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ACCEPTABLE CONSEQUENCES IN EARTHQUAKE ENGINEERING DECISIONS[1]

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SUMMARY

A primary aim of recent advances in analytical frameworks for earthquake engineering has been to create an integrated socio-technical systems perspective, which takes into account the potential consequences of earthquakes - and earthquake engineering - for society as a whole. However, such frameworks have in some cases conceptualized acceptable risk and consequence levels as a static input. This paper shows why such à priori assessment of the acceptability of earthquake consequences as conceived in the Consequence Based Engineering (CBE) framework is likely to be problematic. Specifically, we focus on the framework's assumptions that (i) an individual decision maker would, à priori, be able to choose an acceptable level of consequence for a system of his/her interest and (ii) aggregation of such acceptable consequences across different systems would reflect acceptable earthquake consequences at the societal level. This paper reviews the extensive research on context dependency of acceptable risks and decision making involving interaction of multiple stakeholders to argue against the validity of these assumptions. Support for our arguments comes from an example of the multistage, multistakeholder evaluation, analysis and selection process involved in seismic retrofit decisions for U.S. General Services Administration (GSA) -owned federal buildings. Additional review of research on earthquake mitigation policy making at the local government level supports our arguments. Finally, we describe an alternative "dynamic decision making" approach that entails modifying the CBE framework and using the resulting analytically flexible decision support system as a dynamic tool to aid private, organizational, and societal earthquake deliberation, analysis, and decision making. This analysis suggests an increasing emphasis on interface design issues - including visualization of earthquake engineering and hazard information, representation of uncertainty, and elicitation of user judgments - will be required to improve earthquake decision support.

INTRODUCTION

Recent trends in the US natural disaster planning policy show an increasing emphasis on mitigation (Iwan [1]). Even independent of this, post 9-11, efforts to design measures to reduce losses from low-probability, high risk events such as earthquakes, or intentional attacks, have increased. A dominating argument is that regardless of the low probability of the event (only 7-8 severe earthquakes in US for the entire 20th

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century), its occurrence would cause losses incommensurable with those incurred at earlier times (Robards [2]). Among these efforts are research investments under the National Earthquake Hazard Reduction Program (NEHRP), including the Earthquake Engineering Research Centers funded by the National Science Foundation.

Two paradigms are driving much of the research in these centers: the Performance-Based Earthquake Engineering (PBEE) framework[4], used by the Pacific Earthquake Engineering Research (PEER) group, and the Consequence-Based Engineering (CBE) framework, being developed and applied by the Mid-America Earthquake Center. The broader aim of these frameworks is to assist decision and policy makers in managing earthquake hazards. While the two frameworks share several similarities, a distinctive difference is the concept of acceptable consequences within CBE.

As can be seen from this description of PBEE, it focuses on the performance of engineered facilities, assessed through life-cycle analysis:

> *"Performance-based earthquake engineering implies design, evaluation, and construction of engineered facilities whose performance under common and extreme loads responds to the diverse needs and objectives of owner-users and society. PBEE is based on the premise that performance can be predicted and evaluated with sufficient confidence for the engineer and client jointly to make intelligent and informed decisions based on building life-cycle considerations rather than on construction costs alone." (Krawinkler [3])*

The concept of acceptable consequences in CBE has a laudable goal: to broaden the decision focus from the purely technical to an integrated socio-technical systems perspective, and to take into account the potential consequences of earthquakes - and earthquake engineering - for society as a whole.

This paper examines the definition and implementation of acceptable consequences in the consequence based engineering (CBE) framework, as proposed by Abrams [4] and illustrated in Figure 1. The aim of this paper is to show why the *à priori* assessment of the acceptability of consequences as conceived in the CBE framework is likely to be problematic, and to suggest an alternative approach that entails treating dynamic decision support as a tool for societal decision making.

ACCEPTABLE CONSEQUENCES IN THE CBE FRAMEWORK

The first three steps in the CBE framework as outlined by Abrams [4] are (1) system definition, including hazard identification and definition of system characteristics, (2) rapid estimation of consequences, and then (3) definition of acceptable consequences, including definition of stakeholder needs. All subsequent steps in the framework such as damage synthesis and consequence mitigation hinge on the definition of acceptable consequences.

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[4] From Krawinkler (2000) – frameworks for PBEE available in each of these references: Applied Technology Council. 1989. ATC 20 Procedures for Postearthquake Safety Evaluation of Buildings. Redwood City, Calif.: Applied Technology Council. FEMA. 1997. NEHRP Guidelines for the Seismic Rehabilitation of Buildings. Prepared by the Applied Technology Council. [Washington, D.C.: Federal Emergency Management Agency]. FEMA 273. Structural Engineers Assn. of California (SEAOC), Vision 2000 Committee. April 3, 1995. Performance Based Seismic Engineering of Buildings. J.Soulages, ed. 2 vols. [Sacramento, Calif.]

"A practitioner using the [Consequence-Based Engineering] CBE approach must discuss with his or her stakeholder client what level of consequences they are willing to accept in the event that an earthquake of a given intensity occurs." (Abrams [4])

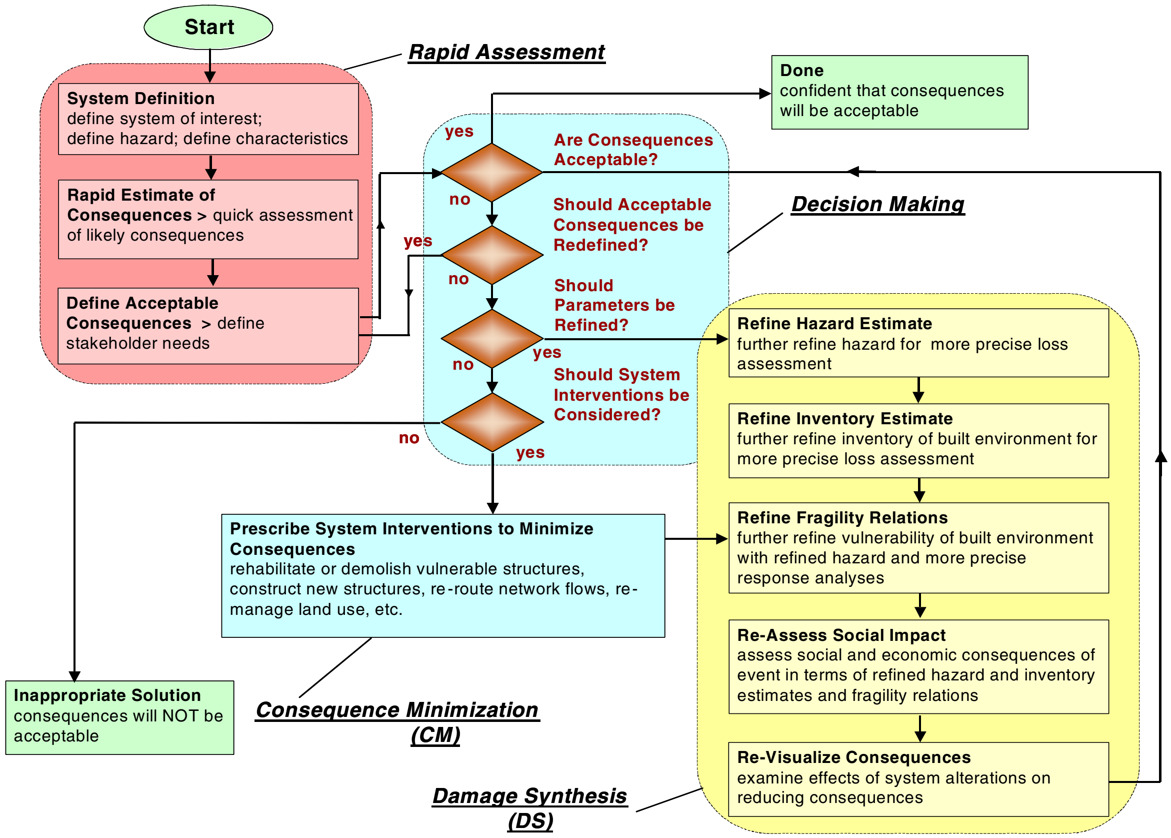

Figure 1: CBE Flowchart

The project aims at identifying "what consequences are possible from seismic hazards and the impact of specific mitigation interactions on reducing these consequences across a system of interest." (Abrams [4]). This implies that this 'component' of the decision making system – acceptable consequences – is construed as an external one: its parameters are estimated in an 'external' process (consultation with stakeholders), then fed into the system, providing guidelines for the selection of response interventions.

Abrams [4] suggest that insurance companies might define acceptable consequences in terms of financial risk, that acceptable disruption of transportation networks might be specified in terms of national economic flows, and that owners of large building stocks, including the federal government, might "define acceptable consequences in terms of what level of business interruptions can be tolerated." While iteration in the definition of acceptable consequences is foreseen in the framework, such iteration is generally characterized as intended to achieve more accuracy than as a problem of complexity of decision making involved in arriving at a definition of acceptable consequences.

"With the iterative approach of the CBE paradigm, however, limiting consequences can be first approximated with conservative bounds for comparison with equally conservative consequence estimates. For low or moderate seismic regions, this first simple iteration may be sufficient. However, if further definition of acceptable consequences is needed for comparison with more

refined estimates of anticipated consequences, then stakeholder concerns can be refined further." Abrams et al (2002).

Within the framework itself, the only stable reference point given for acceptable consequences is the respective "system" itself. That is, any assessment of 'acceptable consequences' – either the 'rapid' initial one (Abrams [4]) or the subsequent "refining of the necessary system interventions" (ibid.) - are based on an underlying, though not extrapolated, concept of the respective system. The definition of acceptable consequences is presented as a step that is distinct from others, including those of system definition and of identifying possible consequences from the earthquake hazard.

To be concrete, it appears that CBE envisions a single decision maker giving an engineer a list of acceptable consequences for a system that he or she owns or has an interest in, and that this process in the aggregate will achieve socially acceptable consequences at a societal scale. As we show in the following, there are several reasons that this is not likely.

DECISION MAKING IN CBE

In the fourth step of the CBE framework – decision making – a fundamental assumption regarding individual and institutional behavior is that the process of decision making is simply choosing between alternatives, as provided by engineers, with iterations designed to increase the amount and quality of information until a decision is reached. The alternatives constitute a (complete) set of possible choices, and the choices are based on certain preferences, characterized with completeness and transitivity. That is, all alternatives can be compared, and all of them can be ranked in unambiguously.

These fundamental properties are, of course, only approximations of actual behaviors. Further, they consider the static situation when all the alternatives are immediately available and the actors have complete or relatively complete information about the alternatives. In such a [formalized] setting making the decision could be approached as a mere computation, in which the process of arriving at the set of choices could be irrelevant. But, as we show in the following, this is not the case. The particular value that a single decision maker would assign to a certain choice cannot necessarily be assessed with confidence à priori. Further, social goals are seldom – if ever - achieved by the mere analytic aggregation of individual preferences, and such an aggregation is unlikely to lead to the same results as other social decision-making processes.

Assessment of Acceptability à priori

As stated succinctly by Fischhoff [5] over two decades ago, acceptable risk problems are decision problems, and so "require a choice among alternative courses of action." CBE explicitly ignores this fundamental context dependency.

Several lines of evidence show that specific framings of risk problems, such as earthquake mitigation decisions, influence subsequent judgments of acceptability (e.g., Johnson [6]; see also Kahneman [7]). Numerous cognitive shortcuts, or heuristics, also influence risk judgments (e.g., Gilovich [8]). Further, consequences are sometimes judged "acceptable" only by virtue of the processes and or events that have produced them. So, for example, judgments of willingness to accept payment to forego a benefit often differ from judgments of willingness to pay for the same benefit (e.g., Kahneman, [9]). There are broad differences in values assigned to deaths from differing causes, as revealed in regulations (Tengs [10]) law suits (e.g., Sunstein[11]), and in explicit judgments of risk acceptability (e.g., Mendeloff [12]; Slovic[13]). Such findings suggest that potential injuries and deaths from earthquake-related building collapse, for example, are likely to be valued differently depending on such factors as:

- whether the collapse is imminent or far in the future (economic analyses find that discount rates vary for future risks, e.g., Cropper [14] [15])
- whether the building is presented as one of many, and what other attributes are evaluated at the same time (e.g., Norinder [16]; Sælensmind [17])
- the relative emphasis given various causal factors in the description of the collapse, for example whether the building was up to code (assignment of causality -- cf McDaniels [18]; van der Pligt [19])
- who might be injured or die (value of statistical life is contingent on age, for example - e.g., Rosen [20]; Bleichrodt [21])

In sum, preferences are constructed (Slovic [22]). Further, the value of any given analysis will be constrained by the process entailed.

Research on individual perceptions of earthquake risks suggests that they may be relatively undervalued, although proximate earthquake events and information do influence risk perceptions, which affect risk reduction preferences and actions (e.g., Berknopf [23]; Lindell [24]; Murdoch [25]). Earthquake hazards are clearly not on the top of the public agenda (Bearke [26]; Robards [2]), and are in general perceived as low probability events, about which 'not too much can be done.' Even in communities with high earthquake risks, earthquake hazards are not ranked high as major problems (Bearke [26]:149), though there can be public support for some kinds of earthquake risk reduction measures (Flynn [27]). Such support may depend as much or more on local politics and resources than on any technical measure of earthquake risk (May [28]).

Decision making at GSA: An example

Seismic retrofit decisions for federally owned buildings illustrate the above - that is, how such decisions depend on decision processes and political contexts.

The General Services Administration (GSA) has three divisions, one of which, the Public Buildings Service, is responsible for managing, maintaining, and protecting federal buildings and courthouses. The condition of every GSA-owned building is reviewed regularly, in a multi-year cycle. This review includes the structural condition and seismic resistance of the building, as well as its resistance to other natural disasters. Decision making about renovation goes through several stages. The first stage of the decision is prioritization of buildings that are under review in any particular year by the GSA regional offices. At this level, the initial prioritization is based on a combination of several factors such as the profitability of the building, the costs of retrofitting, and the overall structural condition of the building including its seismic vulnerability.

The next stage involves preparation of a more detailed Program Development study for each of the prioritized building. Typically, each region comes up with a few such renovation plans each year. At this level, around a dozen people are involved in developing any given plan, including: the GSA building manager, structural, electrical and historical building specialists, financial and asset managers, and regional seismic advocates, and a GSA realty specialist representing the agencies occupying the building. Rarely is input sought from the public or other organizations in preparing the plans. After review by the Assistant Regional Administrator and the Regional Administrator, the Program Development plans are submitted to the GSA Central Office. The Central Office then reprioritizes them based on the total set of Program Development studies received from all regions. These prioritized plans are then submitted to the Office of Management and Budget (OMB) for budget approvals. From OMB, the plans go to Congress for final allocation of renovation funds.[5] This example of decision making for GSA-owned federal buildings

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[5] This description is based on an extended conversation with Bela Palfalvi, the GSA Seismic Program Manager, on 2/24/03, and on his written correction of notes from that conversation.

shows that the engineering analyses are just one of many influences on earthquake mitigation decisions. These decisions are made in complex decision contexts involving multiple stakeholders with multiple values.

Deliberative and Analytic Processes

Determining "acceptable" societal risk, and hence acceptable earthquake consequences, requires deliberation in addition to analysis (e.g., NRC [29]). Evidence to date suggests that participative, democratic processes - not necessarily consensual in character - are likely to improve the quality of societal risk decisions (e.g., Beierle [30]). Further, individuals' judgments regarding what risks are acceptable are constrained by such societal processes, in the form of codes, laws, and institutions. Given the high bargaining cost in determining appropriate responses to earthquakes between individuals and communities, and the scale and scope of earthquakes damage, it is only natural to expect that the earthquake decisions be within the purview of government agencies, and not individual stakeholders.

However, these mitigation policies do not have a single locus of power and focus: given the complexity of the problem and the diversity of consequences, earthquake mitigation efforts are unequally distributed across all levels of government – federal, state and local. Earthquake policies are either regulatory (as in mandatory building codes), based on different incentives (tax relief, development rights, etc.), or informational (disclosure of information); and different levels of government do not share the same responsibilities. Federal policies aim mostly at providing financial and information support regarding earthquake mitigation measures, without actually participating in the decision making and implementation (e.g., HAZUS); state governments act in a similar fashion, of course, considering their own particular problems and state-wide systems: they also create seismic vulnerability standards, set up state-wide safety standards, and provide assistance to local governments; in most cases the actual implementation of any mitigation measures is a primarily a responsibility of local governments.

Examining actual decision-making processes for developing earthquake mitigation policies in local communities reveals its complexity. Research on such decision making in local government suggests that a number of factors influence the type of mitigation policy adopted (Bearke [26]). Typically, earthquake mitigation reaches the local agenda when an earthquake event occurs locally. However, the adoption of a mitigation policy is constrained by several factors, including: low public perceptions of earthquake risk, high upfront costs and uncertain benefits of mitigation actions, and, as mentioned above, lack of technical and financial resources, competing interests among stakeholders and differences in the values stakeholders hold. All of these factors influence the type of mitigation policy adopted – building codes, retrofit ordinances, or disclosure requirements.

Implicit in the adoption of a specific mitigation policy is the recognition of a certain level of acceptable consequences. Fischhoff [5] points out that acceptable risk is "risk associated with the most acceptable option in a particular decision problem." Because the effectiveness of mitigation policies varies with the type of policy (building codes could presumably lead to a different level of mitigation than zoning regulations), it follows that the policies adopted by a community reflect - implicitly - a level of acceptable consequences. So, decisions are made not through the explicit expression of a level of consequences which are considered acceptable, but rather with regard to a given context and a given a set of options, which can then be construed as revealing a level of acceptable consequences.

Further, as argued earlier, aggregation of acceptable consequences for individual stakeholders does not necessarily result in socially acceptable consequences. Because of differing values and competing interests, system-level or societal level acceptable consequences may require deliberative mechanisms rather than the mere aggregation of individual preferences. In general, risk management in socio-technical systems like those earthquake risk mitigation entail are contextually complex, with hierarchical structures - from individual decisions about equipment and surroundings (e.g., decisions and actions by construction workers), up to regulatory bodies and government policy and budgeting (Rasmussen [31]).

Evidence of this is provided by earthquake mitigation policy making in the California community of Palo Alto (Bearke [26]). When the local Palo Alto government came out with an ordinance to make it mandatory for 250 "deficient" buildings to undertake retrofit action, there was widespread opposition from the affected building owners. This led to the formation of a local citizen group to fight the ordinance. After long drawn deliberations, the decision was overturned and a voluntary approach was adopted. In this example, the local government agency's decision was based on a level of acceptable consequences that were not compatible with those of building owners; the voluntary approach eventually adopted did not require every building owner to undertake retrofit action and reflected a different level of acceptable consequences at a societal level.

Such policies predetermine individual stakeholders' decisions and create the context in which their decisions are actually made.

DYNAMIC EARTHQUAKE DECISION MAKING

Dynamic decision making provides an alternative to the notion of engineering structures to meet a list of criteria derived from a 'one-shot' identification of acceptable consequences. As stated by Corner [32], dynamic decision problem structuring acknowledges "dynamic interaction between criteria and alternatives as a decision-maker understands his preferences and expands the set of alternatives." In other words, in practice, effective communication between an earthquake engineer who is designing retrofit or rehabilitation alternatives and a decision maker trying to articulate criteria for success (in this case for reduction of risk, loss or vulnerability; or possibly for increased resilience or sustainability) should insure that earthquake mitigation decisions will evolve.

Dynamic decision making acknowledges that value elicitation should influence solution design, and solution design can lead to clearer value articulation. Implicit in this is that the better the engineer understands the decision maker's needs and values, the more likely his or her designs will be to satisfy those needs. Conversely, the better the decision maker understands how to design possible interventions and the consequences of those interventions, the better he or she is likely to be able to articulate the value of specific system attributes for the engineer, *ceteris paribus*.

Perhaps the most critical step in decision making is structuring the decision. This is implicitly, if not explicitly, realized by most parties in public decision making, and is a key rationale for developing dynamic decision support. A second rationale is the need to develop more flexible approaches to managing risks as technologies and engineering evolve. Integrative and adaptable decision support tools might provide insights into how society can improve on the 20 years that it took for base isolation to move from conceptualization to implementation (cf Krawinkler [3]).

CONCLUSIONS

CBE relies on the assumption that "acceptable [earthquake] consequences" are within the complete[6] set of institutional preferences. While this assumption works reasonably well with regard to trivial/typical choices actors make, its power is probably overestimated in this particular case. Alternatively, interactive

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[6] i.e. having the property 'completeness'

dynamic decision structuring presents the promise of informing decision makers of the likely physical consequences of innovative earthquake mitigation measures, while allowing them to examine the effects of uncertainties, tradeoffs and different decision structures.

REFERENCES

1. Iwan, WD, Cluff, LS, Kimpel, JK, Kunreuther, H., Masaki-Schaltz, SH, Nigg, JM, Rotth Sr, RS, Ryland, H., Stanley, Sr., E, Thomas, FH, Hamilton, RM, Jones, PA, and Parker, SD, "Mitigation emerges as major strategy for reducing losses caused by natural disasters." Science 1999, 284**:** 1943-1947.
2. Robards, KJ, "Earthquake Mitigation Decision Making in Local Government: An Application of Systems Dynamic Modeling." *Dissertation Report, Washington University, 2001.*
3. Krawinkler, H., 2000, Advancing Performance-Based Earthquake Engineering, *Civil and Environmental Engineering, Stanford University, CA*, Available at httpp://nisee.berkeley.edu/lessons/krawinkler.html
4. Abrams, DP, Elnashai, AS, and Beavers, JE, "A new engineering paradigm: Consequence-based Engineering." *Working paper, Mid-America Earthquake Center*, UIUC, 2002.
5. Fischhoff, B., "Acceptable Risk." Cambridge; New York, Cambridge University Press, 1981.
6. Johnson, EJ, Hershey, J., Meszaros, J., and Kunreuther, H. "Framing, probability distortions and insurance decisions." Journal of Risk and Uncertainty 1993, 7**:** 35-51.
7. Kahneman, D., and Tversky, A., "Choices, Values and Frames." Cambridge University Press: New York, New York, 2000.
8. Gilovich, T., Griffin, D., and Kahneman, D. "Heuristics and Biases: The Psychology of Intuitive judgment." Cambridge University Press, Cambridge, U.K., 2002
9. Kahneman, D., Knetsch, J., and Thaler, R. "Experimental tests of the endowment effect and the Coase theorem." Journal of Political Economy 1990, 98: 1325-1348.
10. Tengs, T., Adams, M., Pliskin, J., Safran, D., Siegel, J., Weinstein, M., and Graham, J. "Five-hundred life-saving Interventions and their cost-effectiveness." Risk Analysis 1995, 15: 369-390.
11. Sunstein, CR, Kahneman, D., Schkade, D., and Ritov, I. "Predictably incoherent judgments." Stanford Law Review 2002, 54: 1153-1215.
12. Mendeloff, JM, and Kaplan, RM. "Are large differences in lifesaving costs justified? a psychometric study of the relative value placed on preventing deaths." Risk Analysis 1989, 9: 349-363.
13. Slovic, P. "The Perception of Risk." Earthscan Press, U.K., 2000
14. Cropper, ML, Aydede, SK, and Portney, PR. "Discounting human lives." American Journal of Agricultural Economics 1991, 73: 1410-1415.
15. Cropper, ML, Aydede, SK, and Portney, PR. "Rates of time preference for saving lives." American Economic Association Papers and Proceedings 1992, 82: 469-472.
16. Norinder, A., Hjalte, K., and Persson, U. "Scope and scale insensitivities in a contingent valuation study of risk reductions." Health Policy 2001, 57: 141-153.
17. Sælensmind, K., forthcoming, "Embedding effects in valuation of non-market goods." Transport Policy.
18. McDaniels, T., Cavanagh, AL., and Slovic, P. "Perception of ecological risks from natural hazards." Journal of Risk Research 1998, 2: 31-53.

19. van der Pligt, Els, J., C. M. van Schie, and Hoevenagel, R. “Understanding and valuing environmental issues: the effects of availability and anchoring on judgment.” Zeitschrift für Experimentelle Psychologie 1998, 45: 286-302.
20. Rosen, S. “The value of changes in life expectancy.” Journal of Risk and Uncertainty 1988, 1: 285-304.
21. Bleichrodt, H., and Quiggin, J. “Life-cycle preferences over consumption and health: When is cost-effectiveness analysis equivalent to cost–benefit analysis?” Journal of Health Economics 1999, 18: 681-708.
22. Slovic, P. “The construction of preference.” American Psychologist 1995, 50: 364-371.
23. Berknopf, RL, Brookshire, DS., and Thayer, MA. “Earthquake and volcano hazard notices: an economic evaluation of changes in risk perceptions.” Journal of Environmental Economics and Management 1990, 18: 35-49.
24. Lindell, MK, and Perry, RW. “Household adjustment to earthquake hazard - A review of research.” Environment and Behavior 2000, 32: 461-501.
25. Murdoch, JC, Singh, H., and Thayer, M. “The impact of natural hazards on housing values: the Loma Prieta earthquake.” Journal of the American Real Estate and Urban Economics Association 1993, 21: 167-84.
26. Berke, PR, and Beatley, T. “Planning for Earthquake: Risk, Politics, and Policy.” Baltimore: Johns Hopkins University Press, 1992.
27. Flynn J., Slovic, P., Mertz CK, and Carlisle, C. “Public support for earthquake risk mitigation in Portland, Oregon.” Risk Analysis 1999, 19: 205-216.
28. May, PJ, and Birkland, TA. “Earthquake risk reduction - an examination of local regulatory efforts.” Environmental Management 1994, 18: 923-937.
29. NRC. “Understanding Risk: Informing Decisions in a Democratic Society.” National Research Council, National Academy Press, Washington, D.C., 1996.
30. Beierle, T. “The quality of stake-holder based decisions.” Risk Analysis 2002, 22: 739-749.
31. Rasmussen, J. “Risk management in a dynamic society: A modelling problem.” Safety Science 1997, 27: 183-213.
32. Corner, J., Buchanan, J., and Henig, M. “Dynamic decision problem structuring.” Journal of Multi-Criteria Decision Analysis 2001, 10: 129–141.