boundary layer (figure 1). For each type of inflow conditions, they conduct detailed turbulent velocity measurements around the building, pressure measurements on the model, and lift and drag force calculations for several wind directions. Each group uses a different model. The students compare their data with theoretical calculations (e.g. flow nets, 2DFlow+) and real-fluid flow calculations. All measurements are performed by the students under academic and technical guidance. The experimental phase of the project runs over a whole day or two half days, approximately 7 h per group.

Wind tunnel tests are conducted in the atmospheric boundary layer wind tunnel located in the Gordon McKay Hydraulics Laboratory of the University of Queensland. The cross-section of the wind tunnel test section is 2 m by 3 m. Each building model is 0.6 m high, 0.04 m thick, has a 0.45 m chord length and 20 mm rounded ends. Different cambers are used between groups typically. Each perspex model has 62 pressure tappings and pressure measurements are conducted with a Scanivalve™ system connected to a data acquisition computer scanning the data at 600 Hz. The integration of the time-averaged pressure distributions gives the drag and lift force. Velocity measurements are performed using a single wire 55P11 straight hot-wire, controlled by a constant temperature anemometer (Dantec™ Streamline), and the basic outputs are the mean longitudinal velocity and the longitudinal turbulence intensity. The velocity

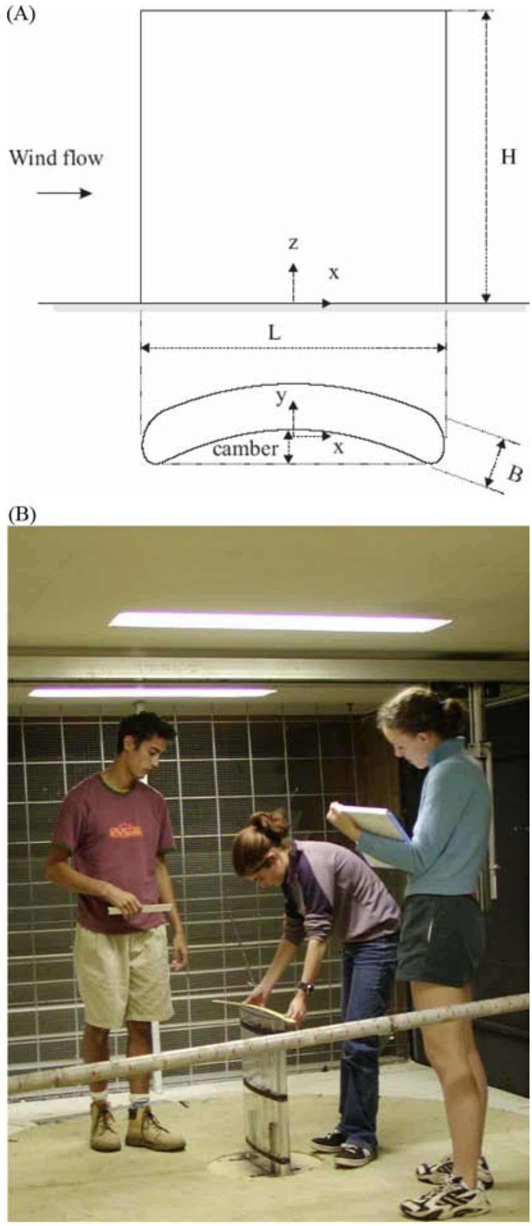

Figure 1. Building model in the atmospheric wind tunnel of the University of Queensland: (a) definition sketch – model dimensions: H = 0.6 m, L = 0.45 m, B = 0.04 m; (b) students in the wind tunnel preparing a model test on the turntable.

distribution data are used to evaluate the momentum integral upstream and downstream of the model to determine the total drag. For direct load measurement, the model is set-up to rotate about a pin connection at the base, with loads derived from measured reaction forces and a force distribution from the boundary layer velocity profile. The inflow conditions are typically a free-stream velocity of about 12 m/s, with a developing boundary layer corresponding to a Category 2 storm/cyclone in a semi-urban area (Australian Standards 1983, Australian Wind Loading Code). The State of Queensland in the North-East of Australia is subjected to several major cyclones each year, and buildings must be designed accordingly. Figure 2

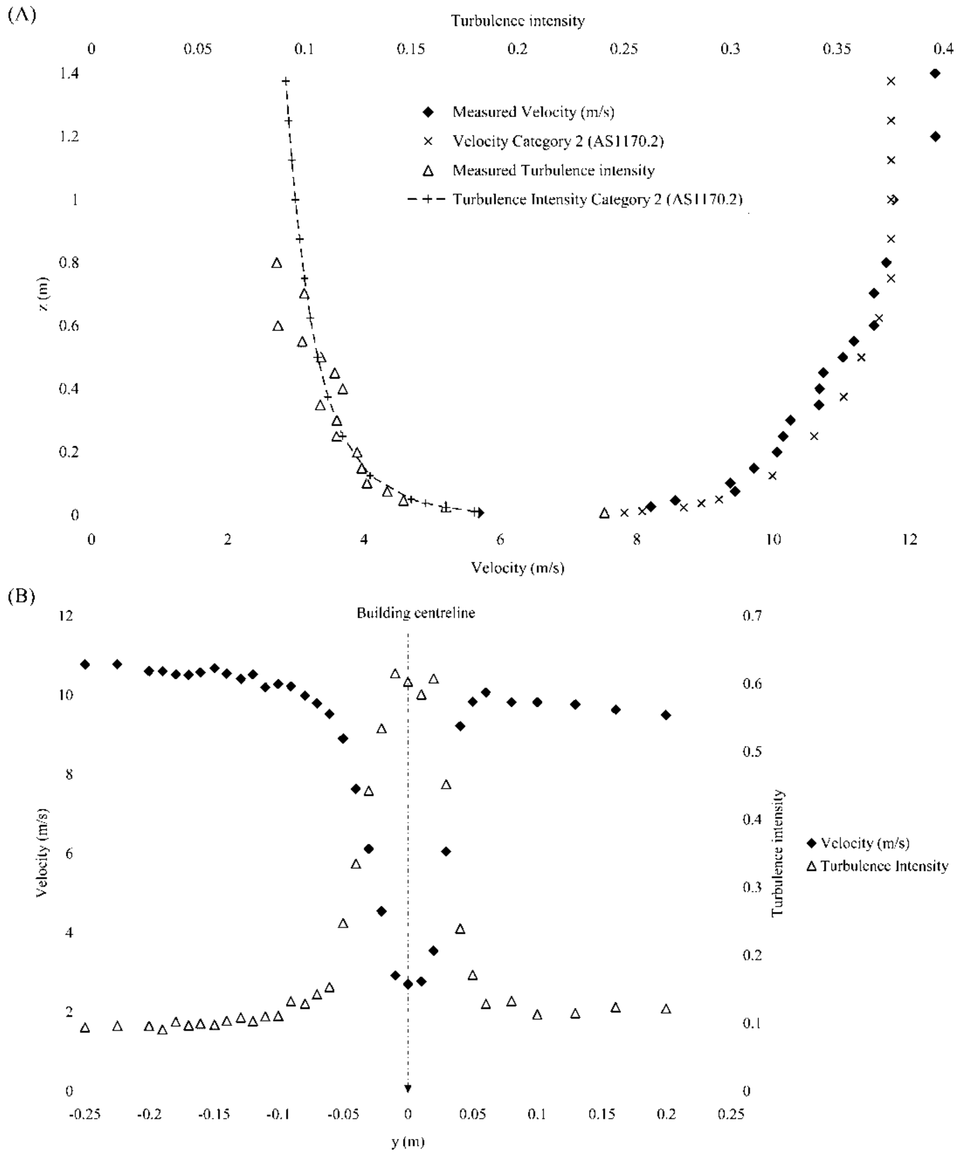

Figure 2. Experimental results in the atmospheric boundary layer wind tunnel in 2005: model 3 (H = 0.6 m, L = 0.45 m, 15% camber) with 12 m/s reference velocity. (a) Vertical distribution of mean longitudinal velocity and turbulence intensity on the tunnel centreline measured upstream of the building model (x = −0.90 m): comparison with Australian Standards (1983) for a category 2 storm/cyclone. (b) Horizontal distributions of mean longitudinal velocity and turbulence intensity in the wake of building model (x = +0.264 m, one building thickness downstream of the trailing edge) at z = 0.3 m above the floor for 0° angle of incidence.

illustrates some typical results in terms of the inflow velocity distribution [figure 2(a)], and the horizontal distribution of velocity and turbulence intensity in the near-wake of the building model [figure 2(b)].

The experiments are complemented by some flow visualization in a Hele-Shaw cell where each group use a boundary shape identical with their building model. The resulting two-dimensional flow patterns are analogous to the ideal-fluid flow calculations and aid the students to draw the flow nets from which they derive the flow velocity and the pressure field using the Bernoulli equation. Measured and predicted pressures are integrated around the body to obtain total lift and drag forces. These are compared with ideal-fluid flow calculations (lift), real-fluid flow calculations (based on standard drag coefficients) and the direct load measurements.

3.2 *Wave loading study*

The wave loading study is designed to promote the students' knowledge of wave theory and wave loading regimes on coastal and offshore structures. It follows directly on a series of four lectures introducing the concepts of linear wave theory, wave dispersion and flow kinematics. An importance feature is the distinction between drag and inertia forces for unsteady flows, hydrodynamic mass and Froude–Krylov inertia forces. The wave loading study synthesises the ideal irrotational flow theory, which is an excellent approximation for pure wave motion, with the boundary layer theory applicable for real fluids which strongly influences the unsteady wave loading regime.

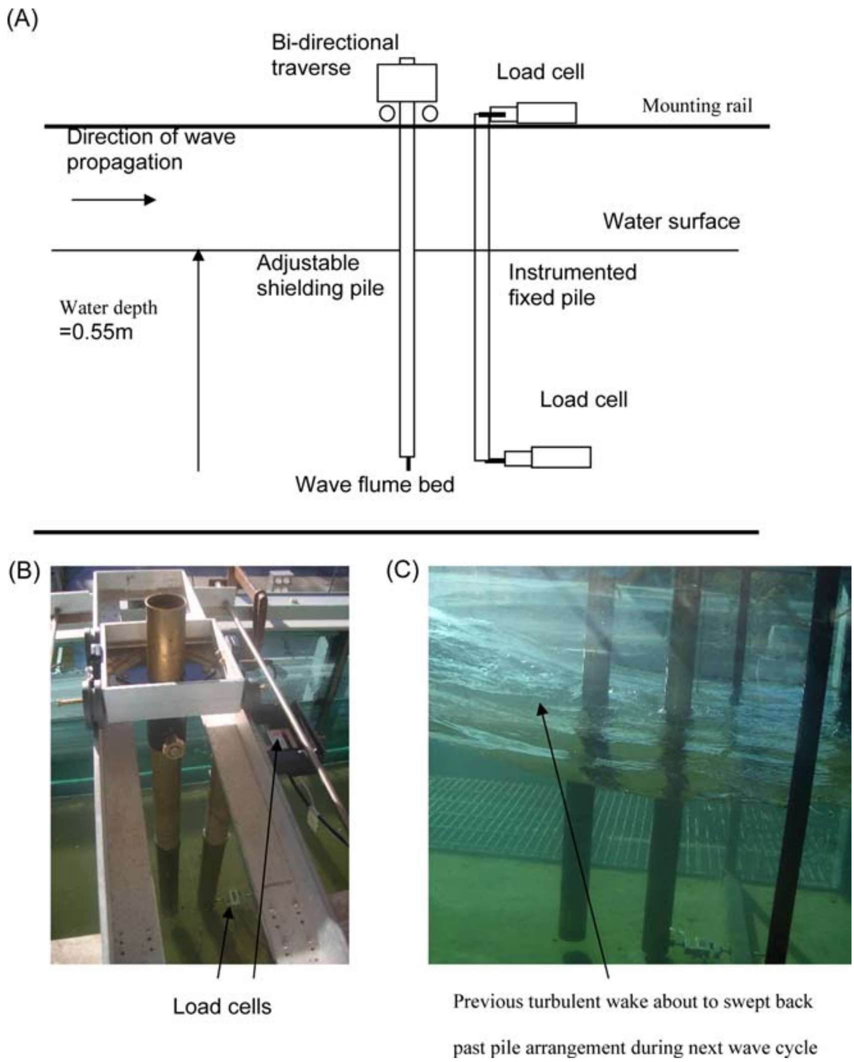

Figure 3. Wave loading project set-up: (a) coastal wave flume – elevation view of pile arrangement: (b) traverse and pile arrangement; (c) pile arrangement during wave loading.

The study investigates the loads on a cylindrical pile (diameter 5–10 cm), first with a single pile and second with the pile sheltered to varying degrees by a second identical pile (figure 3). The experiments are carried out in the Coastal wave flume at the University of Queensland, which is 20 m long, 0.8 m wide, and operates with water depths between 0.3 m and 0.6 m [figure 3(a)]. Wave periods range between 1 and 10 s with wave heights up to 0.2 m. One pile is fixed rigidly between two load cells at the upper and lower ends, and is fixed in position in the flume. The sum of the two measured forces provides the total horizontal load on the pile, while the ratio of upper to lower reaction forces provides a measure of the force distribution in the vertical. A wave gauge is co-located with the centreline of the cylinder to provide surface elevation data. The second pile is held within a traverse arrangement, allowing the pile to be positioned in front or to the side of the fixed pile [figure 3(b)]. Sheltering effects are investigated for different e/D ratios in both in-line and transverse directions, where e is the gap between piles and D is the circular pile diameter.

The load cell data and surface elevation data are logged with real-time display on a laptop computer equipped with data acquisition system and appropriate software. Real-time analysis and data display aids significantly in the student experience, providing confidence and interest in the experimental process. Visual observations complement the measurements to show the complexity of the problem. An example is shown in figure 3(c) where the turbulent wake formed during the previous half wave cycle is about to be swept back past the pile array. The wake and interaction between the two piles is also clearly evident. The wave surface elevation data are compared with linear wave theory. Some discrepancies arise usually from non-linear effects, and this highlights the advantages and disadvantages of the linear wave theory. The measured force data are used to derive drag and inertia loading coefficients using two different approaches (e.g. Sumer and Fredsoe 1997). Students compare the different methods with their experimental results and existing literature data. Once derived, the force coefficients can be used to provide a best fit predicted force-time-history, highlighting the deficiencies of linear wave theory. The experimental phase of the project runs over a whole day or two half days, approximately 7 h.

4. Discussion

4.1 *Group structure and assessment*

Several options are possible in determining the group structure. Either students are placed in a group according to set criteria or at random, or students determine their own groups. While the pedagogic outcomes for individual students and the group dynamics probably depend on the choice made (Felder and Brent 2001), the course structure at the University of Queensland leads often to timetable clashes that restrict choice. Therefore academic staff form the groups based upon students' preferences and timetable availability. Each student then has the option of swapping with another student if both wish to change. Few difficulties have occurred with group dynamics during experimental works with all members usually contributing fully. However, contingency has to be made for illness since the projects run on a tight time-frame and cannot be rescheduled. The group size is dictated by logistics to some extent, but the projects are modified annually to suit. Each project requires extensive commitment; one week of experimental time using the facility and 1–2 days of technical time to set-up, and technical staff are on call throughout. As academics, the lecturers commit 2–3 days over and above normal class hours. Research students are involved if pedagogically appropriate. It is difficult to quantify the overall costs. As an indication, typical rates on a consulting basis are $300/h for both the facility and technical time. One aim of the projects is to introduce students to the complexity of physical model testing, so that they maximize their use of increasingly expensive facilities if they need to do so as professionals.

Each group is required to summarise their experimental results and analysis in an oral presentation in front of the class, other students, and academic and technical staff. This is assessed by their peers (50%) and the academic staff (50%), subject to moderation if required. In addition, students submit a group report which is assessed by the lecturers. Individual tasks within the report are determined by the students themselves. This has led to a small number of problems with group dynamics, when some members believed that others did not contribute fully. To address this, team members might be requested to complete an anonymous peer rating of the contribution from their colleagues and themselves. This is assessed by academic staff and marks may be adjusted in consequence. In future, it is conceivable that groups may be asked to formalize their group work, including meeting times, member tasks/responsibilities, expectations and how to deal with conflicts.

4.2 *Student experience*

A key outcome of the projects is the personal hands-on experience gained by students. While this aspect is difficult to quantify and often ignored by university management, there is no doubt that practical experimental work enhances student's individual experience and personal development. Both authors have experienced this first-hand, and they receive laudatory individual feedback (e.g. Chanson 2004). Group work contributes to new friendships and openings, e.g., between civil and mechanical engineering students, between Australian and international students, and between students and technicians involved in the study. Such personal experiences are at least as important as the academic experience.

Handwritten and verbal student comments added some personal feedback highlighting a strong student motivation for the fluid mechanics course associated with the experimental projects. The projects helped the students to face real professional situations. These motivated them much more than conventional lectures and audio-visual aids (e.g. slides, video). The students understood that they were facing a professional challenge. For example, 'this is awesome', 'fascinating', 'I did not think of the problem that way' (CIVL4160 students' comments on the wind tunnel project). The students demonstrated a greater motivation for hands-on experiences under academic supervision.

This increased interest for the course translated always in higher marks in semester work and examination papers, and, more importantly, a smaller failure rate in the subject. Prior to the introduction of experimental projects, the failure rate in the advanced fluid mechanics subject ranged from 20 to 30%. Since the introduction of professional projects, the failure rate, in the same subject, has been reduced down very significantly. (This trend was clearly noted because the subject curriculum remained unchanged.) In the first two years following the introduction of the project, the failure rate was zero, and 10% in the third year. The impact of the projects on students' performances was noticed among all students.

Anonymous student feedback on the projects was collected in 2003. The anonymous results demonstrated that students considered the projects as an essential component of the fluid mechanics courses and an important aspect of their civil/environmental engineering curriculum. For example, 100% of the students agreed strongly and very strongly that 'the project work was an important component of the subject' and that 'all things considered, project works in industrial facilities are an important component of the curriculum'. Project works encouraged strong group bonding allowing students to gain better in-depth understanding of professional teamwork and designs. Although the students believed that the projects did not replace traditional lectures, a large majority felt that the project experience helped them to think more critically.

While introductory laboratory classes are simple, advanced projects, such as those described above, may be sometimes feared by students. The writers can mention cases of students who were apprehensive about the practical activities prior to the activities. Yet all the students had the courage to take on the challenges and the writers have not experienced a single failure. Discussions with students after the projects indicated that all had a positive learning experience. In particular, students learned the difficulties associated with the complexities of making real measurements, working with advanced, and sometimes 'temperamental', instrumentation and equipment, and the extent to which careful planning can help resolve many issues in the testing process, but invariably never all. There is therefore always the challenge of fixing a problem or finding a way around it. Such experience cannot be gained in the classroom.

Finally it is important to note that the experiment arrangement may require immediate expert technical assistance to change or fix broken apparatus. The availability of technical staff is an essential aspect of this form of teaching, and must not be overlooked during planning. At present the writers are fortunate to have this level of technical assistance available and they believe that it should be properly accounted for in the teaching budget. Indeed the students always learn a great deal from technical staff who are experts in the field of model testing and equipment calibration. At the same time, the projects expose the students to the issues of measurements errors and reliability. This is another pedagogical outcome.

5. Conclusions

Experimental design projects have been introduced systematically in an advanced fluid mechanics subject within undergraduate civil and environmental engineering curricula. The practical work complements traditional lectures and tutorials, and provides opportunities which cannot be learnt in the classroom, real or virtual. Student feedback demonstrates a strong interest for the project phases of the course. This was associated with greater motivation for the course, leading in turn to lower failure rates.

The present study highlights the significant role of real-world projects in the undergraduate teaching of fluid mechanics. Despite budgetary pressures, academics and professionals should not resist trends to reduce or eliminate practical studies from Engineering courses. The current authors do not believe that such trends are in the interest of students or the profession in the longer term. Professionals and industry should be encouraged to make this point when appropriate. Although the preparation and organisation of project work in a large-size facility are a major effort, the outcomes are rewarding for both students and staff. From their own experience, the writers have had great pleasure in guiding their students during real-world projects and to experience their personal development first hand.

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