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A design-based fluid mechanics laboratory

Jack A. Puleo

University of Delaware
Newark, DE, United States of America

ABSTRACT: Civil and environmental engineering students at the University of Delaware conduct the Vessel Project as a new design-based Fluid Mechanics Laboratory. Students are required to design/build/test an apparatus to transport two teammates across the university dive pool and back. The laboratory course focuses on the concepts of buoyancy and stability, while enhancing communication and team work skills. Students are allowed to spend no more than $100 on materials, and are encouraged to use donated items or items free of charge that are located in various laboratories across campus. Students overwhelmingly supported the new course layout relative to a more traditional laboratory course with prescribed testing on multiple devices. Positive comments were largely focused around the ability to be creative, actually build/test a vessel after the design process, and the ability to work as a team. Some comments for improvement were related to apprehension in the use of shop tools and more checkpoints throughout the build process to help teams maintain progress.

Keywords: Civil engineering, active learning, communication skills, stability, buoyancy

INTRODUCTION

Fluid mechanics laboratory courses complement the fluid mechanics lecture by providing additional opportunities for students to investigate theory and practical applications. Most laboratory courses use a variety of apparatuses for investigating fundamental principles, such as: hydrostatics, stability or flow through an orifice or pipe constriction to name a few. The Department of Civil and Environmental Engineering (CEE) at the University of Delaware offers a Fluid Mechanics lecture (3 credits) supplemented by a Fluid Mechanics Laboratory course (1 credit) that itself has a lecture and laboratory component. Prior to 2013, the laboratory course was taken the semester after the lecture course. Many students expressed concern that their grasp of fundamental topics waned making the laboratory course too difficult. The laboratory course was shifted to be coincident with the lecture following 2013 to perhaps remedy that concern. However, alignment of topics throughout the semester was difficult with many of the laboratory exercises consisting of material that was beyond fundamental fluid mechanics topics or had yet to be covered in the main lecture.

The laboratory course prior to 2013 consisted of seven exercises: 1) hydrostatic force on a planar surface; 2) stability of a floating body; 3) flow from an orifice opening in a tank; 4) hydraulic jump phenomena; 5) flow rate measurement and energy losses; 6) impact of a water jet - conservation of linear momentum; and 7) the nature of turbulence. Students were also provided introductory material on statistical analysis.

The lecture component of the laboratory course consisted of introductory lectures of material related to the exercise and apparatus (two exercises discussed per lecture). Handouts explaining the theory behind the exercise, the required analysis and the report scoring rubric were also provided. PhD students and faculty then explained to the students during the actual laboratory time the exercise and apparatus use. Students worked in groups of 10-12 on one of the two apparatuses. Having only two apparatuses being used per time block was necessary for proper oversight. However, the apparatuses only accommodated 2-3 students at a given time meaning that many students did not participate actively in the apparatus set up, data collection or inquiry. Students within the 10-12 person working group would then form teams of 2-3 for performing analysis on the collected data and writing the laboratory report. The effort required for each exercise seemed excessive for a 1 credit course. Exercises 6 and 7 were removed beginning in 2014.

Regardless of work load, the laboratory exercises are somewhat formulaic and students often share results from one year to the next. In short, the faculty were keen to develop a new approach to the Fluid Mechanics Laboratory course in CEE that addressed several deficiencies. Student surveys indicated the course was not beneficial for them to understand real world processes and the material was not engaging. Surveys of constituents including former students and employers highlighted the need for improved communication and team work from recent CEE graduates.

In addition, a design-based course with actual fabrication and testing would enable students to feel ownership of the project, see the actual results and address some of the weaknesses (communications, team work) highlighted by constituents. These concepts of hands-on approach to learning possibly through teamwork and communication have been shown to enhance comprehension of science and engineering topics [1-3]. Thus, a new approach to the Fluid Mechanics Laboratory course was conceived beginning in 2017.

THE FLUID MECHANICS VESSEL PROJECT

The Vessel Project (VP) was conceived to provide students an interesting and exciting design and fabrication experience, where they could apply theory to (and test) an actual fluid mechanics concept. Other alternative fluid mechanics laboratories have also been proposed based on pump and piping design [4], nozzle design [5], and a water-powered wheeled vehicle [6]. The VP exercise focuses on two main fluid mechanics concepts that are taught early in the semester: buoyancy and stability.

Students were provided the following:

Task

Your task/mission is to design/develop/construct/test/redesign some apparatus/device to transport you and a team member (two people total) across the university indoor dive well and back (20 m each way; must turn device around). Your entire team will consist of four to six members, but only two can make the journey.

Stipulations

1. You may not purchase or use some ready-made device (e.g. boat, kiddie pool, tub) or a kit that accomplishes the same function.
2. You may not spend more than $100 on parts for your device. Be creative and where possible incorporate used/free materials.
3. The device can be built during laboratory hours, while working in the Structures Laboratory, Coastal Engineering Laboratory or Mechanical Engineering Laboratory. Additional construction efforts can occur at your home or elsewhere on your own time.
4. The devices will be tested in the university dive well (lifeguard on duty) requiring two team members in the device with the real possibility of getting wet.
5. Your device must be able to be transported and fit through a single door to the dive well or be able to be fastened together on site in less than 15 minutes.
6. The device must have somewhere to attach a safety rope.
7. A winner for the fastest time across the dive well will be crowned.

Report

Your report should have the following format:

1. Title page with the title/name of the team, device, names of the students in the group and the date of report submission.
2. Objectives and problem statement.
3. Background research with appropriate citations and requirements for your device.
4. Your thought process/brainstorm for the vessel showing alternate approaches (including sketches) and the one your team actually decided upon and why.
5. Theoretical background showing your buoyancy and stability calculations. You must use equation editor or similar and provide drawings using a drawing package to indicate what is being done. Example hand calculations can be included in the appendices if necessary.
6. A CAD drawing of your chosen device.
7. An itemised budget for your chosen device.
8. The procedures and approach used to build the device. It is important that you document the process. Documentation requires the steps taken, as well as procedures and accompanying photographs.
9. Results. These contain a description of how your device performed upon testing. There may only be minimal quantitative analysis in this section.
10. Discuss how your device performed, where you believe it went awry if it did not perform well, and regardless of performance, how you may improve for next time. In an actual design process, the improvements would be made and additional testing undertaken. The semester time frame does not generally allow for this.
11. Appendices if necessary.

BUOYANCY AND STABILITY

Buoyancy is determined following Archimedes' Principle where a partially submerged object displaces its own weight in fluid as:

$$F_B = W_{disp} = \rho g V_{disp}, \quad (1)$$

where F_B is the buoyant force, W_{disp} is the displaced weight of the fluid defined by the fluid density (ρ), gravitational acceleration (g) and displaced volume (V_{disp}). Stability is estimated from the nautical engineering equation of static stability [7] using the metacentric height (MG) as:

$$MG = (I / V_{disp}) - GB, \quad (2)$$

where I is the moment of inertia of about the waterline area of the vessel and GB is the initial distance between the centre of gravity (CG) and centre of buoyancy (CB). The moment of inertia is relatively straightforward to calculate for simple geometric shapes of waterline area, such as rectangles and circles as chosen for most vessels. More complicated shapes are approximated with simple geometries to facilitate calculation. The centre of gravity is an estimated value based on the two students chosen to pilot the vessel and their assumed position during the trial. The centre of buoyancy as half the vertical distance of the submerged depth, depends on Equation 1, the weight of the students and material used to design the vessel, and the vessel dimensions.

IMPLEMENTATION

The semester is 15 weeks long with the Fluid Mechanics Laboratory generally beginning in the 3rd week after students have obtained some preliminary introduction to fluid properties and hydrostatic pressure. The concept of buoyancy is presented in the week 3 laboratory lecture and roughly coincides with the presentation in the regular Fluid Mechanics course lecture. Mandatory shop training must also be completed by week 3. The laboratory exercise, following the basic design process (Figure 1), and laboratory reports are discussed in the laboratory section when students are instructed to form their groups. The concept of stability is presented in the week 4 laboratory lecture. Students work with their group on their preliminary designs in the laboratory section in weeks 4 and 5. The professor meets with each group to discuss their sketches and inquire about any potential issues that may arise with respect to buoyancy/stability/constructability. Students are encouraged to develop a spreadsheet for buoyancy and stability, such that part dimensions/sizes and material property values can be manipulated to determine the effect on the vessel.

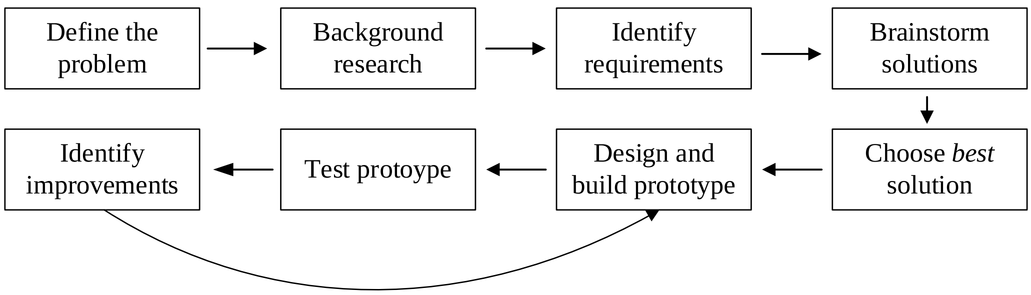

Figure 1: Schematic of the engineering design process.

Each group presents to the class in week 6 their chosen design, including initial buoyancy and stability calculations. Students in the class are encouraged to ask questions and the professor uses this presentation to provide final feedback and approval to continue (or requirement to modify) on the chosen design. A final CAD drawing and buoyancy and stability calculations are due in week 7. Students work with their groups in weeks 6 through 10 in the actual fabrication aspect of the project and the report. The professor is available during some laboratory sections to provide feedback and answer questions from the groups. Students often realise during the design process that their fabrication approach was not feasible or the material choice was too difficult to work with. These modifications are part of the learning experience and generally arise from communication aspects within the team. Thus, they are deemed appropriate so long as students document the changes in their final report.

Students continue to work on their vessel and report in weeks 12 and 13 and are encouraged to personalise the vessel by developing a team theme and adding artistic touches. The vessels are tested in week 14 in the university dive well. Vessel travel across the well and back is timed and notes on the vessel buoyancy and stability are recorded. Groups are allowed to test their vessel more than once after each group has had an initial trial. Students work in their groups in week 15 to finalise their reports and determine potential design flaws, remedies and how their vessel buoyancy and stability compared to theory. A wrap up discussion with winners identified occurs in the laboratory lecture of week 15.

Student designs vary widely in concept and construction (see Figure 2). Some student teams choose to select the most basic vessel as a large barge shaped object that, provided is large enough, is guaranteed to be stable. Other teams have focused on novel designs of the vessel and/or the propulsion mechanism even though propulsion is not part of the specified learning outcomes. Regardless of design, vessels sometimes have difficulty in buoyancy, stability or both (e.g. Figure 2F, 2G and 2H); where a failed vessel provides numerous learning opportunities as part of the design process.

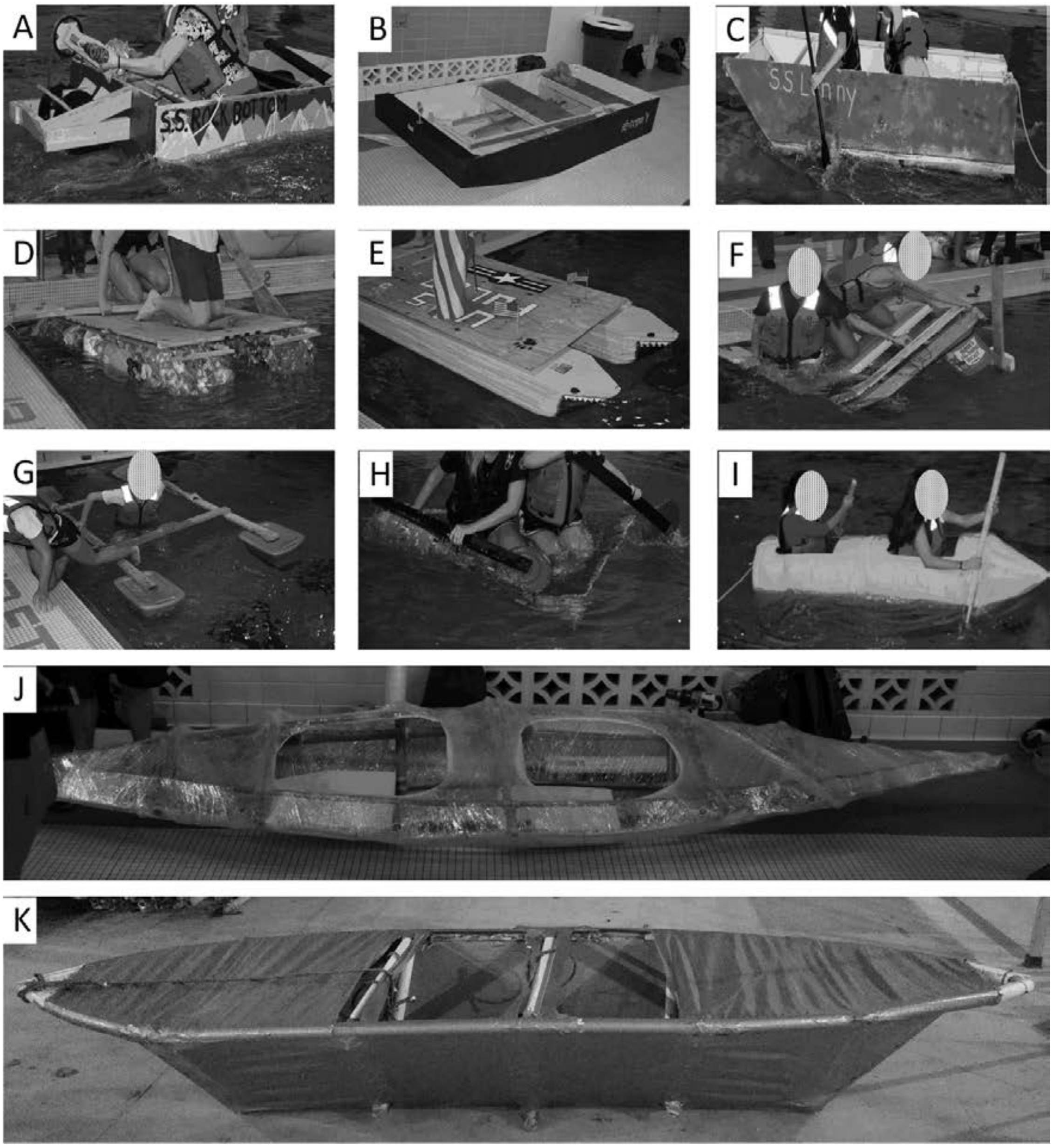

Figure 2: Example VP designs: 2A-2C) barge or jon boat style vessels; 2D-2E) pontoon style vessels using plastic bottles, foam or sealed buckets; 2G-2I) alternative vessel styles using different materials or shapes; and 2J-2K) two of the most unique vessels to date: kayak shaped vessels with bamboo structural elements and plastic wrap skin or with PVC structural elements and duct tape skin.

RESULTS AND DISCUSSION

The design-based laboratory approach was assessed through a post-course student survey in 2019. Students were asked a variety of questions (Table 1) related to the course design, material delivery and course expectations. Responses for questions 1 through 9 were on a scale from: strongly agree - 1 to strongly disagree - 5.

The high scores to questions 1 and 2 (mean, M, 4.41-4.43 and standard deviation, SD, 0.67-0.69) and low score to question 3 (M = 1.68; SD = 0.58) indicate the laboratory course was effective at reinforcing the concepts of buoyancy and stability learned in the classroom. Questions 4 and 5 were related to communication, a skill often cited by constituents, where undergraduate engineering students need improvement. The low scores (Table 1) reflect that the design-based laboratory is also effective at enhancing these skills.

Questions 6-8 were related to the logistics of design/build process. Students overwhelmingly indicated an enjoyment of the process, where they were able to actually build a tangible object and test it. Yet, there was a lack of enthusiasm to refine designs and re-test after the initial trials. Many students were comfortable with the actual build aspect of the laboratory project. However, 14 of the 79 students surveyed indicated some level of apprehension. Students were required to undertake an on-line shop training course, and the course instructor was often available to assist students and provide small group equipment training. But, the lack of hands-on training for the entire class is an area for improvement for future iterations of the course; where a training effort at the beginning of the semester is warranted.

Questions 9-10 were related to the course design and workload. Students overwhelmingly preferred the design/build concept for the course relative to a traditional Fluid Mechanics Laboratory course using multiple apparatuses, where the exercises are more prescribed. In addition, 75 of the 79 respondents indicated the workload for the 1-credit course was about right.

Students were asked two additional questions (example responses provided in Table 2): 11) In your opinion, what is the most positive aspect of the Fluid Mechanics Laboratory course? and 12) What is one thing you would improve for the Fluid Mechanics Laboratory course? There was considerable overlap in the responses with only examples provided. For example, many students appreciated the ability to be creative and not constrained by specific criteria. However, some students did request more guidance with check points along the way. These and other aspects, such as improved shop hours and introduction to shop tool usage can be addressed easily in future iterations of the course.

Table 1: Survey questions and response values.

Survey statement/question	1	2	3	4	5	M	SD
1) The Fluid Mechanics Laboratory course was NOT sufficient in helping me understand the concepts of buoyancy.	0	2	2	36	39	4.41	0.67
2) The Fluid Mechanics Laboratory course was NOT sufficient in helping me understand the concepts of stability.	0	2	3	33	41	4.43	0.69
3) The Fluid Mechanics Laboratory course helped reinforce concepts learned in the Fluid Mechanics lecture.	29	47	2	1	0	1.68	0.58
4) The Fluid Mechanics Laboratory course enhanced my ability to work in a team setting.	24	36	14	5	0	2.00	0.86
5) The Fluid Mechanics Laboratory course enhanced my ability to communicate with other students on a group design project.	26	40	10	3	0	1.87	0.77
6) I was uncomfortable with the build aspect of the laboratory (using power tools, adhesives, etc).	4	10	7	35	23	3.80	1.14
7) I enjoyed being able to design something with few constraints and then being able to test it.	56	22	0	1	0	1.31	0.54
8) I would prefer if my group had the opportunity to refine the design after initial testing and test again a short time (e.g. 2 weeks) later.	7	25	17	27	3	2.92	1.08
9) I would prefer to have a more traditional Fluid Mechanics Laboratory course, where I work on several different apparatuses through the semester.	3	1	5	21	49	4.41	0.96
10) The workload for this one credit Fluid Mechanics Laboratory course is excessive*.	2	75	2	N/A	N/A	2.00	0.22

* Scale for this question is: excessive - 1; about right - 2; too little - 3

Table 2: Example written responses for questions 11 and 12.

11) In your opinion, what is the most positive aspect of the Fluid Mechanics Laboratory course?	12) What is one thing you would improve for the Fluid Mechanics Laboratory course?
Working together as a group to build something we designed on paper. *Coming together at the end to test everyone's boats.* *It actually felt like I accomplished something.* *I liked how free it was to try something different/unique. Big fan of the few constraints and ability to be creative.* *Working as a team.* *Hands-on experience with designing and creating as well as working in a group.*	*More checkpoints along the way for the boat building.* *Add a time to test vessel before final test.* *Have mandatory team meeting times.* *Brief class presentation on how some tools are used.* *Have a little more in the written instructions.* *More flexible workshop hours* *More instruction/guidance.*

CONCLUSIONS

A design-based Fluid Mechanics Laboratory course was created to enhance communication skills, and hands-on student experiences with an open-ended exercise on buoyancy and stability. Students were tasked with a Vessel Project to design/construct an apparatus that could transport two team members across the university dive pool and back. The project required students to quantify buoyancy characteristics of the apparatus, including submerged depth (draft), estimate stability, develop a build plan, construct and test the apparatus, and write a final report detailing the process including potential improvements to their design.

Students overwhelmingly enjoyed the course as compared to a traditional Fluid Mechanics Laboratory course involving more prescribed (formulaic) testing on various devices. Students also commented on the positive experience working in a group and being able to express creativity in their apparatus design. Some expressed apprehension with the build process, including use of shop tools even after taking an on-line shop training course. Students had four to five weeks for the actual build process. Yet, many groups rushed to finish their build in the last week before testing. Some students expressed a desire to have intermittent checkpoints during the build process to alleviate some of the last-minute aspect of the build.

A more detailed build checklist with milestones will be incorporated in future iterations of the course. Additionally, one laboratory lecture will be devoted to hands-on practice with shop tools.

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BIOGRAPHY

Jack A. Puleo received the BS degree in oceanography from Humboldt State University (Arcata, CA, USA) in 1996, the MSc degree in oceanography from Oregon State University (Corvallis, OR, USA) 1998, and the PhD degree in coastal engineering from the University of Florida (Gainesville, FL, USA) in 2004. From 1998 to 2004, he worked as a research oceanographer with the Naval Research Laboratory, Washington, DC, USA. He was Assistant Professor, Associate Professor and now a Professor and Associate Chair in the Department of Civil and Environmental Engineering at the University of Delaware, Newark, DE, USA (2004 - present). He is also the Director of the Centre for Applied Coastal Research and an Associate Editor for the Journal of Waterway, Port, Coastal, and Ocean Engineering.