Teaching Probabilistic Methods in Civil Engineering

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Abstract

All aspects of civil engineering, including planning, design, analysis, construction and maintenance require a basic understanding of randomness and statistical variability, uncertainty, and risk. Most civil engineering curricula offer a single course in probability and statistics. Often, such a course is not taught by a member of the (civil) engineering faculty, but is taught in the mathematics or statistics departments. Even if the course is taught by civil engineering faculty, it may not be taught using a text designed for a civil engineering (or even an engineering) course. These conditions serve to further isolate the course from the rest of the (coherent) curriculum. Without clear integration into the rest of their academic program, students often fail to see the purpose for such a course, and treat it as an isolated learning experience. The reasons for these conditions are discussed in this paper, and suggestions are made for effectively incorporating (integrating) these important concepts into the undergraduate civil engineering curriculum.

Introduction

Concepts of uncertainty, randomness, and risk are becoming increasingly relevant in the educational training of civil engineers. As engineers have been called upon more and more to make decisions, or provide the necessary information on which others can base decisions, in the face of limited or incomplete information, uncertainties in the engineering properties of materials and in the demands placed upon engineered systems, and design for natural and man-made hazards, training in the concepts of probability, statistics, risk, and reliability (in an engineering context) has become more critical. There is a trend toward placing civil engineering design on a probabilistic limit states basis. The last decade alone has seen the introduction of limit states codes (i.e. LRFD) for steel, wood, and highway bridges. Issues of condition assessment, life-cycle performance analysis, and service (operating) life extension also require that engineers have a solid understanding of the fundamentals of probability and reliability. Despite all of this, the treatment of these concepts in most civil engineering (CE) curricula is handled in a cursory and all too often isolated way. The reasons for this are explored in this paper, as well as suggestions for effectively incorporating (integrating) these important concepts into the undergraduate civil engineering curriculum.

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Statement of Need

It is instructive to examine the current treatment of probability and statistics in civil engineering curricula. While the following discussion does not apply to all programs, nor is it the intention of the author to generalize the "state" of undergraduate civil engineering education, these observations are based on his own experiences at a number of different universities, discussions with colleagues at many other schools, and the results of recently conducted surveys to identify how and when probabilistic concepts are being introduced.

Establishing the Importance

Events occurring in nature are inherently *uncertain*. These include structural and environmental loads as well as naturally occurring materials. Manufactured products, made of natural or man-made materials, exhibit varying degrees of *variability*. Statistical modeling and parameter estimation will be subject to uncertainty due to limited sample sizes and methods of data collection/measurement. An understanding of the sources and degrees of *uncertainty* and *variability* is needed in civil engineering design and planning. In particular, this is needed to effectively treat topics such as safety, redundancy, and risk.

Many civil engineering curricula do not adequately address uncertainty concepts, probability, statistical analysis, or their application to civil engineering problems. In many cases, owing to accreditation requirements (past and present), some treatment of statistics is included in the curriculum. Often, fundamental probability theory receives very little attention. More advanced topics such as risk analysis, design of experiments, and reliability are generally not covered at the undergraduate level.

Introducing the concepts early

The first question we must ask is *when* are we introducing probability theory and the basic concepts of statistical analysis, risk, and uncertainty in the curriculum? In many cases, this is sometime during the second or third year. There are advantages and disadvantages to both. In the second year, the concepts can be introduced early enough to become a 'fundamental' knowledge-base (toolbox) for upper level courses. However, the student at this point has had relatively little introduction to the areas of specialization within civil engineering.

The next question we must ask is *how* are these concepts being reinforced in later course? Are we effectively utilizing the skills and concepts in upper level technical electives? Is statistical analysis (estimation) required in lab reports? Are the concepts of safety and/or risk being incorporated into design projects?

The most critical questions, however, may be the following: Who is teaching the class (which department)? What is the title of the class? What text is being used? What is the background of the instructor? What types of problems are being solved / assigned? All of these directly affect the students' perception of the course, their level of interest, and ultimately their likelihood to learn and use the material. These issues will be discussed later.

Clearly, upon reflection on these questions, the following statement can be made: The concepts (tools) of probability and statistics should be introduced early AND should be reinforced throughout the curriculum.

Reinforcing the concepts: Continuity in the curriculum

This is often a significant flaw in the approach taken to introduce probability/statistics in the undergraduate engineering curriculum, in all fields. Departments have a tendency to "provide" the course in their program (often only to meet ABET or other requirements), but fail to "promote" the knowledge in subsequent classes. A class in this topic, as with any applied mathematical topic, must be thoughtfully, effectively, and convincingly incorporated into the overall program of study. Otherwise the course is perceived as "isolated" suggesting a lack of importance. This confuses the students and detracts from the effectiveness of the course.

Classes in the upperclass years should be targeted for including probability/statistics components. To the extent possible, these should include all areas of civil engineering, at all levels of instruction. Terminology and concepts should be the same throughout. Departments should take 'ownership' for the course, either *directly* by teaching the course themselves, or *indirectly* by overseeing the teaching of the (external) class to ensure the content is adequate and appropriate, and providing civil engineering problem sets to the (external) instructor. There are several highly regarded and widely used texts containing a large number of civil engineering problems (e.g., Ang and Tang, 1975; Benjamin and Cornell, 1970).

One possible schedule for introduction and integration of probability/statistics concepts into an undergraduate civil engineering program is shown below. It is emphasized that this is only one possible strategy that effectively accomplishes the desired objectives. There are obviously many others.

Freshman Year

Introduce fundamental concepts in introductory engineering course(s). These include sources of uncertainty and variability, basic statistical descriptors (mean, standard deviation), and histograms (frequency plots).

Sophomore Year

Re-introduce uncertainty/variability concepts in second-year engineering courses (Strength of Materials, Fluid Mechanics, Hydrology, CE Measurements, etc.) Introduce more advanced topics including: parameter and modeling uncertainty, material property variability, factors of safety, and basis for design values.

Junior/Senior Years

The following concepts can be covered in the technical elective classes: probabilistic bases for modern structural design codes, statistical methods in hydrology, incorporating uncertainty into project planning and scheduling, factors of safety in geotechnical engineering design, basis for load and resistance variables in load standards and materials standards, and concepts of risk analysis, relative risk, and risk-based decision making.

Some specific (fundamental) concepts

In this section, four examples of specific concepts, all of a fundamental nature, are described along with the significance for their inclusion in the undergraduate civil engineering curriculum. Where possible, suggestions are made for where these concepts should be introduced and how they might be presented in the context of specific courses.

1. Frequency Distributions (Probability Mass/Density Functions), Relative Uncertainty

This is perhaps the most basic probability concept. Most students have been introduced to the concept of a histogram and its construction from a set of data. It is relatively simple to move from a discrete graphical representation to a continuous one. Similarly, the concepts of probability mass and density are readily understood.

When introducing the concept of a frequency distribution, perhaps in a first-year “introductory engineering” course, the evaluation of actual probabilities should also be presented. For example, it can be shown that the probability that a random variable lies in some range can be found by simple integration of the density function. It is reasonable to suggest that this early presentation concentrate on the Normal (and perhaps the Lognormal) distribution. Other distributions which more accurately model specific random phenomena can then be introduced. Finally, the notion of relative uncertainty, as described by the degree of variability (or dispersion in the density function) should be presented. These very simple concepts form the basis for a greater understanding and treatment of uncertainty in engineering.

2. Percentiles, Basis of Design Values

As early as the first course in strength of materials, the concept of selection of design values should be presented. Students are faced with numerous tables, in both textbooks and handbooks, containing what they are told are the geometric and resistance properties of materials. For example, in the early mechanics course, students begin to gain a feel for the relative strengths of common structural materials. However, no indication is given as to the relative variability of these quantities, nor of the basis for the selection of these tabulated values. To leave them with the impression that these are simply “mean” (or even worse, deterministic) values is clearly inappropriate. The estimation of a “5th-percentile” strength value (or a “95th-percentile” load value) is a simple concept to present (see Fig. 1), building upon the concepts described above. (Again, the discussion is likely to be limited to one or two distribution forms at this point. A more thorough treatment of distributions should remain part of the existing course in probability and statistics.)

An understanding of the basis for the selection of tabulated design values will help students in their later studies of uncertainty, redundancy and safety. It will also serve to better prepare them for working with and understanding modern limit states design codes.

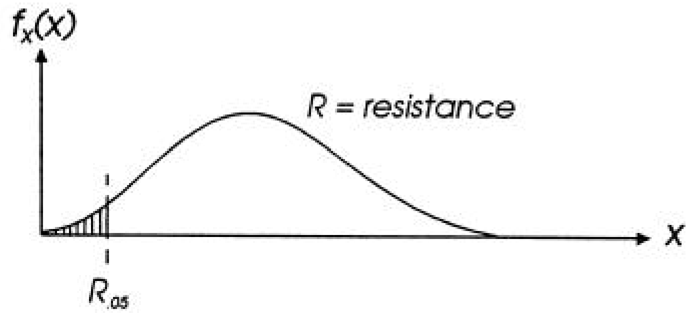

Figure 1. 5th-percentile resistance values

3. The Basic "R-S" Reliability Problem (Capacity-Demand)

Civil engineering design is almost always concerned with issues of capacity vs. demand. Clearly, for most applications, these quantities are both uncertain and therefore the *margin of safety* defined by $C - D$ (or $R - S$) is itself random (C = capacity, D = demand, R = resistance, S = load). Simple deterministic, or even mean-value methods are often misleading since they fail to account for the variability of C and D. When teaching design methods which are based on a capacity-demand analysis, it seems reasonable therefore to present these quantities as random variables. These types of problems are widely encountered in the design of structural, geotechnical, environmental and hydraulic systems. Using only basic concepts of probability density functions (i.e., Normal) and statistical independence, elementary concepts of reliability-based design may be presented (see Fig. 2). These concepts are gaining wide acceptance in the civil engineering design community, forming the basis for many modern-day codes and, to a lesser but growing extent, performance-based standards.

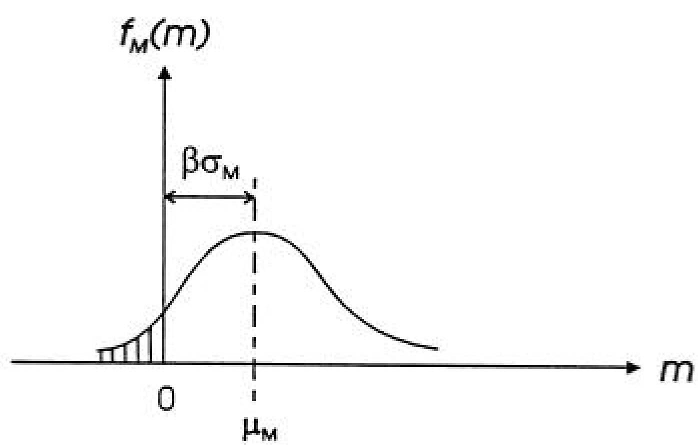

Figure 2. Basic *R-S* Reliability Problem, Safety Margin $M = R - S$

4. *Probabilistic Analysis of Civil Engineering Systems*

Civil engineers design civil engineering “systems”, whether they are structural, geotechnical, transportation, hydraulic, or otherwise. Fault trees and event trees represent pictorially the order in which events in a system can occur, and thus provides a schematic representation of system behavior (see Fig. 3). If the measure of performance for each sub-system or element can be described probabilistically (e.g., failure rate, probability of *x* fatalities given failure, etc.), then an estimate of system risk (probability of system “failure”) can be inferred from probabilistic analysis of the fault and event trees. This may be used as a decision-making tool to optimize performance/safety or to ensure compliance to performance criteria (or regulations). For example, it has been suggested that an appropriate “safety target” be 1×10^{-6} fatalities/year for failure of large dams. If element performance is assumed normally distributed, then probabilistic descriptions of system risk (including system risk variability) can be readily formulated using basic probability concepts. This will illustrate the essential ideas of probabilistic risk assessment and thus provide useful insights into risk management.

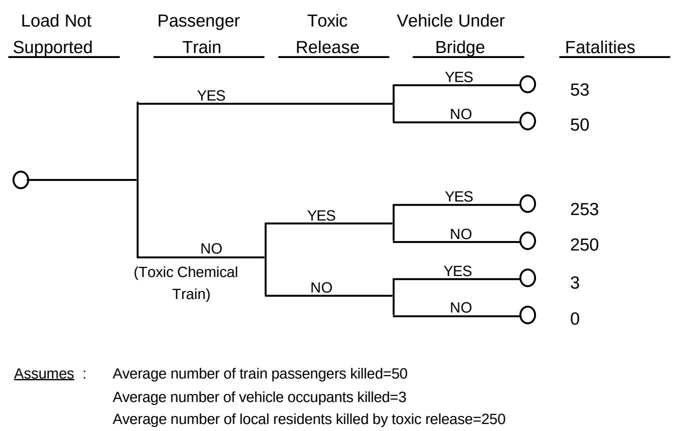

Figure 3. Event Tree for Consequences of Railway Bridge Collapse

ABET 2000

The first program criteria under ‘Section 2. Curriculum’ for Civil Engineering Programs is as follows:

> “Graduates of the program must demonstrate a proficiency in mathematics through differential equations, probability and statistics, calculus-based physics, and general chemistry.”

This is different from previous ABET requirements of a specific course on probability/statistics, and places the responsibility for defining “proficiency” in the hands of the individual department. For example, this might be accomplished by utilizing probability and statistics throughout the civil engineering curriculum, introducing the concepts early on, and without a specific course on the subject. This is not likely for reasons that will be discussed below. Rather, it is very likely most programs will continue to require a specific course. Thus, the pitfalls that were present under the old ABET requirements (isolated course, inappropriate course content, lack of engineering applications) will likely exist under the ABET 2000 system as well. However, ABET 2000 provides opportunities for departments to modify their curricula to take more direct responsibility for the treatment of these important topics. For example, if outside departments are unable or unwilling to modify the class to meet the ABET program criteria (as interpreted by the department), the opportunity now exists to move that class back into the civil engineering department.

First Decisions

The *choice of textbook* for a course in probability and statistics can be one of the most important decisions affecting the success (effectiveness) of the class. Many instructors choose one of the numerous available texts aimed more broadly at engineers and/or scientists. These books are unable to provide students with the range of civil engineering application problems that texts such as those by Ang/Tang or Benjamin/Cornell provide. The tendency when using a non-engineering (or non-CE) text is to focus more on generic types of problems and less on actual civil engineering topics. While some might argue that the "classical" texts by Ang/Tang and Benjamin/Cornell are no longer current (they were published in 1975 and 1970, respectively), the probability and statistics concepts have not changed and (more significantly) the presentation of a large number of CE applications renders these texts far superior for use in civil engineering departments. These texts address topics in all areas of civil engineering. Furthermore, with careful selection of problems, a course using one of these texts can be taught almost anywhere in the CE curriculum. Ideally such a course would be taught after the introductory civil engineering courses, perhaps in the junior year. However, curriculum restrictions may require that the course be offered as an "early" departmental requirement in the sophomore year. In either case, a text written by and for civil engineers with ample problems (both worked examples and problems for assignment) can be used effectively. It is unfortunate that more texts for civil engineers on this topic do not exist; however, the two "classical" texts and a small number of others that have been published recently are highly adequate and are far more suitable than books written for more general audiences.

The *instructor's background* also plays a critical role in the successful delivery of a probability and statistics course in civil engineering. The instructor should have (1) a solid background in applied probability and statistics, and (2) a broad-based training in civil engineering. The former ensures the instructor has the qualifications to teach the subject matter and to convey practical applications, while the latter ensures that the instructor understands the range of civil engineering applications to which the concepts may be applied.

The choice of *course title* can be important for (at least) two reasons. First, the correct title can help to effectively convey to the students the subject matter and its relevance to civil engineering. Second, if the course is being taught outside the department and the prospect of moving the course into the CE department raises "proprietary" issues (turf wars have been known to start over such well-meaning efforts), a change in course title can help "disguise" the department's intentions. In view of these points, course titles that are probably *not* effective include:

Probability and Statistics for Engineers

Statistics for Engineers and Scientists

Preferable alternatives might include:

Probabilistic Methods in Civil Engineering

Civil Engineering Systems

Finally, care must be taken to ensure that the *course is not isolated* in the CE curriculum. Moving the course into the civil engineering department (if it is not already taught there) is the first step. Decisions about the course title, its location in the curriculum, and choices of text and instructor are the next steps. However, the course will remain isolated (at least it will be perceived that way by the students) if it is not integrated with the rest of the CE curriculum. *The concepts must be reinforced in subsequent courses.*

Opportunities

While the challenges of developing, integrating, or improving a CE probability and statistics course are many, particularly if the class is currently being taught outside the department, there are significant opportunities. First, a well-designed and well-taught class in applied probability and statistical methods can be one of the most effective *cross-cutting courses* in a modern curriculum. Increased demands (restrictions) on curricula are being accompanied by an increased emphasis on an integrated curriculum and calls for multi-disciplinary approaches to teaching. This particular course has the potential to truly cross (CE) areas; this may well be one of the greatest selling points of such a class.

A well-developed course in probability and statistics in civil engineering can provide the necessary *background for advanced study* in topics such as risk analysis and design for natural hazards. Many departments are starting to offer these types of technical electives in the senior year (perhaps offered as dual-level courses). If the students do not have adequate preparation in the fundamental concepts of probability and statistics *and* their application to CE problems, instructors must devote valuable time from these specialized electives to the (re-)"introduction" of applied probability and statistics. A strong background in probability theory and statistical estimation is also important for advanced study in areas such as systems analysis, optimization, modeling, simulation, decision analysis, risk assessment, hazard analysis, and reliability.

References

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Benjamin, J.R. and Cornell, C.A. (1970), *Probability, Statistics, and Decision for Civil Engineers,* McGraw-Hill, New York.

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