Introduction

Civil infrastructure facilities are designed to withstand demands imposed by their service requirements and by natural environmental events. The normal design process usually results in a constructed facility with a degree of integrity that is also available to withstand challenges from unforeseen events. However, events outside the design envelope, including extreme storms or earthquakes, fires, accidents and malevolent attack, may cause severe damage or precipitate a catastrophic collapse. Changes in design and construction practices over the past several decades have made some modern structural systems vulnerable to such events. Social and political factors also have led to an increase in abnormal events that may pose a threat to civil infrastructure. Finally, public awareness of infrastructure performance and safety issues has increased markedly during the past thirty years as a result of well-publicized natural and man-made disasters. The prospect of improving practices to enhance facility robustness and to lessen the likelihood of unacceptable damage from low-probability, high-consequence threats now is receiving heightened interest among engineers and other design professionals.¹

Modeling of constructed facilities and enhancing their robustness through the design and construction process involves numerous uncertainties. These uncertainties give rise to risk, which must be managed in the public interest through both technical and non-technical means. Risk management of constructed facilities often involves difficult choices. Achieving reductions in risk for multiple hazards generally requires additional investment, which must be balanced against competing demands for finite resources and temporal constraints. Such issues must be communicated among the project stakeholders – the prospective owner, project developer, architect, engineer, contractor, occupants or tenants (if they can be identified at the project development phase) – and to the regulatory community and the public at large to achieve feasible and effective solutions. To determine the performance objectives for a project, competing risks must be measured and communicated to non-technically trained decision-makers in such a way that the full dimensions of risk can be understood and effective strategies can be implemented for its management. The performance of civil infrastructure during recent natural disasters has drawn attention to deficiencies in sociopolitical approaches to hazard management, but appears to have done little to change infrastructure performance expectations on the part of the public.²

¹ A special issue of the Journal of Performance of Constructed Facilities, ASCE, Vol. 20, No. 4, November 2006, is devoted to mitigating the potential for progressive (or disproportionate) structural collapse.
² A notable exception is in the seismic risk arena, where the surge in interest in performance-based earthquake engineering following the Northridge Earthquake of 1994 stems from the recognition that
Framework for risk assessment and engineering decision analysis

Risk can be thought of as involving three components: hazard, consequences, and context (Elms, 1992). The hazard is a threat or peril - earthquake, fire, terrorist attack - that has the potential for causing harm. In some instances, the hazardous event (or spectrum of such events) can be defined in terms of annual frequency. More often than not, however, it is necessary to envision a set of hazardous scenarios, without regard to their probability or frequency of occurrence (Garrick, et al, 2004). The occurrence of the hazard has consequences – damage to or collapse of the constructed facility, personal injury, direct and indirect economic losses, damage to the environment – which must be measured by an appropriate metric reflective of the decision-maker’s value system. Finally, there is the context – individuals or groups at risk and decision-makers concerned with managing risk may have different value systems and may take different views on how investments in risk reduction must be balanced against available resources.

Quantitative measures of risk are required to achieve ordinal rankings of decision preferences. A basic mathematical framework for risk assessment of a constructed facility is provided by the familiar theorem of total probability:

\[
P[\text{Loss} > \vartheta] = \sum_{H} \sum_{LS} \sum_{DS} P[\text{Loss} > \vartheta | DS] P[DS | LS] P[LS | H] P[H]
\]

The term \( P[H] \) = annual probability of occurrence of hazard \( H \) [for rare events, \( P[H] \) is numerically equivalent to the annual mean rate of occurrence, \( \lambda_H \), which is more easily estimated from the data maintained by public agencies]; \( P[LS | H] \) = conditional probability of a structural limit state (yielding, fracture, instability), given the occurrence of \( H \); \( P[DS | LS] \) = conditional probability of damage state \( DS \) (e.g., negligible, minor, moderate, major, severe) arising from structural damage, and \( P[\text{Loss} > \vartheta | D] \) = annual probability (mean frequency) of loss exceeding \( \vartheta \), given a particular damage state. If the hazard is defined in terms of a scenario (or set of scenarios), the risk assessment equation becomes,

\[
P[\text{Loss} > \vartheta | \text{Scenario}] = \sum_{LS} \sum_{DS} P[\text{Loss} > \vartheta | D] P[DS | LS] P[LS | \text{Scenario}]
\]

The parameter \( \vartheta \) is a loss metric: number of injuries or death, damage costs exceeding a fraction of overall replacement costs, loss of opportunity costs, etc, depending on the objectives of the assessment.

Equations (1) and (2) deconstruct the risk analysis into its major constituents and, as an added feature, along disciplinary lines. Reading these equations from right to left conveys the order in which the risk assessment and mitigation process should be approached. Engineering strategies seldom have an impact on \( \lambda_H \), which is affected by other means – changing the facility site or controlling access, installing protective barriers, proscribing hazardous substances, installing annunciators, etc. An analysis of the frequencies of competing hazards allows trivial hazards to be screened and appropriate risk mitigation strategies to be devised for those hazards that lead to unacceptable increases in building failure rates above the de
If the scenario approach is adopted because of a lack of data on hazard frequency, the loss (risk) estimate is conditional, and difficult to benchmark against competing risks associated with other hazards. Engineering design directly impacts the probabilities $P[LS|H]$, $P[DS|LS]$ and $P[LS|Scenario]$. Finally, the conditional probability, $P[Loss > \vartheta|D]$, is best determined by the building owner (or manager) and insurance underwriter, as it involves estimation of losses in revenue or business opportunity and the cost required to insure those losses. It should be emphasized that cost-effective risk mitigation strategies require appropriate attention to all terms in Equations (1) and (2) and thus a multi-disciplinary approach to risk mitigation.

Risk tolerance and communication

Assessment of $P[Loss > \vartheta]$ or $P[Loss > \vartheta|Scenario]$, once determined, and decisions regarding risk mitigation depend on the decision-maker’s view on the acceptability of risk and on whether/how investments in risk reduction should be balanced against available resources. Most individuals are risk-averse, while governments and large corporations tend to be more risk-neutral (Slovic, 2000; Faber and Stewart, 2003). Recent studies, summarized by Corotis (2003), have indicated that acceptance of risk is based more on its perception than on the actual probability of occurrence and that biases in perception, whether or not they are well-founded, shape decisions. Reid (2000) has suggested that individuals view risks as negligible if they are comparable to mortality risk from natural hazards (on the order $10^{-6}$/yr) and as unacceptable if comparable to mortality from disease (on the order $10^{-3}$/yr in the 30 to 40 age group). Although mortality statistics from disease and accidents are often used to benchmark risks (e.g., automobile traffic fatalities in the United States have been on the order of $2 \times 10^{-4}$/yr for many years), comparisons of annual frequencies from disparate events must consider differences in exposure, consequences and whether the risk is incurred voluntarily; attempts to correct for such effects are subjective. Consideration of acceptable risk in quantitative terms for civil infrastructure facilities, the construction of which often has been regulated by public codes, is a relatively new development (Ellingwood, 2001; 2007).

Risk communication requires a continuing dialogue among the members of the project team and other project stakeholders, aimed at facilitating understanding basic issues and enhancing the credibility and acceptance of the results of the risk assessment. A starting point is in understanding the significance of “low-probability, high-consequence events.” A criterion must be established to identify the (relatively small) subset of projects where the threat of such events is sufficient to warrant additional measures to provide robustness and general structural integrity. Although there currently is no agreement as to precisely what this criterion should be, one might expect that it would include size/extent of the facility, the nature of its anticipated use, and the potential impact of damage or a catastrophic failure on the surrounding community. The hazards and risks posed for such constructed facilities must be identified and analyzed, and those that are not dominant contributors should be screened out early in the design process. The screening process is difficult when the hazard cannot be quantified, alternative scenarios are considered, and Equation (2) is used as the basis for assessing and communicating the building risk. On the other hand, many of the decision-makers who control the resources available for risk mitigation find the scenario approach more understandable than a fully coupled risk analysis leading to a statement that “the design-basis event has an annual probability of 0.01%” (or, equivalently, a return period of

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4 The de minimis threshold defines the annual frequency below which societies normally do not impose any regulatory requirements for risk management. This level is thought to be on the order of $10^{-7}$ to $10^{-6}$/year (Pate-Cornell, 1994).
10,000 years). Finally, the facility performance objectives and loss metrics must be clearly identified and agreed upon, and uncertainty analysis should be a central part of the decision model. Tradeoffs that occur between investment and risk reduction must be treated candidly, and the entire decision process must be made as transparent as possible. All sources of uncertainty, from the hazard occurrence to the response of the structural system, must be considered, propagated through the risk analysis, and displayed clearly to obtain an accurate picture of the risk.

Closure

Professionalism requires an acknowledgement that proper engineering design involves looking beyond minimum code requirements. The project design team should take responsibility for documenting that steps have been taken to achieve a measure of robustness that is sufficient that the occurrence of hazardous natural or man-made events outside the design envelope will not lead to unacceptable damage or to human or economic losses. The technical feasibility and effectiveness of specific provisions depend on social attitudes and economic constraints, as well as specific design practices and construction technologies. The project team must acknowledge that uncertainty in achieving the project performance goals and objectives cannot be eliminated entirely; that risks presented by events outside the customary design envelope cannot be avoided; but that reduction in risk can be achieved through both technical and non-technical measures by additional investment in design and construction practices that enhance robustness of civil infrastructure systems.

References


