An Integrated Approach to Teaching Engineering Design and Design Decision-making

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Abstract

An extensive case study to facilitate design instruction at the U.S. Naval Academy is described. "Restoration of a Coral Reef" is a semester-long engineering design experience involving five related exercises. These exercises provide a useful context in which discuss and apply various design tools and methods used in different phases of the engineering design process -- from problem assessment through project planning and construction cost estimating. Students also have opportunity to experience design-team interactions and develop communication skills associated with the design report.

Introduction

At the U.S. Naval Academy, ocean engineering students gain understanding of the design process and are introduced to many tools of the design engineer in the introductory design course, EN461: Ocean Systems Engineering Design (OSED) I. Classroom instruction covers the basic principles used to design beams and columns of structural concrete, steel and timber. Fundamentals of computer-aided drafting, construction cost estimating, engineering economics, hydrographic surveying and project planning are also introduced. The principle course goal is to provide opportunity for students to gain sufficient knowledge to apply effectively the methods and tools of the design engineer to accomplish a capstone design project in the follow-on course, EN462: OSED II.

Given the breath of topical coverage, EN461 instructors are challenged to present the material in a way that integrates, rather than segregates, the various design topics. An effective avenue for design methods and tools integration was identified in recent documentation of two coral reef restoration projects accomplished in the Florida Keys.[1-3]

In 1989, the oilfield supply vessel *M/V Alec Owen Maitland* ran aground upon a living coral reef within the Florida Keys National Marine Sanctuary. In an unrelated incident, during the same year, the *M/V Elpis* grounded on another reef in the same sanctuary. Physical damage to the reef substrate and impact on the local marine biota was severe at both sites. Natural ecological recovery was considered unlikely. Under its Damage Assessment and Restoration Program, NOAA recovered more than $3M from the responsible parties to offset costs of damage assessment and restoration of the affected areas. Subsequently, in 1995, each site was structurally restored by removing coral rubble, stabilizing the underlying reef structure, and recreating the original bathymetry with a structurally-sound foundation that would support natural-species colonization.[1]

Restoration efforts at the *Maitland* site were developed into an extensive case study that encompasses most phases of the design process. The case study begins with problem identification and assessment, extends through concept and preliminary design, and concludes with construction project planning and detailed cost estimating. The semester-long project is segmented into five related exercises that begin with a description of the damaged event. The name of the vessel and the site location are changed, and much of the pre- and post-damaged site bathymetries are retained but disguised so as not to hinder student creativity. Actual details of the restoration technique, schedule and costs are introduced in the later exercises to provide, as best possible, a real-world design experience. An overview of the exercises, the engineering design and decision-making requirements, and results of case-study implementation follow. Also, aspects of reef restoration at the *M/V Elpis* grounding site are presented as a future case-study alternative.

Case Study Introduction

During the fall semester (1998), fifteen four-person design teams participated in the coral reef restoration case study. As an introduction to the study, design teams were advised that:

“. . . during pre-commissioning trials in June 1998, the U.S. minesweeper M/S Ravage ran aground on a coral reef off the northwest coast of Bermuda. Both the grounding and attempts to free the vessel resulted in significant damage to the reef substrate and associate marine organisms . . . In anticipation of possible restoration efforts, Seabee divers from Underwater Construction Team One recently accomplished an underwater depth survey of the damaged site. Traditional taut-line vertical profiling and triangulation techniques from two theodolite stations on shore were used to accomplish the survey . . . ”

It was also noted that: *“The reported incident is fictional and any similarity with actual events may be coincidental.”*

Each design team was provided with hydrographic survey data and required to prepare contour lines of the post-damaged reef bathymetry. From a contour comparison of damaged and adjacent areas, a best estimate of the pre-damaged bathymetry was decided. The damaged extent was then characterized and presented in the format of a (land) surveyor’s report. The typical report included a minimum of three vertical profile sections and, using spreadsheet graphics, a three-dimensional plot of the pre- and post-damaged bathymetries. If the survey data was properly interpreted, design teams discovered that the damage area extended more than 5300 ft^2 (in plan) and totaled 250 yd^3. The maximum change in vertical relief was 2.5-3.0 feet. Submission of the surveyor’s report completed the first of five exercises.

Concept Generation and Assessment

Following a week of instruction in brainstorming techniques and design concept generation, the second exercise was introduced. Design teams were advised that British authorities were seeking an innovative solution for coral reef restoration. Two principal design goals of the client were to reduce further damage to adjacent reef areas, and to provide a structurally-sound foundation upon which local natural biota would attach and colonize. Other design criteria included aesthetic acceptability, construction feasibility, expediency in reef recovery, and total cost (both construction and long-term maintenance). These criteria were not necessarily of equal importance.

Each design team was tasked to identify a minimum of three alternative restoration concepts and submit a formal proposal for client consideration. These concepts might involve "off-the-shelf" components or be entirely innovative. Their proposal was to include a text description and detailed sketch of each concept, as applied to site conditions, and a discussion of concept advantages and disadvantages with respect to the client's criteria.

Design team proposals were evaluated for concept creativity and practicality, description of concepts, and overall format and content of the proposal. About 18-20 distinct restoration alternatives were proposed by the teams. Among the commercial concepts suggested were Fish Havens™ and Reef Balls™. More innovative concepts included bundles of concrete-filled PVC tubing and recycled tires. Another practical scheme called for placement of limestone quarry rock in the depression and filling the voids with concrete mortar. One design team suggested a "concrete block unit" very similar in form and concept to that used at the *Maitland* restoration site.

Acting on behalf of the British authorities, the course instructors selected eight of the proposed alternatives for further evaluation. The concrete block units, limestone quarry rock, PVC tubes, Fish Havens, Reef Balls and Armorflex™ mat units were selected both for reasons of practicality and technical feasibility. The recycled tires and a compacted "auto-bus" alternative were included because of their uniqueness.

During the concept generation and proposal development exercise, students were learning how best to make design decisions under conditions of risk and uncertainty and with single and multiple objectives. Methods to decide the relative importance of different design criteria were discussed and many classroom examples involving design decisions were resolved using a decision-matrix technique.[4] Shortly afterwards, design teams were provided with brief descriptions and sketches of the eight selected concepts and an instructor-generated effectiveness matrix. The effectiveness matrix, shown in Table 1, reflects a qualified assessment of each concept with respect to eight attributes common to ecological restorations. These attributes were similar to those used in selecting the reef restoration alternative at the *M/V Maitland* grounding site. *(Please note that entries in the matrix have not been authenticated nor are they claimed to be accurate.)*

As a third case-study exercise, design teams were required to establish the relative importance of the eight attributes and, by using a decision matrix, complete a quantitative assessment of the eight competing concepts. Using independently-derived weighting factors for the attributes and utility scales for the instructors' assessments, thirteen of the fifteen design teams identified *Concrete Block Units (CBUs)* as the most favored alternative. One team favored *Reef Balls* and another, the *PVC Tubes*. In each of the latter cases, *Concrete Block Units* had the second highest overall effectiveness value. Without much deliberation, the "authorities" accepted the near-unanimous recommendation to use CBUs.

Table 1. Criteria Effectiveness Matrix

ALTERNATIVES	PERFORMANCE			
	Technical Feasibility	Collateral Injury	P/t Reduce Add'l Injury	Recovery Time [yrs]
ArmorFlex Units*	very good	moderate	mod-high	5 - 7
Concrete Block Units	very good	moderate	high	3 - 5
*Fish Havens**	good	mod-low	moderate	10 - 15
Limestone Q-Rock	good	mod-high	high	7 - 10
PVC Tubes (filled)	very good	mod-low	mod-high	5 - 7
Recycled Autobus	marginal	mod-high	low	> 20
Recycled Tires	fair	low	mod-low	15 - 20
*Reef Balls**	good	low	moderate	7 - 10

ALTERNATIVES	ACCEPTABILITY		COST	
	Aesthetics	Enhance State-of-Art	Construction [$ K]	Maintenance [$K/yr]
ArmorFlex Units*	very good	high	1500	100
Concrete Block Units	excellent	mod-high	1200	50
*Fish Havens**	acceptable	mod-high	1600	120
Limestone Q-Rock	good	moderate	800	30
PVC Tubes (filled)	good	high	1000	60
Recycled Autobus	poor	low	350	150
Recycled Tires	marginal	low	300	150
*Reef Balls**	very good	moderate	1800	120

*ArmorFlex, Fish Havens and Reef Balls are trademarks of ARMORTEC, Artificial Reefs Inc., and Reef Ball Development Group, Ltd., respectively.

Detailed Structural Design

For the fourth exercise, design teams were advised that their design contract had been extended. They were now tasked to prepare detailed structural designs of two uniquely-sized CBU's . . . a Low-relief unit measuring 18' by 12' in plan form, and a High-relief unit sized 12' by 8'. For hydraulic stability, both units were to weigh a minimum of 8 tons; however, to facilitate handling, neither was to exceed 10 tons. Live and dead load conditions were defined. Since our students had recently learned to design structural concrete beams using ultimate strength design (USD) methods, they were advised to design the CBUs as one-way slabs that can be designed and evaluated as beams. Design recommendations were presented in a design report that included a dimensioned drawing of each unit with required (longitudinal) reinforcement. Results of this exercise were interesting. Most design teams expressed more difficulty in load interpretation (i.e., structural mechanics) than in applying USD methods.

Project Planning and Construction Cost Estimating

As a final exercise, design teams were provided with a 36-task activity list which indicated precedence activities, task durations, and critical resources required by each task. Tasks included mobilization and demobilization (m&d) of critical equipment, material procurement, staged fabrication and placement of CBUs, acceptance inspection and site restoration. The critical resources were a cement plant for CBU fabrication; a shallow-draft barge and a deepdraft barge (with tugs) for offshore operations; a dive team(s) for underwater operations; and a scow, tug, and small craft for sea-to-shore transfer of material and personnel. Design teams also received a table of unit costs for m&d [$ per R/T], material procurement [$ per unit], and labor and equipment resources [$ per day while on site]. The construction tasks, durations and associated costs used in this exercise were similar to those experienced during *Maitland* site restoration.

The "authorities" required that each design team develop a feasible construction plan and cost estimate for completing the structural restoration using CBUs. This tasking was assigned under the guise of needing both a plan and cost estimate for funding authorization and to evaluate the bid price of competing construction contractors. Using CPM methods, design teams determined an early start schedule (and activity float) that was modified, as necessary, to avoid resource conflicts. Using the modified schedule, an estimate of construction cost was determined taking account of differing on-site costs depending whether a particular resource was in a working or stand-by status. The goal was to achieve a minimum cost schedule which would accomplish the structural restoration within a prescribed weather window of 90-days duration. As appropriate, design teams could recommend that standby resources be retired for economy or that duplicate resources be employed to shorten construction time. However, either option would necessarily incur additional m&d costs.

By taking advantage of activity float, all teams were able to identify a construction schedule that would avoid resource conflicts and complete the reef restoration within 88 days. Also, by using two dive teams, the time on site of one of two construction barges could be reduced, thereby minimizing construction cost. Depending on the specifics of each design team's activity schedule, cost estimates of construction varied from $1.5M to $1.7M. These estimates were reasonable considering modifications to the actual activities and the unit costs of the engineer's estimate developed for the *Maitland* site restoration.[2]

Conclusion

In summary, this coral reef restoration case study involved our students in various phases of the design process. The design methods and tools learned through classroom instruction were applied to a practical, real-world ocean engineering design and construction project. Many students expressed appreciation of the integrated nature of the coral reef restoration exercises, which they found both challenging and thought-provoking. For those seeking more information about the exercises, detailed descriptions and data appear in the companion reference.[5]

Also significant, our students learned of new technologies in the field of ecological restoration, a discipline of ever-increasing significance in an environmentally-conscious world. Just recently, participants at an international conference had opportunity to share and learn of new and innovative approaches to coral reef assessment and restoration.[6] Similarly, the instructors of our introductory design course, EN461, hope that this case study has enhanced understanding and sparked our students' interest in the management of coral reefs and other ecological systems.

Next year's case study will likely be based on the characteristics of the damage and restoration at the *M/V Elpis* grounding site. That damage can be characterized primarily by the formation of two adjacent craters. Restoration involved mechanical transfer of coral rubble back into the depressions, placement of lime rock boulders atop the rubble, and filling the voids with carbonate sand. This technique was not unlike one of the proposed student concepts. In place of the CBU design exercise, design teams may be tasked to prepare detailed designs of the steel anchor piling used to moor the construction barge. Details of the *Elpis* site restoration including costs and schedule can be found in many of the same *Maitland* references.[1, 2]

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Acknowledgments

The author wishes to express his appreciation to both Mr. Kevin R. Bodge of Olsen Associates, Inc., Ft. Lauderdale, FL, and Dr. Daniel J. Sheehy of Aquabio Inc., Arlington, MA, who so graciously shared of their real-world experience and documentation, without which this case study could not have been developed. LT Scott Finlayson, CEC, U.S. Navy, is recognized for his assistance in implementing the various case-study exercises within the ocean engineering design classes at U.S.N.A. Finally, the midshipmen of EN461 should be acknowledged for their perseverence and continued interest in coral reef restoration as the project evolved step-by-step throughout the semester.

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