Bridging the Gap between Theory and Practice through Capstone Design

Section I: Project Description

The culminating design experience for Civil Engineering (CE) undergraduates at our university was once realized through a course entitled Senior Project. Individual students or multi-student teams would work independently (outside the traditional classroom setting), with periodic guidance from a faculty advisor of their choosing. This system worked well during the first several years of our program's existence. However, by 2005, our graduating senior class numbered well over 100 students. Small issues that had always been associated with the Senior Project course had grown into full-fledged problems that required immediate attention. Specifically:

- It had become difficult for faculty and students to come up with novel projects.
- Projects often involved only one or two of the traditional civil engineering subdisciplines (environmental, geotechnical, structural, transportation, and water resources engineering).
- Projects often focused more on analysis than design.
- The technical work undertaken often failed to adequately account for the many non-technical issues that control the direction of real-world design.
- Several faculty members were spending a great deal of time on senior project advising, which was keeping them out of the classroom and limiting their ability to pursue other professional development activities.
- Project report and assessment standards varied considerably from one faculty member to another.
- Senior Project grades were, on average, much higher than those awarded in the department's traditional (directed study) lecture/lab-type courses.
- Students frequently failed to complete their projects by the end of their final term in residence, which delayed their degree conferral dates and affected their eligibility to sit for the Professional Engineer licensing exams.

In 2006, a new Senior Design sequence was implemented to correct the deficiencies and problems noted above and provide a more valuable learning experience for the students. Course content was selected to ensure that each senior had an opportunity to (1) acquire a variety of professional skills that are used on a daily basis by civil engineering designers, (2) participate, as a member of a multidisciplinary team, in a major culminating design experience, and (3) demonstrate minimum proficiency in geotechnical, structural, transportation, and water resources engineering.

The new course includes seminar-style presentations on such professional issues as communication styles, assertiveness and interpersonal communication, team building, professional licensure, professional ethics, qualifications-based selection, project management and delegation, environmental compliance and permitting, sustainability, professional liability insurance, risk management, contracts, project advocacy, and avoiding litigation. The course also provides formal instruction in most of the knowledge areas that typically appear in the morning (breadth) session of the NCEES Principles and Practice of Engineering Exam. These technical modules focus on such quantitative considerations as bearing capacity of shallow foundations, axial capacity of deep foundations, consolidation settlement, reinforced concrete spread footing design, reinforced concrete stem wall design, masonry design, timber design, seismic analysis and design, geometric highway design, pavement design, storm water collection and management, culvert design, closed channel flow, and pumps.

The primary outside-of-class activity focuses on a specific private development project or multidisciplinary infrastructure project that would benefit one of the local communities. The project is selected before the course begins, with assistance from local consulting engineers and public works personnel. The project must be broad-based, and an adequate set of field data must be available. During the first term, the students prepare a written Statement of Qualifications (SOQ) in response to a specific Request for Qualifications (RFQ). During the second term, the students progress to the design phase and prepare a written Design Report that includes a full set of technical calculations and design drawings. Each term, the students must also present their ideas orally, during a formal 50-minute interview, to a panel consisting of both faculty and senior-level practitioners (all of whom are licensed Professional Engineers).

Because all work (except for exams) is done as a member of a multidisciplinary team, considerable thought is given to selecting team rosters. The students complete a survey at the first class meeting that defines (1) their academic coursework, (2) their industrial experience, (3) their experience and familiarity with computer-aided design (CAD) software, (4) their status with respect to Engineer-In-Training (EIT) certification, and (5) their current grade point average (GPA). The Course Coordinator uses this information to subdivide the class into 6-person teams, ensuring that each team has a comparable degree of technical breadth and depth, practical experience, professional preparation, and ability (as measured by CAD proficiency and GPA). A class of 180 students would therefore translate into 30 six-person design teams. Each member of a given team is assigned a specific role (geotechnical specialist, structural specialist, etc.) that is in keeping with his/her elective coursework and industrial experience.

The new capstone design course has been offered four times to date. The four projects involved: the design of a commercial office complex with associated parking and municipal roadway improvements (in 2006); the design of a two-lane emergency access bridge over a protected creek for a local municipality (in 2007); the design of a residential housing development with associated municipal drainage and roadway improvements (in 2008); and the design of a high school football stadium, track, and parking lot with associated roundabout improvement (in 2009).

The 2008 Senior Design project involved the design of a high-density, multi-family residential development for a local municipality in dire need of additional low- to medium-income housing. The design activities were complicated by aesthetic considerations (since this is an infill project, and any new development must have a minimal impact on existing vistas and be consistent with the City's vision, as laid out in its various planning documents) as well as environmental issues (since the 6.5 acre site includes steep slopes, protected vegetation, and a seasonal creek that drains into a major regional river). Each student team was required to create a specific design proposal that, at a minimum, addressed each of the issues enumerated below:

General:

- Site design including an improvement plan showing the location of all dwellings, retaining walls, roads, parking areas, and key drainage features.

Geotechnical / Structural:

- Foundation design for dwellings.
- Lateral support system or retaining wall design (critical section only).
- Material and compaction specifications for all fill and pavement sections.
- Structural design for the vertical and lateral load resisting systems.

Transportation / Traffic:

- Geometric alignment of all intra-parcel roads.
- Pavement cross-section design for roads and parking areas.
- Striping plan and recommended signage.
- Recommendations for improvements to Streets A, B, and/or C that are consistent with both the Circulation Element of the General Plan and the Traffic Impact Analysis performed for this development.

Utilities / Water Resources:

- Recommendations for preventing surface erosion.
- Recommendations for maintaining the quality of storm water discharge.
- Intra-parcel storm water management system design and detailing.
- Storm drain design to verify the adequacy of an existing culvert.

Other:

- Environmental compliance and permitting.
- Project advocacy in the context of community review.

Each student team was provided with an identical set of data including architectural drawings, local and regional geologic information, a site-specific soils engineering report, traffic studies, rainfall intensity-duration-frequency curves, streamflow data, and AutoCAD files defining the site topography and the location of all existing utilities. All design solutions were required to conform to all applicable local codes and standards.

Each student team was required to present their design recommendations in a comprehensive written report and a 20-minute PowerPoint-based presentation (which was followed by a 20-minute question and answer session and a 10-minute debriefing). The written report included a summary of the proposed design, supported by high quality engineering drawings and a series of appendices containing well-organized and well-documented engineering calculations. The report also included a discussion of the team's overall approach to completing the work, recommendations for conducting the required public review, and suggestions for how best to obtain all necessary approvals and permits.

Section II: Collaboration of Faculty, Students, and Professional Engineers

Delivery occurs via a two meeting per week lecture-lab format that is valued at 3 quarter units per term (or 6 quarter units for the two-term sequence). Non-technical topics are discussed in a 110-minute Tuesday evening lecture session, and technical topics are presented in a 170-minute Thursday evening design lab. The first half of the design lab is devoted to a review of the evening's analysis/design packet, and the last half of the lab session is spent on team-based solving of a formal quantitative assignment.

The non-technical seminars are held in a room that is large enough to accommodate the entire class. However, the design labs are held in four separate sections to promote closer instructor-student interaction during the associated activities. On any given Thursday evening, one-quarter of the class will be dealing with geotechnics, one-quarter of the class will be focusing on structures, one-quarter of the class will be studying highway/pavement design, and one-quarter of the class will be working with water resources. Each week, the lab instructors rotate between homerooms, so that every student receives identical instruction by the time a particular four-week rotation ends.

The instructional team consists of 3-4 faculty and 24-30 senior-level practitioners. **All members of the instructional team are licensed or appropriately certified.** Each member of the instructional team has one or more of the following roles:

> **Course Coordinator** (1). The Course Coordinator is solely responsible for the content and administration of the course. He or she is responsible for moderating the Tuesday evening seminars and ruling on all requests for special consideration with respect to any administrative matter (including absences from class, due dates of assignments, date and time of exams, grades, etc).
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> **Section Instructors** (4-6). The Section Instructors are responsible for leading the Thursday evening technical breakout sessions. A particular Section Instructor or Instructional Team will appear once in each section during each scheduled 4-week rotation. The Section Instructors are professors or practitioners with technical expertise in each of the following four discipline areas: (1) geotechnical analysis and foundation design, (2) structural analysis and design, (3) traffic/transportation engineering and highway/pavement design, and (4) water resources and water supply/distribution.
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> **Guest Speakers** (12~16). Each Guest Speaker is responsible for preparing and delivering one of the Tuesday evening non-technical seminars. The Guest Speakers are senior-level practitioners who are well versed in the topic to be discussed, and who can select cases from their own personal experience to support the theoretical aspects of the seminar. For example, a past presenter of the "Leadership and Motivation" seminar is Chairman of the Board of a highly respected consulting firm and a Past President of the American Society of Civil Engineers (ASCE). The person who delivers the "Professional Ethics" seminar has been honored with the Engineer of the Year Award from a State Society affiliated with the National Society of Professional Engineers (NSPE).
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> **Project Advisors** (2). The Project Advisors hold senior-level positions within the consulting firm or public works department that is sponsoring the SOQ/Design Project. These individuals are extremely familiar with the nuances of the specific project being undertaken by the students, and they serve as the primary off-campus contacts for project-related questions.

Interview Panel Members (12). The Interview Panel Members are responsible for reviewing the student-authored written SOQs and Design Reports and evaluating those same student teams during two 50-minute interviews (one each term). Interviews simultaneously take place in four separate venues, with each panel consisting of one tenured/tenure-track faculty, one senior-level consulting engineer, and one senior-level practitioner from a local public works agency.

In 2008, the instructional team consisted of four faculty and 27 senior-level practitioners, making this a true faculty-industry collaboration. The course ran smoothly because of its very well-defined organizational structure and a universally enthusiastic team.

Section III: Benefit to the Health, Safety, and Welfare of the Public

Fundamental Canon 1 of the ASCE Code of Ethics (2006) states that, "Engineers shall hold paramount the safety, health, and welfare of the public and shall strive to comply with the principles of sustainable development in the performance of their professional duties." In practice, Fundamental Canon 1 is satisfied, in part: through the application of appropriate engineering judgments and practices (Guideline 1a); through the preparation and/or approval of design documents that are determined to be safe for public health and welfare, and in conformity with accepted engineering standards (Guideline 1b); by being of constructive service to the community (Guideline 1e); and by protecting and improving the environment (Guideline 1f). All course outcomes and activities are designed to foster learning in one or more of these areas.

Section IV: Impact on Raising Social Consciousness

Civil Engineering is truly a people-serving profession, so the primary outside-of-class activity focuses on a specific private development or infrastructure project that would benefit one of the local communities. This requires the students to familiarize themselves not just with the applicable engineering codes and standards but also with the various planning documents that lay out the municipality's vision for the future. Student SOQs and Design Reports are expected to address issues such as environmental compliance/permitting and project advocacy in the context of community review, and many of the questions posed during the 50-minute interviews are designed to reveal the students' appreciation for these issues. Indeed, the course is designed to address a specific program outcome that requires graduates to demonstrate an ability to develop community consensus building techniques for a civil engineering design project.

Section V: Impact of Partnering Teaching and Professional Practice and Section VI: Multidiscipline and/or Allied Profession Participation

With an instructional team that consists of 3-4 faculty and 24-30 practitioners, the course is a true faculty-industry collaboration. The practitioners bring with them years of experience in numerous areas, including engineering, land surveying, construction, environmental science, business, and law. Overall, the ability of the multidisciplinary instructional team to work together to achieve course outcomes sets a terrific example for the students. Those who participate on the instructional team genuinely enjoy the experience of working with the students and collaborating with other professionals. In the eyes of many of the students enrolled, the enthusiastic involvement of so many design professionals as section instructors, speakers, project advisors, and interview panel members is what validates the course and makes it such a great bridge between theory and practice. To be sure, a course of this breadth and degree of realism simply would not be possible without the participation of our practitioner partners.

Section VII: Knowledge or Skills Gained

Over 600 civil engineering majors have completed the new Senior Design sequence during the past four years. The new lecture-lab format has corrected the two most nagging administrative issues associated with the old individual study format: project completion and project grade. The use of a structured delivery mode – with common activities, assignments, and assessment standards – has so far led to completion rates of 100% and has brought the average grade awarded in the capstone course back in line with the Department average for its senior-level electives.

The Senior Design course incorporates many opportunities for assessing student learning at an especially critical point (just prior to graduation) using a consistent methodology. Quantitative analysis/design assignments, qualitative reflection exercises, written project reports, oral project presentations, exam problems, and student/evaluator surveys are used to assess student learning relative to more than 40 program-specific technical and non-technical performance metrics and outcomes, including most of the professional skills embedded in the ABET criteria (general and program specific). These criteria state, among other things, that graduates: understand professional and ethical responsibility; be able to explain concepts in business, management, leadership, and public policy; and be able to explain the importance of professional licensure (all of which are covered in some detail during the Tuesday evening seminars). Scoring rubrics and multiple reviewers are used whenever possible to assess student work. Metric goals are used to define acceptable levels of student achievement. A unique and important aspect of the Senior Design course is that engineering professionals (from outside the program) now assess the abilities of all of our graduates relative to numerous technical and non-technical outcomes.

The Senior Design course is especially well suited for the assessment of student design skills. Each year, four different reviewers (using detailed rubrics) grade the written SOQ and Design Reports. Average Design Report scores for the past four years are shown in Table 1. Average scores in all categories exceeded our metric goal of 70%, indicating that the students have acceptable design skills. However, the students' understanding of codes and standards (Category 1) and the students' ability to prepare engineering drawings (Category 3) suggest that there is room for improvement in these areas. Indeed, lower scores for these areas were confirmed through post-course surveys completed by the interview panel members, as well as through data collected in other courses. These assessment results have inspired program improvements in these subject areas (including a complete revamping the freshman-level CAD offerings).

Valuable assessment data have also been collected with respect to our students' written and verbal communication skills, technical prowess in the different civil engineering emphasis areas, and problem solving abilities. However, a complete discussion of our Senior Design assessment results is beyond the scope of this brief project summary.

Table 1: Average Written Design Report Scores by Category

Category Description	Assessment Scores (as a %)			
	2006	2007	2008	2009
Project Understanding and Interpretation of Applicable Codes and Standards	73	76	80	79
Design Approach	78	76	77	79
Design Summary and Engineering Drawings	80	75	73	75
Design Calculations	82	85	82	85
Presentation and Overall Impact	75	77	74	78

Most of our recent graduates have not yet qualified (by virtue of insufficient post-baccalaureate design experience) to sit for the Professional Engineer licensing exam, so it's not yet possible to measure the effect this course has had on pass rate. However, test results provided by NCEES show that annual pass rates for the FE exam have steadily increased since 2006. In addition, surveys of our graduating senior class conducted during the past four years reveal that about 95% of our students earn their EIT/FE Certificate prior to graduation (even though such certification is not a degree requirement). At the very least, the new course has led to an increased awareness of the importance of professional licensure and an increased desire to seek it. Indeed, a baseline survey conducted as part of the 2009 Senior Design course revealed that 90% of this year's graduating senior class (145 of 160 students) intended to earn a PE license. All evidence indicates that the new course has fostered learning and enabled our graduates to be better prepared for the practice of Civil Engineering. On this basis, it may be concluded that the course has been an overwhelming success.

Section VIII: Viability of Technology Used

The capstone design sequence described in this paper has enabled the Civil Engineering Department at our university to meet a variety of program-level goals, including (1) ensuring that each senior has a similar culminating design experience, (2) ensuring that each senior actually completes his/her final design report prior to leaving campus, and (3) ensuring that each senior's work will be evaluated using a single assessment standard. The course sequence also appears to satisfy a number of ABET-mandated program requirements by ensuring that each senior has an opportunity to (1) acquire a variety of professional skills that are used on a daily basis by civil engineering designers, (2) participate, as a member of a multidisciplinary team, in a major culminating design experience, and (3) demonstrate minimum proficiency in geotechnical, structural, transportation, and water resources engineering.

Physical facility requirements include one large lecture hall for the non-technical seminars and four medium-sized classrooms for the technical breakout sessions. The number of students that can be accommodated in any particular term depends almost entirely on the availability of appropriately sized classrooms. Hence, the capstone design model described herein could be used by virtually any degree program or institution, regardless of size.