Risk Acceptance and Risk Communication

March 26-27, 2007
Stanford University
Stanford, California, USA

Workshop sponsors:

American Society of Civil Engineering's Engineering Mechanics Division
Joint Committee on Structural Safety
The John A. Blume Earthquake Engineering Center

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Workshop Program

Monday, March 26th
Tresidder Building, Oak East room

8:00 am	**Registration**
8:20 am	**Welcome, meeting purpose, and overview**, *Jack Baker*

Quantifying and communicating uncertainties (Moderator: Ton Vrouwenvelder)

8:40 am	Confidence and risk, *Stuart Reid*
9:00 am	Risk communication with generalized uncertainty and linguistics, *Ross Corotis*
9:20 am	Epistemic or aleatory? Does it matter? *Armen Der Kiureghian, Ove Ditlevsen*
9:40 am	Quantifying and communicating uncertainties in seismic risk assessment, *Bruce Ellingwood*
10:00 am	Discussion
10:15 am	**Break**

Risk acceptance for existing structures (Moderator: Bruce Ellingwood)

10:45 am	Target safety criteria for existing structures, *Dimitris Diamantidis, Paolo Bazzurro*
11:05 am	Efficient seismic risk assessment and retrofit prioritization model for transportation networks, *Renee Lee, Anne Kiremidjian*
11:25 am	Decision analysis for seismic retrofit of structures, *Ryan Williams, Paolo Gardoni, Joseph Bracci*
11:45 am	Discussion
12:00 pm	**Lunch**

Calibrating design codes and obtaining target risk levels (Moderator: Michael Faber)

1:20 pm	Structural safety requirements based on notional risks associated with current practice, *Peter Tanner, Angel Arteaga*
1:40 pm	Development of accidental collapse limit state criteria for offshore structures, *Torgeir Moan*
2:00 pm	Flood control and societal capacity to commit resources, *Niels Lind, Mahesh Pandey, Jatin Nathwani*
2:20 pm	Using risk as a basis for establishing tolerable performance: an approach for building regulation, *Brian Meacham*
2:40 pm	Calibration of safety factors for seismic stability of foundation grounds and surrounding slopes in nuclear power sites, *Yasuki Ohtori, Hiroshi Soraoka, Tomoyoshi Takeda*
3:00 pm	Discussion
3:15 pm	**Break**
3:45 pm	**Break-out session: risk acceptance success stories**
4:30 pm	**Close**
7:00 pm	**Dinner: Stanford Faculty Club**

Workshop Program — Tuesday, March 27th

Tresidder Building, Oak East Room

Advanced uncertainty modeling for risk calculations (Moderator: Ove Ditlevsen)

8:30 am	Assessing the seismic collapse risk of reinforced concrete frame structures, including effects of modeling uncertainties, *Abbie Liel, Curt Haselton, Gregory Deierlein, Jack Baker*
8:50 am	Risk acceptance in deteriorating structural systems, *Daniel Straub, Armen Der Kiureghian*
9:10 am	Failure consequences in flood engineering, *Ton Vrouwenvelder*
9:30 am	Acceptance Criteria for Components of Complex Systems using Hierarchical System Models, *K. Nishijima, Marc Maes, Jean Goyet, Michael Faber*
9:50 am	Discussion

10:10 am **Break**

Considerations beyond expected costs (Moderator: Ross Corotis)

10:40 am	Risk measures beyond expected cost for decision making in performance-based earthquake engineering, *Terje Haukaas*
11:00 am	Decision making subject to aversion of low frequency high consequences event, *Michael Faber, Matthias Schubert and Jack Baker*
11:20 am	Justification of risk-taking through reasoning, reasonableness and practicability, *Des Hartford*
11:40 am	Cost and benefit including life, limb and environmental damage measured in time units, *Ove Ditlevsen, Peter Friis-Hansen*
12:00 pm	Discussion

12:20 pm **Lunch**

Risk assessment and risk acceptance for complex systems (Moderator: Anne Kiremidjian)

2:00 pm	Risk assessment of dynamic urban infrastructures, *Leonardo Dueñas-Osorio*
2:20 pm	Probabilistic Comparison of Seismic Design Response Spectra, *Sei'ichiro Fukushima, Tsuyoshi Takada*
2:40 pm	Modeling demand surge, *Auguste Boissonnade*
3:00 pm	Risk-quantification of complex systems by matrix-based system reliability method, *Junho Song, Won Hee Kang*
3:20 pm	Discussion

3:40 pm **Break**

4:00 pm	**Break-out session: practical and research needs to promote risk-based tools**
5:00 pm	**Summary of break out sessions, consensus points, and future directions**

5:30 pm **Close, reception at Stanford Faculty Club**

Program Details

Venue

The workshop will be held at Stanford University, in Stanford, California. All workshop events will be held in the Tresidder Building's Oak East Room, with the exception of the banquet on March 26th and the reception on March 27th. Those two events will be held at the Stanford Faculty Club, across from the Tresidder Building.

Reception Details

Tickets for two drinks at the reception are included with your registration. Additional drink tickets can be purchased for $5 each at the reception.

Aim of the workshop

Engineering design requirements are created with the intention to implicitly or explicitly ensure that structures achieve an acceptable level of safety. Developments in performance-based engineering, structural reliability and decision theory have enabled researchers to better predict the reliability of designed structures, and to make design decisions based on the risks associated with failures. Fully utilizing these abilities requires that criteria for risk acceptability be known or identifiable, and that affected parties be able to understand these risks. This workshop is aimed at gathering experts in the field for the purpose of identifying state-of-the-art practices. At the conclusion of the workshop, a discussion will be held to identify points of consensus as well as issues requiring further consideration.

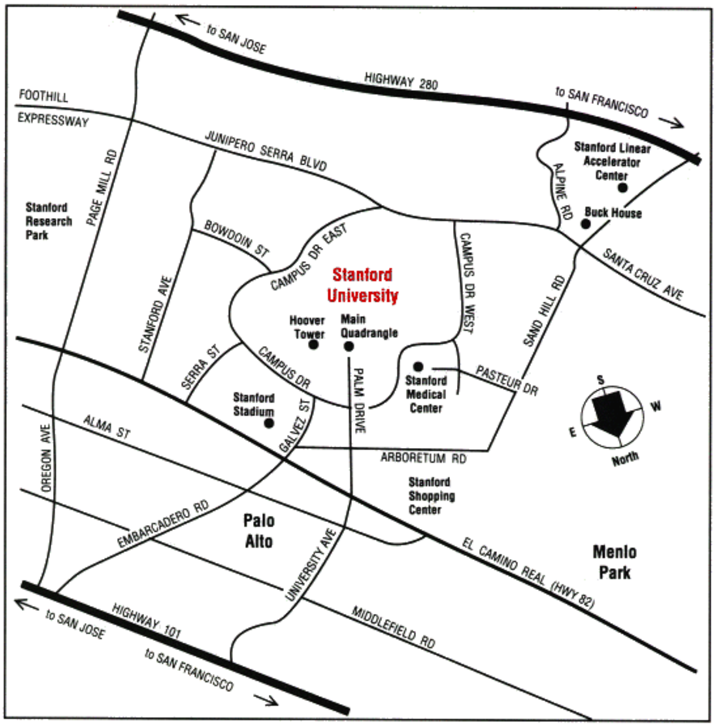
Workshop organizing committee:

Jack Baker, Stanford University, USA
Bruce Ellingwood, Georgia Institute of Technology, USA
Michael Faber, ETH Zurich, Switzerland

Technical committee

Ross Corotis, University of Colorado, USA
Armen Der Kiureghian, University of California, Berkeley, USA
Roger Ghanem, University of Southern California, USA
Anne Kiremidjian, Stanford University, USA
Marc Maes, University of Calgary, Canada
Peter May, University of Washington, USA
Torgeir Moan, Norwegian University of Science and Technology, Norway
Mahesh Pandey, University of Waterloo, Canada
Mark Stewart, University of Newcastle, Australia
Ton Vrouwenvelder, TNO Delft, Netherlands

Palo Alto/Stanford Area Map



A more detailed campus map will be provided in your registration packet.

Modeling demand surge

Auguste Boissonnade

Risk Management Solutions

Although there is a large body of literature on assessing the impact of catastrophic events, there is little available research quantifying and modeling the local impact of such events on the cost and length of reconstruction. Currently available econometric models such as Input-Output (IO) and Computable General Equilibrium (CGE) models have limitations. Also, very little research exists that quantifies the demand surge, defined as the sudden increase in the cost of repairs due to amplified payments, following a catastrophic event or a series of events. The demand surge is an important component of the overall economic impact of cat events and needs to be better understood.

The years 2004 and 2005 were a record-setting period for natural disasters with dramatic consequences in human lives and economic losses. The impacts of these catastrophic events have been felt and still are felt in some regions. During this period, econometric data including construction costs were collected in order to quantify the events' impact on the cost of reconstruction. This provided a basis for assessing the change in repair costs after these historical events, and for quantifying the demand surge (after removing the underlying baseline trends), at several dozens of locations across the affected areas. The results of this work were used to develop a relatively simple economic model, dependent on information available at the county level, which uses econometric metrics prior to the event as well as the losses following catastrophic events. This session will present the preliminary results of this investigation.

Risk communication with generalized uncertainty and linguistics

Ross B. Corotis

University of Colorado at Boulder

Civil Engineers have the opportunity and obligation to lead society to more effective decision-making for built environment risk trade-offs. This paper addresses the gap between classical mathematical analysis and the linguistic-based issues and factors that play a major role on societal decisions.

A large stumbling block is the utilization of the fairly extensive literature in social psychology related to risk avoidance, in formal mathematical decision frameworks based on probabilistic analysis. Fundamental principles of generalized information theory may be helpful in casting sociological considerations of perceived risk into linguistic frameworks so that the mathematics of information theory can be applied to develop decision guidelines. Fuzzy set theory is one example where probability-based uncertainty has been broadened to incorporate linguistic input. Other examples are monotone measures, such as Möbius representations, imprecise probabilities and decision weights, as well as Shannon entropy.

This paper discusses several approaches to generalized uncertainty including uncertainty measurement, fuzzy sets and generalized belief measures. It addresses risk and risk perception issues, including risk factors for the built environment, the relationship of hazards and activity, issues critical for built environment decisions and linguistic risk assessment. The paper concludes with an example of generalized uncertainty and linguistics.

Epistemic or aleatory? Does it matter?

Armen Der Kiureghian[1] and Ove Ditlevsen[2]

[1] *Taisei Professor of Civil Engineering, University of California, Berkeley*
[2] *Professor Emeritus, Department of Mechanical Engineering, Technical University of Denmark*

A risk or reliability analyst is often confronted with the question of what the nature of uncertainties is (aleatory = intrinsic, or epistemic = knowledge-based) and how they should be accounted for in the assessment of risk and reliability. Can they be separated? Should they be separated?

Uncertainties in risk and reliability assessment arise from natural variability in phenomena such as capacities and demands, from imperfections in mathematical models used to describe physical relations between various quantities of interest, from statistical uncertainty due to small sample size, and from measurement errors. In some cases the nature of these uncertainties is obvious. For example, statistical uncertainties are epistemic in nature. But is natural variability in capacities and demands aleatory or epistemic? How is it for an existing structure versus a planned one? What are the components of model uncertainty and are they epistemic or aleatory? What is the effect of epistemic uncertainties on system reliability, or on the reliability of time-varying systems?

Some codes of practice, e.g., the NRC code in the US, require separate accounting of the aleatory and epistemic uncertainties. On the other hand, ordinary risk-based decision-making advocates no differentiation between the two. Does the separation of uncertainty types serve a purpose?

This talk will try to be provocative in addressing the above issues and in raising some more questions. Numerical examples will be presented to demonstrate some of the ideas and main effects.

Target safety criteria for existing structures

Dimitris Diamantidis[1] and Paolo Bazzurro[2]

[1] *University of Applied Sciences, Regensburg, Germany.*
[2] *AIR Worldwide, San Francisco, California*

Due to the social and economic need of utilizing existing structures, damage assessment and safety evaluation of existing structures are of major concern. In fact more than half of the budget spent for construction activities in developed countries is related to retrofit of structures.

Criteria for safety acceptance of existing structures should be based on present guidelines, standards and methodologies. The mere fact that the structure fulfils the code of its time of construction cannot be decisive. Codes have changed over time due, for example, to technology development and experience gained with the performance of structures when struck by past events. This does not mean, however, that if a new code with more severe requirements compared to the old one comes into practice, old buildings should be deemed unsafe. A "discount" in the safety requirements for existing structures may be simply unavoidable due to economical and legal constraints. In fact many authorities set the precedent that the acceptable seismic performance objectives for existing buildings maybe somewhat lower than those for new ones.

The present contribution discusses current risk acceptability criteria for existing structures based on:

a) experience gained from European practice (examples are shown)
b) review of current criteria for existing structures in seismic regions in the USA
c) analysis of the recommendations given by the Joint Committee on Structural Safety
d) cost benefit approach including implied costs to avert fatalities

Suggestions for future recommendations for a performance-based retrofit of existing structures are provided.

Cost and benefit including life, limb and environmental damage measured in time units

Ove Ditlevsen and Peter Friis-Hansen

Department of Mechanical Engineering, Technical University of Denmark

An engineering activity is planned to be realized within a statistically homogeneous economical region. By dividing all costs and benefits in the expected net cost equation by the average wage per time unit over the population of the region the equation gets physical dimension as time, and the equation becomes independent of local inflation and purchase power.

The equation may contain terms that represent loss of life and limb, and possibly also environmental damages. Such terms have in the past been considered as intangibles causing them to be excluded from the cost-benefit analysis. However, ideas based on macro economical reasoning have in the last decade opened possibilities of making rational evaluations (e.g. by use of the life quality index (LQI) defined in [1,2] and extensively studied and applied in [3,4], or, for environmental damage, the Nature preservation willingness index defined in [5]).

In the time formulation the life and limb losses may at a first glance simply be written as the increment of the expected life time in good health caused by the loss giving accident. However, this would be an over-simplification because a part of the loss is work time of larger societal value than the free time. The correction can be made by use of the criterion of invariance of the LQI, or, directly in time units, by use of invariance of the life quality time allocation index (LQTAI) defined in [6, 7, 8]. The results may be slightly different because the LQTAI is an extended more general version of the LQI. This paper gives a short recapitulation of the authors' thoughts behind the LQTAI including its empirical support. To the authors' surprise these thoughts and the supporting empirical findings have turned out to be controversial.

For large projects the decision making by the owner is restricted by public requirements. The owner is primarily focused on maximizing the profit only including the direct costs to be spent on insurance premiums and damage compensations. These costs are often much less than the societal value of life and limb as obtained from the invariance of the LQI or the LQTAI. Therefore the society must consider the possibility of this larger loss and protect itself under the consideration that the society has a positive interest in the realization of the project. Rational reasoning leads to a public accept criterion formulated in [9] and recapitulated herein.

Finally the paper gives an example of using the LQTAI to assess the expected societal time value loss of life and limb due to a fire on a ferry.

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[2] M.D. Pandey, J.S. Nathwani, and N.C. Lind. The derivation and calibration of the life quality index (LQI) from economical principles. *Structural Safety*, 28(4):341–360, 2006.

[3] R. Rackwitz. Optimization and risk acceptability based on the life quality index. *Structural Safety*, 24(2-4):297–332, 2002.

[4] R. Rackwitz, A. Lentz, and M.Faber. Socio-economically sustainable civil engineering infrastructures by optimization. *Structural Safety*, 27(3):187–229, 2005.

[5] P. Friis-Hansen and O.Ditlevsen. Nature preservation acceptance model applied to tanker oil spill simulations. *Structural Safety*, 25(1), 2003.

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[7] O. Ditlevsen andP. Friis-Hansen. Life quality index – an empirical ora normative concept? *International Journal of Risk Assessment and Management*, in press, 2007.

[8] O. Ditlevsen. Model of observed stochastic balance between work and free time supporting the LQTAI definition. Preliminary reference: Preprint No. OD 2006-07, MEK, DTU, Kgs.Lyngby, Denmark. Submitted February 2006 to Structural Safety. Downloadable from http://www.mek.dtu.dk/staff/od/papers.htm, 2006.

[9] O. Ditlevsen.Decision modeling and acceptance criteria. *Structural Safety*, 25(2):165–191, 2003.

Risk assessment of complex infrastructures

Leonardo Dueñas-Osorio

Department of Civil and Environmental Engineering, Rice University

Urban infrastructures are entities that exhibit the properties of *complex systems*. These systems consist of a large number of interacting elements, which display emergent properties that cannot be inferred by only knowing the properties of individual elements. The behavior of these systems does not result from the existence of a central controller, and estimation of their performance is highly dependent on their *topology* and the *dynamics* that take place within them to balance supply and demand flows.

Traditional risk assessment methods for networked systems focus on the performance of individual elements of the system, or in more refined cases, on the performance of a combination of series/parallel subsystems equivalent to the original network. These approaches eliminate the effects of network evolution (i.e., growth and topological changes), and network dynamics (i.e., balancing supply and demand fluctuations), on the reliability and risk assessment of geographically distributed infrastructures.

In this study, the performance of benchmark electric power networks is governed not only by the probabilities of failure of their elements, but also by thresholds on their flow carrying-capacities, and their ability to redistribute flow. These features allow the occurrence of *cascading failures*, which seriously affect conventional risk and reliability assessments for networked systems.

In general, the cascading phenomenon occurs when a particular element of a network ceases to provide its intended function—due to either internal or external disturbances of any intensity. The flow traversing that element has to be redistributed to adjacent elements, which usually function close to their maximum capacity. Some of these adjacent elements may be operating so close to their capacity that the additional inflow from the redistribution can induce failure. This process repeats itself until either the network locally absorbs the disruption, or, if the set of initial conditions are all unfavorable, until a large portion of the network losses its functionality.

The quantification of relative risks associated with frequent, but small size outages, and infrequent, but large avalanche-type outages, will provide valuable input for prioritizing investments in system maintenance and component upgrades. However, it is also observed that in some cases the largest outage in the power networks equals their own size. This result implies that the risk in electric power systems remains approximately constant, or that small and large size outages are equally important for risk control and consequence minimization.

Quantifying and communicating uncertainties in seismic risk assessment

Bruce R. Ellingwood

School of Civil and Environmental Engineering, Georgia Institute of Technology

The earthquake hazard is paramount among the natural hazards impacting civil infrastructure. In the United States, the impacts of three major earthquakes in recent times – San Fernando in 1971, Loma Prieta in 1989, and Northridge in 1994 – have highlighted the limitations in scientific and engineering knowledge concerning earthquakes and their socio-economic impact on urban populations and have provided the impetus for significant advances in engineering practices for earthquake-resistant design of buildings, bridges, lifelines and other civil infrastructure. Notwithstanding these advances, uncertainties in seismicity and in the response of buildings, bridges, transportation networks and lifelines are among the largest of the natural phenomena hazards confronting engineers and managers of civil infrastructure. The inevitable consequence of these uncertainties is risk that civil infrastructure will fail to perform as intended or as expected by the owner, occupant , or society as a whole. This risk must be managed in the public interest by engineers, code-writers and other regulatory authorities since it is not feasible to eliminate it entirely. In recent years, the structural engineering and regulatory communities have found that structural reliability and risk analysis tools provide an essential framework to model uncertainties associated with earthquake prediction and infrastructure response and to trade off potential investments in infrastructure risk reduction against limited resources.

Much of the research to date on the performance of civil infrastructure during and after earthquakes has concentrated on areas exposed to high seismic hazard. However, research in the past three decades has revealed that the earthquake hazard in other areas (e.g., the Central and Eastern United States) may be non-negligible when viewed on a competing risk basis with other extreme natural phenomena hazards. Building design, regulatory practices, and social attitudes toward earthquake risk differ in these areas, and civil infrastructure generally is not designed to withstand ground motions of the magnitude that modern seismology indicates are possible or probable. As a result, the risk to affected communities (measured in terms of economic or social consequences) may be far more severe than has been commonly believed.

The state of the art in uncertainty modeling and risk analysis now has advanced to the point where integrated approaches to earthquake hazard analysis, performance evaluation for civil infrastructure, and seismic risk management are feasible. Consequence-based engineering (CBE) is a new paradigm for seismic risk assessment and reduction across regions or interconnected systems, enabling the effects of uncertainties and benefits of alternate seismic risk mitigation strategies to be assessed in terms of their impact on the performance of the built environment during a spectrum of earthquake hazards and on the affected population. CBE is the unifying principle for research being conducted by the Mid-America Earthquake Center at the University of Illinois at Urbana-Champaign, one of the three university earthquake research centers in the United States sponsored by the National Science Foundation. This paper reviews some recent advances in uncertainty modeling and risk-based decision tools that are accessible to a spectrum of stakeholders with different skills and talents – architects, engineers, urban planners, insurance underwriters, and local governmental agencies and regulatory authorities – and identifies some of the research issues that must be addressed to make further advances toward risk-informed decision-making for civil infrastructure at risk from natural hazards. An integrated approach to the problem provides stakeholders with a structured framework for thinking about uncertainty and how public safety and economic well-being may be threatened by the failure of civil infrastructure to perform under a spectrum of seismic events. The benefits of such an approach are an improved ability to assess the effectiveness of various risk mitigation strategies in terms of risk reduction per dollar invested, and thus a better allocation of public and private resources for managing risk.

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6. Porter, K.A. and A.S. Kiremidjian and J.S. LeGrue (2001), "Assembly-based vulnerability of buildings and its use in performance evaluation," *Earthquake Spectra, EERI* 17(2):291 – 312.

7. Rosenblueth, E. (1976), "Towards optimum design through building codes," *J. Struct. Div. ASCE* 102():591-607.

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10. Wen, Y.K., B.R.Ellingwood, and J. Bracci (2004), "Vulnerability function framework for consequence-based engineering," Report DS-4, Mid-America Earthquake Center, University of Illinois at Urbana-Champaign, Urbana, IL (http://mae.ce.uiuc.edu).

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Decision making subject to aversion of low frequency high consequences events

Michael Faber[1], Matthias Schubert[1] and Jack Baker[2]

[1] *Swiss Federal Institute of Technology, Zurich*
[2] *Department of Civil & Environmental Engineering, Stanford University*

Depending on the situation at hand, decision makers may feel uneasy with the direct application of expected utility as basis for decision ranking. There are principally two reasons for this: either the decision maker is uncertain about the assessment of the consequences entering the utility function or the probabilistic modeling of the uncertainties. In order to account for the possible misjudgments of utility decision makers feel inclined to behave risk averse – i.e. give more weight in the decision making to rare events of high consequences (typically events for which knowledge and experience is limited) compared to more frequent events with lower consequences (for which the knowledge and experience may be extensive). In applied risk based decision making the inclusion of risk aversion is often made by use of the so-called risk aversion factors. In many applications risk aversion factors are introduced such that possible large consequences due to rare events are weighted higher than more frequently occurring events with smaller consequences.

The present paper starts out with a discussion of the various reasons for risk averse behavior of decision makers. Thereafter, based on a literature review an overview of different approaches for use of risk aversion factors is provided. Based on this overview it is shown that the use of risk aversion factors may be related to one general and important issue in risk assessment, namely uncertainties associated with the system understanding and definition. Furthermore it is shown that the use of risk aversion factors may introduce several problems associated with modeling consistency but also more ethical problems when life risks are concerned. Finally, a consequence model framework is introduced which by explicit representation of direct and indirect consequences associated with physical changes of a considered system as well as indirect consequences due to risk perception of the public may provide an improved basis for system understanding and representation in risk assessment. Examples of illustrative character are provided to illustrate problems and possible solutions.

Probabilistic comparison of seismic design response spectra

Sei'ichiro Fukushima[1] and Tsuyoshi Takada[2]

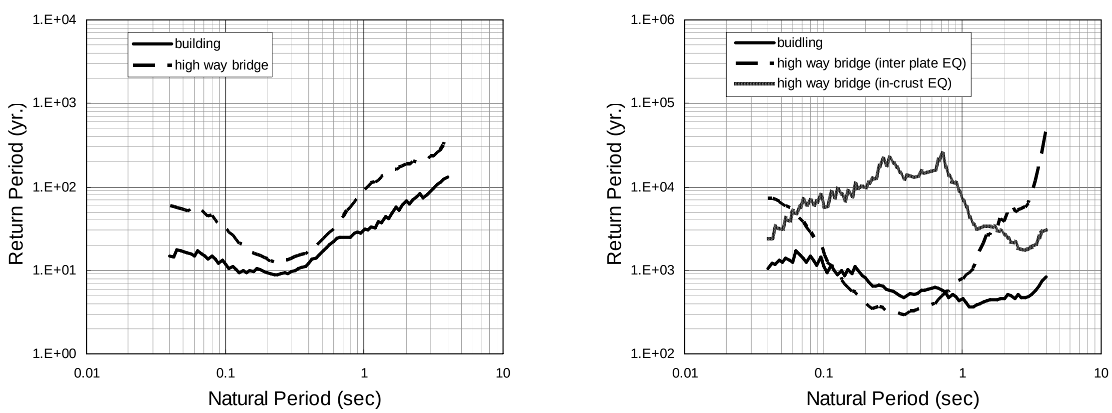
[1] *Tokyo Electric Power Services*
[2] *Faculty of Engineering, University of Tokyo*

Since the performance of building against earthquakes is described by limit states and their exceedance probability, seismic load for building shall also be examined not only from the viewpoint of intensity but also from that of occurrence probability.

This paper compares two seismic response spectra; one is for building and the other is for high way bridge with soil type 1. For the comparison of occurrence probability, we newly introduced the concept of return period spectrum that shows the relationship between the natural period and the return period. The return period spectrum is evaluated from the design response spectrum and uniform hazard spectrum. The uniform hazard spectrum is calculated by probabilistic seismic hazard analysis.

By applying the above procedure to seven major cities in Japan; Sapporo, Sendai, Niigata, Tokyo, Nagoya, Osaka and Fukuoka, the following findings are obtained; for the serviceability limit, the difference in two response spectra is relatively small comparing with that in sites, and, design response spectra for high way bridge corresponding to the ultimate limit for the in-crust earthquake gives the considerably long return period.

Special thanks are given to Dr. Inoue, Dr. Ishida, Dr. Ishii, Prof. Emeritus Ishiyama, Prof. Matsumura, Dr. Nakamura, Prof. Soda, Dr. Tamura and Dr. Todo for their comments and suggestions on this paper.



Example of Return Period Spectrum

Justification of risk-taking through reasoning, reasonableness and practicability

D.N.D. Hartford

BC Hydro

The demand to specify what is "safe" by means of a simple determinant is virtually universal across society. However, such simplicity of determination with respect to the vast array of situations where safety is a consideration is rare, and is arguably a chimera, because safety is fundamentally a relative concept regardless how it might be defined in a dictionary.

This paper presents the view that the form and nature of "criteria for risk acceptability" are primarily political constructs determined by the legal and political frameworks of the jurisdiction where the risk is to be taken and the consequences of failure are absorbed. Accordingly, the paper presents the view that the matter of risk acceptance criteria is a complex matter of socio-economics and politics, informed by the engineering and natural sciences and then "made to work in practice" by the professions (doctors, engineers, lawyers, etc.).

The paper begins by explaining the historical and legal background to risk acceptance criteria in general, pointing out the distinct difference between risk acceptance in terms of common law and that of the Roman/Napoleonic legal code system. The difference between the quantitative risk acceptance criteria of the Roman/Napoleonic code legal system and the role if quantified risk in the determination of the Tolerability of Risk in the common law system will be discussed.

The paper then outlines the principles of risk regulation in the common law system which provides the Safety Case framework, whereby the tolerability and even the acceptability of risk can be established. The paper will then attempt to integrate all of the topics of the workshop within an overall analytical event tree/fault tree framework that is applicable to both the common law and Roman/Napoleonic legal systems. The paper will explain why in terms of the Roman/Napoleonic system, once the risk acceptance criteria are set in law, the most important thing for the analysts to do is "get the numbers right" whereas in terms of the common law system, the numbers are only the starting point of an reasoned argument pertaining to the tolerability of the risk.

The paper concludes by outlining why in terms of the common law system, risk acceptance is largely a reasoned argument that should always err on the side of safety through demonstration that risks have been reduced As Low As Reasonably Practicable. The matter of "practicability" being a matter of engineering whereas the matter of "reasonableness" is ultimately a societal matter, the validity of which can only be known after the Courts have ruled following an accident.

Risk measures beyond expected cost for decision making in performance-based earthquake engineering

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Traditional structural risk analysis has been largely focused on the possibility of loss of structural integrity. That is, the uncertain outcome is a discrete random variable with two possible states; fail or safe. In this paradigm, design criteria to ensure life safety has been implemented in design codes, which has gained a predominant role in structural engineering practice. However, it has become apparent that the lack of information about expected structural performance, such as damage, repair cost, business interruption, etc is an unacceptable weakness of the sole reliance on design codes. The emerging performance-based engineering approach is devised to address this shortcoming by complementing the codified approach with damage/loss predictions.

The consideration of damage carries the promise of a renaissance for structural reliability analysis. This is because the uncertainties that influence damage are typically accounted for in a more complete manner than the causes of structural collapse. Structural collapses are frequently caused by ignored effects, human error, etc, which calls into question the quality of a traditional reliability results. The finite element reliability methodology is employed in this paper, where sophisticated structural & damage models are utilized in conjunction with advanced reliability methods with hundreds of random variables to represent material, geometry, and load parameters. Of particular interest in this paper is the fact that, contrary to the traditional fail/safe approach, damage is a continuous random variable. This motivates the exploration of enriched risk measures in the present study.

A rational basis for decision making under uncertainty is minimization of total expected cost. In the traditional approach, in which the possible outcomes are either failure (collapse with an associated failure cost) or safe (with no cost), the expected cost is simply the product of the failure probability and the failure cost. This product is the traditional measure of risk. The presence of multiple risks is handled by summation of the aforementioned products. The resulting total expected cost includes similar contributions from low probability/high consequence events and high probability/low consequence events. However, this approach has been criticized because it may misrepresent the relative importance of potentially irreversible high consequence events. A novel technique is proposed in this paper, in which the minimization of expected damage/loss, that is, minimization of the central moment of the probability distribution of the damage/loss, is replaced by the minimization of a measure that includes the dispersion in the probability distribution of the damage/loss. Several measures that represent alternatives to the expected cost approach are explored. Numerical examples with sophisticated finite element structural models are presented to compare the optimal risk-based decisions with those from the traditional expected cost approach.

Efficient seismic risk assessment and retrofit prioritization model for transportation networks

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Current seismic risk models for transportation networks have quantified the expectation of loss due to bridge damage and due to driver delay time in the event of a large scenario earthquake. For a spatially distributed system such as a transportation network, carrying out a probabilistic seismic hazard assessment becomes analytically infeasible and computationally difficult. Considering the effect of component correlations in the physical and operational loss analysis is a necessary element of the risk assessment process, but adds further complexity to the modelling requirements.

Two goals of this paper are to introduce an efficient way of selecting scenarios for a probabilistic seismic hazard assessment and to address and evaluate improvements in ground motion sampling techniques for these correlated random variables. Stochastic network analysis models require an imposing number of variables and constraints. By themselves, these models require large run times for even small-scale networks. Risk modelers are thus incentivized to ensure that stochastic inputs are both robust and efficient.

Another goal of this paper is to understand how correlation in ground motion affects the least cost path from a given origin to a given destination on a transportation network, and how these effects come into play in a retrofit prioritization model. Consideration of direct physical loss to components, network reliability, and losses to the network due to driver delay time, are all considered in the model under certain cost constraints. The seismic risk to the transportation network can be assessed through application of these models on a real network located in the San Francisco Bay Region.

Assessing the seismic collapse risk of reinforced concrete frame structures, including effects of modeling uncertainties

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A primary goal of seismic provisions in building codes and retrofit legislation is to protect life safety and prevent structural collapse. The extent to which design specifications and guidelines meet this objective is highly variable and, until recently, poorly quantified. Performance-based earthquake engineering, as developed by the Pacific Earthquake Engineering (PEER) Center and others, utilizes new simulation technologies and provides a methodology for evaluating many aspects of structural performance, including the assessment of collapse risk. The authors have conducted detailed studies of the collapse performance of 65 modern reinforced concrete special moment frames and 30 reinforced concrete non-ductile moment frames typical of construction in the 1960s and 1970s. The structures considered vary in design parameters such as height, bay spacing, and lateral resisting system (ie. space and perimeter frame structures). The collapse assessments obtained for these existing and new reinforced concrete frame structures gauge the seismic safety of reinforced concrete frame structures in high seismic regions. These predictions can be used to calibrate changes to engineering design requirements in building codes, as in the ATC-63 project for quantifying building systems response parameters. The detailed collapse performance assessment process is documented elsewhere.

Many aspects of the assessment process, including the treatment of modeling uncertainties, can have a significant impact on the evaluated collapse performance. Many researchers have varied uncertain modeling parameters, including damping, mass, and material strengths, and concluded that these variables make a relatively small contribution to the overall uncertainty in seismic performance predictions. However, these studies have primarily focused on pre-collapse performance. In contrast, we show that in collapse assessment the modeling uncertainties associated with deformation capacity and other parameters critical to collapse prediction are important, and can in fact dominate the assessment.

The effects of modeling uncertainty on predictions of collapse performance for reinforced concrete frame structures are quantitatively and qualitatively described in this study. Uncertainties in strength, stiffness, deformation capacity, and cyclic deterioration are considered for both ductile and non-ductile structures of 1, 4, and 12 stories. Due to the computationally intensive nature of these analyses, the effect of these uncertainties in modeling are studied through creation of a response surface from the results of sensitivity analyses. From the response surface, Monte Carlo simulation is used to quantify the effect of these uncertainties on the predicted collapse capacity for each structure. In addition, the effects of correlation assumptions are examined through a parametric study. Based on these detailed studies, recommendations are made for approximately incorporating modeling uncertainties in predictions of collapse capacity.

Flood control and societal capacity to commit resources

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Flood is among the severest causes of natural or man-made catastrophes. With a growing world population the need to live in flood-prone areas has grown, and so has the risk to life and property. This paper proposes three alternatives to flood risk assessment that each may help provide for better (more rational and defendable) design of flood control structures (1) Time series data analysis by cross-entropy minimization; (2) deriving society's capacity to control risks from welfare economics; and (3) discounting risks, but only up to the end of the financing period.

Cross-entropy minimization. The familiar "tail problem" of rare-even risk analysis is especially important in flood data analysis because the hydrological regime cannot be assumed stable and known. Arbitrarily assuming a mathematical model will often add an appreciable amount of information in comparison with that of the sample data. Cross-entropy minimization can compare a broad spectrum of distribution types to determine the best fitting model F. This model does not, however, comply with the constraints that all n data points i should satisfy $G_i = i/(n+1)$. The method further defines the least-information distribution G that complies and minimizes the totalinformation.

Society's capacity to commit resources to control risks is a well-defined quantity that for fatalities derives from the *time principle* that the reduction of a risk to life or health should cost no more, in terms of the time to produce the wealth equal to its cost, than the consequent expected increase in life expectancy. This time principle, in turn, follows from the requirement that the associated increment to the *Life Quality Index* (LQI) should not be negative. The LQI is a well-defined social indicator that can be derived from the classical theory of welfare economics.

Discounting risks is necessary, but if done at a constant rate, however small, it trivializes risks in the far future that flood control must be concerned with. There is an ethical requirement to valuate risks to present and future generations equally. This requirement, it is shown, places discounting in relation to the period of financing of any long term project: Risks beyond the this period should be discounted only up to the end of the financing period.

The impact of each of these three considerations is examined by several examples and some recommendations for analysis are made.

Using risk as a basis for establishing tolerable performance: an approach for building regulation

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For many engineers and designers, the performance environment promises greater opportunities to apply analytical tools and methods to design safe, cost effective, and aesthetically pleasing buildings. For many regulators and enforcement officials, however, performance-based approaches are met with skepticism and concern, as the desired performance is not always well defined and agreed, the perceived certainty associated with compliance with prescriptive design requirements is no longer be assured, and there is concern that the data, tools and methods – necessary to assure that performance-based designed buildings achieve the levels of performance and risk deemed tolerable to society – are lacking.

As a means to help resolve the concerns of regulatory and enforcement officials, while retaining the flexibility in design desired by the design community, risk information can be used to better define the expected performance of buildings. Using a risk-informed performance-based approach, the process involves characterizing the risks associated with buildings, occupants and operations under a range of hazard and non-hazard conditions, understanding the performance desired given those risks and hazards, identifying unambiguous criteria related to the agreed performance, and properly linking risk levels, performance levels, performance criteria, and data, tools and methods needed for analysis, review and approval. Given the range in stakeholder risk perceptions and performance expectations, it is essential to conduct the process within an analytical deliberative construct to help facilitate a mutual understanding of hazards, risk perceptions, appropriateness of data, tools and methods, and potential solutions.

This paper explores the use of a risk-informed performance-based approach for establishing tolerable levels of building performance. It draws from the experience of several countries grappling with the challenge of defining tolerable levels of building performance and their exploration into using risk as a basis for these levels. Examples are provided from regulatory activities in Australia, New Zealand and the United States.

Development of accidental collapse limit state criteria for offshore structures

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Accident experiences for offshore structures suggest that an Accidental Collapse Limit State (ALS) is necessary to complement other safety measures to achieve an acceptable risk level. The philosophy behind such criteria is old, but until recently robustness criteria in codes have in general been vague. Exceptions are found in codes for e.g. offshore structures (ISO,1994; NORSOK,2002). The recently completed NORSOK (2002) requirements are quantitative, i.e. the ALS check is specified as a survival check of a damaged structural system. The NORSOK requirements are quantitative, i.e. the ALS check is specified as a survival check of a damaged structural system. The damage may be due to accidental loads such as fires, explosions, ship impacts or fabrication defects corresponding to an annual exceedance probability of 10-4. Survival of the damaged structure under relevant characteristic payloads and environmental loads with an annual exceedance probability of 10^{-2}, should be demonstrated. Moreover, the implementation of such criteria requires methods for demonstrating compliance (Moan et al., 2002; Skallerud and Amdahl, 2002).

In this paper, accident experiences that form the basis for the NORSOK code are summarized. The basis for the acceptance criteria and how they are implemented in the codified probabilistic design criteria is outlined. Risk analysis methodology to establish relevant accidental conditions is discussed. In these analyses possible risk reduction by use of sprinkler/inert gas system or fire walls for fires and fenders for collisions, should be accounted for. Methods for predicting accidental damage and survival of the damaged steel structures are briefly outlined. To estimate damage, i.e. permanent deformation, rupture etc of parts of the structure, nonlinear material and geometrical structural behaviour need to be accounted for. Compliance with the survivability requirement for the damaged system can in some cases be demonstrated by removing the damaged parts, and then accomplishing a conventional ultimate limit state design check, based on a global linear structural analysis and component design checks using truly ultimate strength formulations. However, such methods may be very conservative and more accurate nonlinear analysis methods should be applied. While in general nonlinear finite element methods need to be applied, simplified methods, e.g. based on plastic mechanisms, are developed and calibrated using more refined methods, to limit the computational effort required. Finally, the trend towards establishing more prescriptive ALS requirements is briefly touched upon.

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Acceptance criteria for components of complex systems using hierarchical system models

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Typically engineered systems are built up by components which through their connections with other components provide the desired functionality of the system expressed in terms of one or more attributes. This perspective may indeed be useful for considering a broad range and interpretations of engineered systems ranging from construction processes over water distribution systems to structural systems.

One of the characteristics of engineered systems is that whereas the individual components may be standardized in regard to quality and/reliability the systems as such often cannot be standardized due to their uniqueness. The system performance will depend on the way the components are interconnected to provide the system function as well as on the choice of quality/reliability of the individual components.

For the design and maintenance of systems it is thus expedient that given requirements to the attributes of the performance of system can be translated into requirements for the components of the system given the way the components are connected.

In the present paper the problem outlined in the foregoing is addressed in the context of a hierarchical system representation developed for risk assessment of engineered systems by the Joint Committee on Structural Safety. Taking basis in engineered structures it is described how this framework may be applied to optimize the reliability and/or the risk acceptance criteria for components of structures based on specified requirements to the reliability and/or risk acceptance criteria for the considered structural system.

An example is provided to illustrate the proposed methodology where the identification of optimal risk acceptance criteria is considered for welded details in FPSO ship hull structures. The starting point for the optimization is a given requirement to the overall maximum acceptable risk of failure for the ship hull. The ship hull structure is represented by a hierarchical model utilizing the capabilities of object based Bayesian Probabilistic Net models. The object function on the basis of which the optimization is performed includes total service life expected costs, including inspection and maintenance planning considering fatigue damages as well costs of repairs and failure of the hull structure.

Calibration of safety factors for seismic stability of foundation grounds and surrounding slopes in nuclear power sites

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This paper probabilistically investigates the evaluation standard values for sliding safety factors (resistance / driving force) in the "Technical Guidelines for Aseismic Design of Nuclear Power Plants (JEAG4601-1987)" in Japan. The standard values for foundation grounds and surrounding slopes in nuclear power sites were regulated based on the engineering judgments, previous knowledge and so forth. Therefore, those values explicitly don't have probabilistic meanings. To define those values, literature survey was carried out and questionnaire survey were made to existing power plants for electric power companies. Based on those results the relation of the standard value between analysis methods (dynamic, static, conventional), and the relation of the standard values between foundation grounds and surrounding slopes were investigated. As a result of this calibration study, the standard values regulated in the JEAG-4601 well explained probabilistically, and soil structures satisfied the standard values were sufficiently safe.

Confidence and risk

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In the field of quantitative risk assessment, risk-based decision-making is often treated as a 'scientific' exercise which, if carried out 'correctly', yields objective and optimal solutions, based on quantitative methods of risk 'analysis' and 'evaluation', that should be implemented through rational risk 'management' strategies based on 'communication' of the analysis results. However, in the context of social policy making, the basis of this approach has been characterised as 'naïve positivism', and there is a general consensus that 'scientistically' inclined policy makers need to recognise the importance of divergent value systems in risk assessment.

Similarly, the author has previously argued that risk acceptance depends fundamentally on complex value judgements, and acceptable risks can be derived only from acceptable processes of risk management, based on value judgements appropriate to the circumstances. Acceptable risk levels cannot be defined as predetermined factors in such risk management processes. Although general criteria for risk acceptance cannot be explicitly defined in simple terms, general principles for determining realistic risk acceptance criteria have been described with regard to the need for risk exposure, control of the risk, and fairness. For a risk to be acceptable, there must be a real need for the risk exposure, the risk must be dependably controlled, and there must be a fair and equitable distribution of costs, risks and benefits.

In this paper, attention is focused on the dependability of risk controls, based on relevant risk control mechanisms (including risk-based structural design procedures) and associated residual risk estimates provided by risk analysts. A risk-based decision will not be accepted unless the decision-makers are trusted, and unless the stake-holders have confidence in critical risk estimates provided by risk analysts. An important question that arises is: how can a stake-holder assess the degree of confidence they should place in a risk estimate or a risk-based decision process?

In relation to the safety of structures, risks are usually assessed with regard to the probability of failure. Thus safety is characterised by a Bayesian probability measure that accounts for all relevant uncertainties. However, the question remains: what is the relationship between the estimated probability of failure and the level of confidence (of the stakeholder) that a structure is 'safe'?

Bayesian probabilities of failure account for many uncertainties of different types (including statistical, aleatory and epistemological uncertainities). Different levels of confidence may be associated with the treatment of different types of uncertainty.

The paper will discuss the relationship between confidence and risk. Alternative treatments of different types of risk will be illustrated with regard to the use of prototype test results for risk-based structural design. The sampling uncertainty associated with prototype test results can be included with the other uncertainties to obtain an estimate of the total (Bayesian) probability of failure. However, a different representation can be obtained by treating the sampling variability separately and evaluating the statistical confidence associated with reliability estimates. Conclusions will be presented concerning the characterisation and influence of confidence in risk-based decision-making.

Risk-quantification of complex systems by matrix-based system reliability method

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Many structures and lifelines are complex "systems" whose states are described as the Boolean functions of "component" events such as the occurrences of structural failure modes and the failures of members or substructures. For decision-makings on structural designs, retrofits, repairs and social/economic policies, it is essential to quantify the reliability of such systems in an efficient manner. The computation of system reliability is a challenging task because of the complexity caused by the system event definition, the statistical dependence between component events and the lack of information. This paper presents a Matrix-based System Reliability (MSR) method, which estimates the probabilities of complex system events by simple matrix computations. Unlike existing system reliability methods whose complexity highly depends on that of the system definition, the MSR method is uniformly applied to general systems by representing a target event by "system matrix." Since this system matrix can be obtained by algebraic manipulations of other system matrices, this method provides a more convenient way of identifying and handling the system event than other methods based on conventional formulations such as link sets and cut sets. If one has incomplete information on component failure probabilities or statistical dependence between components, the matrix-based framework enables us to estimate the lower and upper bounds on the system failure probability based on the available information. This is equivalent to the linear programming (LP) bounds method [1] that guarantees the narrowest possible bounds without any ordering-dependency issues. The LP bounds method has been successfully applied to structural systems [1], lifeline systems [2,3,5] and systems under stochastic excitations [4]. Numerical examples of various complex systems will demonstrate the proposed MSR method. Also discussed are the possible uses of the method during decision making processes on complex structural systems [3,5].

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Risk acceptance in deteriorating structural systems

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Typically, codes specify design criteria and safety factors for individual structural components. In modern codes, reliability-based code calibration is applied to determine those criteria and factors. In some instances, e.g. for fatigue limit states in the Eurocode [1], safety factors are specified as a function of the consequences of component failure and as a function of the possibility to detect a defect. In addition, it has been proposed to let the target reliability (and consequently design criteria) be a function of the relative cost of a safety measure, thus including risk-based optimization in codified design [2].

In principle, target reliabilities provided in [2] are valid for all failure modes in structural systems including deterioration. However, deterioration failure modes exhibit some fundamental differences as compared to other failure modes. This includes the nature of statistical dependence (correlation) among different components and the fact that deterioration may be observed. When selecting target reliabilities for deterioration limit states of individual system components, one must account for these factors. As deterioration is often a problem in existing structures, the choice of the target reliability may have significant economical impacts.

The aim of the paper is to present an overview on the different factors influencing risk acceptance for deterioration in structural system, with a particular emphasis on highly redundant systems. A numerical study will be performed to investigate the effect of correlation among deterioration at different locations within the system and the influence of inspection/monitoring for systems with different degrees of redundancy and for different types of deterioration behavior. Finally, the selection of target reliabilities for the different situations will be discussed.

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Structural safety requirements based on notional risks associated with current practice

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Structural design codes must deal with the safety issue either implicitly or explicitly. Under the implicit approach used in daily practice the risks relating to a specific project are not quantified, a situation that entails important drawbacks since structural safety decision-making is not based on rational criteria and is therefore subject to possible over-reaction; furthermore, current rules are unsuited to the analysis of innovative technologies and may stifle the implementation of new solutions.

With the progressive acknowledgement of the consequences of these shortcomings in the existing legislation, some of the more recent codes have begun to include explicit risk analysis in structural design. However, inasmuch as the regulations presently in force establish only a general framework for explicitly addressing the safety issue, such methods for analysing risk have been virtually ignored in everyday practice to date. There is therefore a need to develop simple methods, models and decision criteria geared to the practical application of risk analysis in structural design.

The results of risk analysis should be compared to safety requirements when deciding whether the system analysed is acceptable. The most logical approach is to establish acceptable risk to be at the level of inherent risk set out in existing structural standards, inasmuch as they represent normal practice and are therefore regarded to be acceptable by definition. Acceptable risks therefore depend on the degree of reliability implicitly required by such standards, which in turn depends on the level of uncertainty associated with standardized rules. The difficulty lies in the fact that the degree of uncertainty associated with the standards in force has not been established explicitly. Moreover, since the rules in most current standards have not been calibrated with consistent criteria, the level of reliability required according to such standards is likewise unknown.

The establishment of a rational basis for decision-making is stressed in the paper, in keeping with both the level of structural reliability required and acceptance criteria for structure-related risk. In this context, the following issues are addressed:

- Determination of the state of uncertainty associated with the rules set out in the existing standards on structural design.
- Deduction of the level of reliability implicitly required in such standards.
- Development of mathematical models to estimate the consequences of structural failure.
- Determination of the acceptable level of risk associated with structures.

Failure consequences in flood engineering

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When a dike breach occurs, huge amounts of water will flow into the protected area causing substantial damage in most cases. These damages are multi-dimensional and relate to the vulnerability of human, economic and environmental values. Available models for the following categories will be discussed:

- *People*: fatalities and (mental) injured, including the effects of evacuation;
- *Lifelines*: energy supply, telecommunication, water supply, transport etcetera;
- *Buildings* and other material goods;
- *Economy*: direct economic losses (e.g. industry and agriculture) and indirect economic losses (e.g. disruption of production chains);
- *Environnent:* impact of polluants, etcetera.

Consequences are far from deterministic. Differences in time and place of breaches in the primary protection system may cause substantial differences in inundation patterns. Also the behaviour of internal elements like roads and regional dikes is unpredictable. Different flood patterns in their turn will give rise to completely different consequences in the various damage categories. Additionally, flooding of one area may or may not have influence on the safety of other regions.

Questions related to uncertainties encountered in the consequence analysis will be addressed. The first issue is about dealing with uncertainties in estimating the risks and subsequently how to deal with them in the decision analysis. How do uncertainties affect the optimal mitigating measures, both from the economic optimization point of view as also from the aspect of human safety.

Decision analysis for seismic retrofit of structures

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Investors and owners of buildings in geographic regions subject to seismic hazards are faced with the decision of whether or not to retrofit existing structures in order to lower their potential economic losses due to seismic events. This decision becomes even more challenging in low-risk, high-consequence seismic areas such as those located in the New Madrid Fault Zone. Currently, building owners in Mid-America have inadequate data and methods to make informed decisions on whether or not seismic retrofitting is appropriate for their buildings.

A prescribed method is outlined to determine the expected value of economic benefit resulting from seismic retrofitting. A case study of reinforced concrete structures of varying heights in Memphis, Tennessee is performed using the prescribed method to determine the length of time required to recoup the cost of retrofitting. The method of integration of seismic vulnerability and hazard is used to determine the estimated annual loss (*EAL*). Seismic vulnerability functions, developed from Mid-America Earthquake Center research, are utilized in this solution. The average annual frequency of experiencing ground motion intensity is determined by differentiating hazard exceedance curves available for locations throughout the United States from the United States Geological Survey.

The expected value of economic benefit of a seismic retrofit of a building is calculated. In discussions with practicing engineers from a business perspective, a seismic retrofit of a structure is a viable option if a positive economic benefit can be achieved in about a five-year planning period. Additionally, for the case study considering the same five-year planning period, a sensitivity analysis is conducted to determine the total indirect costs for retrofit viability.