ISGSR2007 First International Symposium on Geotechnical Safety & Risk
Oct. 18~19, 2007 Shanghai
Tongji University, China

Assessing and Managing Risks due to Natural Hazards

M. H. Faber
ETH-Zürich, Institute of Structural Engineering, Zürich, Switzerland.

ABSTRACT: This paper presents recent developments on methodologies for the assessment and management of risks due to natural hazards. First a review is made on system characteristics commonly applied in the field of natural hazards risk management at large scale. Thereafter, a general model framework is proposed for the representation of consequences and knowledge based on recent developments within the Joint Committee on Structural Safety (JCSS). The proposed framework explicitly accounts for two significant characteristics of systems, namely indicators and conditional dependencies. This in turn suggests that when using this framework a Bayesian statistical framework for risk assessment is advantageous and it is shown how generic Bayesian risk models may be formulated to facilitate the analysis using Bayesian Probabilistic Nets (BPN's). It is outlined and discussed how the proposed model framework may be applied for risk management problems considering natural hazards at large geographical scales. Finally an example is provided on the application of the framework based on recent and ongoing research on management of risks due to earthquakes.

1 INTRODUCTION

Over the years great efforts have been invested into a wide range of the different problem complexes involved in engineering decision making. The engineering perspective in problem solving has developed from being rather narrowly focusing on individual technical problems in isolation to a far more holistic consideration of all interactions between a considered engineering problem and the rest of the world over time.

The development of a rational basis for optimal decision making takes it origin in the fundamental axioms of utility theory by von Neumann and Morgenstern (1943) complemented with the Bayesian decision theory by Raiffa and Schlaifer (1961). Since then a significant number of researchers have contributed to the understanding of this theoretical basis by investigating and questioning its foundation and by applying it for the purpose of decision making in various types of application areas.

In parallel to the mentioned theoretical developments on risk based decision making, significant efforts have been directed on establishing procedural frameworks for risk assessment and risk analysis see e.g. AS/NZS 4360 (1999) and Faber and Stewart (2003) for an overview. Most of these developments have been initiated by governments and/or industries with the purpose of protecting the interests of both individuals and society in general, against possible adverse effects from economical activities and societal developments. These generic procedural frameworks constitute relevant and useful support in regard to which procedural steps to consider in risk based decision making but do not provide much guidance on how to appropriately represent or model the considered problem in consistency with the available knowledge about the problem. This concerns in particular the important aspects of representing the mechanisms leading to consequences, representing how uncertainties influence the statistical characteristics of consequences and most importantly how risks may be updated and managed by utilization of additional knowledge.

During the last four decades the Joint Committee on Structural Safety (JCSS) has explored the merits of the Bayesian decision theory for the purpose of supporting engineering decision making; first in the field of structural design JCSS Probabilistic Model Code (PMC) (2001) and more recently in the development of a general guideline for risk based engineering decision making Faber et al. (2007a). In the present paper the focus is directed on how this guideline may enhance an efficient and consistent management of risks due to natural hazards. First a short discussion is given on the general aspects of the problem together with some of the typically applied system characteristics. Thereafter, the framework for risk based decision making proposed by the JCSS is presented with specific remarks on its adaptation for management of risks due to natural hazards. Finally it is illustrated how the suggested modelling framework has been applied on selected aspects relating to the management of risks due to earthquake hazards.

2 THE NATURAL HAZARDS RISK MANAGEMENT PROBLEM

Natural hazards constitute a significant risk contribution in most countries of the world; however, the relevant types, intensities and associated risks depend strongly on the specific location. In more developed parts of the world risks due to natural hazards usually are not endangering the existence of the societies located there but this is unfortunately rather common in many developing countries.

Despite the different premises in developed and developing countries the common issue is that efficient and informed decision making is a prerequisite for improved quality of life of the individuals in society. It is in this context the engineering profession is facing one of its major challenges; supporting societal decision making on the management of natural hazards.

Risk management may be seen relative to the occurrence of events of natural hazards; i.e. risk management in the situations before, during and after the event of a natural hazard. This is because the possible decision alternatives or boundary conditions for decision making change over the corresponding time frame. Before a hazard occurs the issue of concern is to optimize investments into safe guarding or so-called preventive measures such as e.g. protecting societal assets, adequately designing and strengthening societal infrastructure as well as developing preparedness and emergency strategies. During the event of a natural hazard the issue is to limit damages by rescue, evacuation and aid actions. After an event the situation is to some degree comparable to the situation before the event, however, after the event resources might be very limited and the main concern might be to re-establish societal functionality as well as to safeguard in regard to the possible next event. In Fig.1 the different decision situations and the focus of risk management for natural hazards is illustrated for the case of management of earthquake risks in an urban area.

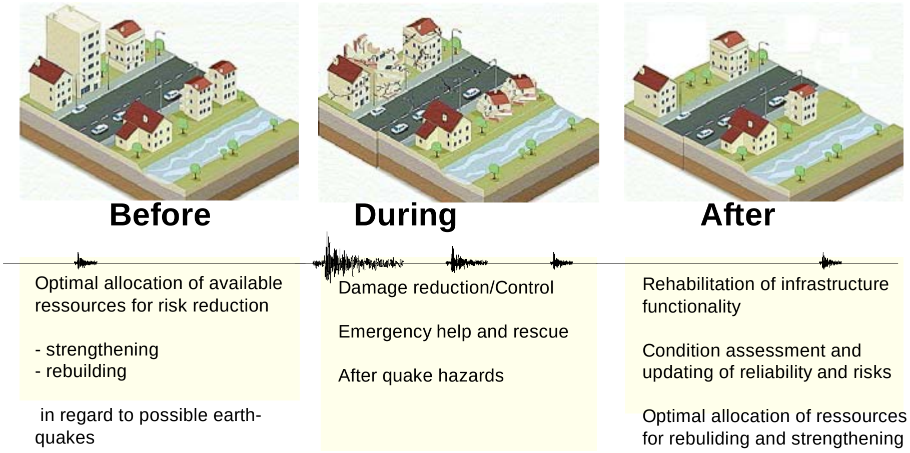

Fig.1 Decision situations for management of earthquake risks, Bayraktarli et al. (2004)

The characteristics of natural hazards are very different depending on the individual hazard types. Gravitational hazards such as meteorite impact, rock-fall, landslides and avalanches are generally very suddenly occurring events. The same applies for earthquakes, tsunamis and volcanic eruptions. Floods and fire storms are generally more slowly evolving and climatic changes and e.g. droughts are much slower again. In a risk management context the characterization of hazards take these differences in to account in order to facilitate a realistic assessment of the possible consequences as well as to allow for the identification of possible relevant measures of risk reduction. For suddenly occurring events usually the probability of the event itself is needed; e.g. the probability that a flood will occur or the probability of an earthquake. However, more characteristics or indicators are needed such as to facilitate a modelling of the possible consequences of the event. Considering earthquakes typically applied indicators are the Peak Ground Acceleration (PGA) and the earthquake magnitude (M), see e.g. Bayraktarli et al., (2006). These indicators are useful because knowledge about them provide basis for assessing the potential damages caused by earthquakes such as liquefaction of soil and damages to buildings caused by the dynamic excitation from the earthquake.

The consequences which potentially may be caused by different hazards are manifold and generally depend strongly on the specific characteristics of the hazard as well as the location where it occurs. A range of different terms to characterize the effect of natural hazards are applied across the different disciplines. Among these, vulnerability, resilience, robustness and adaptive capacity are used most frequently.

In Alwang et al., (2001) a review is provided on different interpretations of vulnerability from a wide range of different disciplines. There it is emphasized that vulnerability should be related to risk in terms of expected potential future losses considering all possible events which may lead to such. Furthermore, it is underlined that vulnerability needs to be related to a time reference. In vulnerability assessments such as performed in the context of decision making for allocation of support to developing countries (see Alwang et al., (2001)) the discussion repeatedly focuses on the importance of specific consideration of losses beyond a certain threshold defining a state where a system or society will no longer operate adequately, e.g. not provide livelihoods with a certain minimum standard of living. Throughout the literature vulnerability is seen as a multidimensional property of a considered system including basically all aspects of significance for managing risks. Thereby also political and organizational aspects, available resources as well as the ability to prevent, respond, adapt and learn.

The term resilience in accordance with its Latin origin may be associated with a systems elastic ability to return to its original state after some perturbation. Usually, in risk assessment resilience is applied in a qualitative manner as a descriptor of a considered system’s or society’s ability to rehabilitate its main functions, e.g. such as e.g. livelihood, appreciating that the considered system may indeed be very dissipative, i.e. far from elastic, see e.g. Klein et al., (2003) and changes in its state variables are associated with significant losses. The same or similar meanings are typically associated with the term adaptive capacity, see Brooks, (2003) which serves as a measure of the ability of a given system to adapt to new situations and thereby maintain and or even improve functionality.

Robustness is often applied to characterize the response of a system to given changes in the system state variables. Different interpretations of robustness are available in the different disciplines. In structural engineering a robust structural system is understood as a structure which will not loose functionality at a rate or extent disproportional to the cause of the change in the state variables. In the context of risk assessment the meaning of robustness is generally very close to the meaning of resilience and adaptive capacity; the later mentioned being a characteristic of a systems ability to sustain, reduce and manage losses such that the system as such may survive.

As it might be realized from the outline of the existing terminology in the field of natural hazards risk management there is a certain overlapping of the meaning of the applied terms. Furthermore, the use of the terms seems to have a strong rooting in disciplinary traditions.

3 THE JCSS FRAMEWORK FOR RISK BASED DECISION MAKING

In Faber et al., (2007a) an outline of the JCSS guideline on risk based decision making in engineering is provided. This guideline is of a very general or generic character and can in principle be applied for any type of engineering decision making problem, however, with a certain interpretation. In the following the JCSS guideline is presented together with interpretations and discussions relating to its use for the purpose of natural hazards risk management.

3.1 Risk based decision making

Due to the fact that our understanding of the aspects involved in natural hazards risk management problems is far less than perfect and that we are only able to model the involved physical processes as well as human interactions in rather uncertain terms the decision problem is subject to significant uncertainty. It is thus not possible to assess the result of decisions in certain terms; there is no way to assess with certainty the consequences resulting from the decisions we make. However, what can be assessed are the risks associated with the different decision alternatives. Based on risk assessments decision alternatives may thereby be consistently ranked, see Raiffa and Schlaifer, (1961). If the concept of risk as the simple product between probability of occurrence of an event with consequences and the consequence of the event is widened to include also the aspects of the benefits achieved from the decisions then risk may be related directly to the concept of utility from the economical decision theory and a whole methodical framework is made available for the consistent identification of optimal decisions. This framework is considered to comprise the theoretical basis for risk based decision making and the following is concerned about the application of this for the purpose of risk based decision making for society.

3.2 Decisions and Decision makers

Engineering decision making and risk assessment for the management of natural hazards is usually performed on behalf of society. It is thus useful to consider a society as an entity of people for which common preferences may be identified exogenous boundary conditions are the same and which share common resources. It is clear that this definition may be applied to unions of states or countries, individual states and countries as well as local communities depending on the context of the decision making, however, it is seen that the geographical limitations are not essential even though they often in reality are implicitly given by the other attributes. Considering a state or a country as a society it may be realized that such a society may comprise a hierarchical structure of societies defined at lower levels, such as cantons, municipalities and communities; each society with their set of attributes partly defined through the societies at higher level.

3.3 Risk Based Decision Making

In Fig.2 risk based decision making is illustrated in a societal context from an intergenerational perspective; see also Faber and Nishijima, (2004). Within each generation decisions have to be made which will not only affect the concerned generation but all subsequent generations. It should be emphasized that the definition of the system in principle must include a full inventory of all potentially occurring consequences as well as all possible scenarios of events which could lead to the consequences. In the face of management of risk due to natural hazards this aspect is of significant importance when hazards related to climatic changes are considered, but also not least when assessing the impact of changes on the environment or landscape made by humans. There is a significant coupling between the activities of humans and the mechanics of hazards; this interaction must be accounted for in the decision making; avoiding decision making which on a short term in beneficial but in a longer and sustainable perspective is clearly inappropriate.

At an intra-generational level the characteristics of the system consist of the knowledge about the considered assets within a geographically bounded area and the surrounding world, the available decision alternatives and criteria (preferences) for assessing the utility associated with the different decision alternatives. The assets comprise in principle jointly and individually any value i.e. functionality, object, person and environmental quality which may be damaged or lost as a consequence of the natural hazards within the considered area. A very significant part of risk based decision making in practice is concerned about the identification of the characteristics of the assets, the interrelations with the surrounding world (i.e. how may consequences evolve outside of the considered geographical area) as well as the identification of acceptance criteria, possible consequences and their probabilities of occurrence. Managing risks is done by "buying" physical changes of the considered assets (e.g. protection, warning, strengthening, re-allocation) and by "buying" knowledge about the assets (how susceptible are they against natural hazards and how are they best safeguarded) and the surrounding world (the characteristics of possible hazards) such that the objectives of the decision making are optimized.

A system representation can be performed in terms of logically interrelated constituents at various levels of detail or scale in time and space. Constituents may be humans, physical components, procedural processes and human activities and thus partly include the assets, however, their interrelation in forming joint functions constitute additional assets. The appropriate level of detail or scale depends on the physical or procedural characteristics or any other logical entity of the considered problem as well as the spatial and temporal characteristics of consequences. The important issue when a system model is developed is that it facilitates a risk assessment and risk ranking of decision alternatives which is consistent with available knowledge about the system and which facilitates that risks may be updated according to knowledge which may be available at future times.

3.4 System Representation in Risk Assessment

In Fig.2 risk based decision making is illustrated in a societal context from an intergenerational perspective; see also Faber and Nishijima, (2004). Within each generation decisions have to be made which will not only affect the concerned generation but all subsequent generations. It should be emphasized that the definition of the system in principle must include a full inventory of all potentially occurring consequences as well as all possible scenarios of events which could lead to the consequences. In the face of management of risk due to natural hazards this aspect is of significant importance when hazards related to climatic changes are considered, but also not least when assessing the impact of changes on the environment or landscape made by humans. There is a significant coupling between the activities of humans and the mechanics of hazards; this interaction must be accounted for in the decision making; avoiding decision making which on a short term in beneficial but in a longer and sustainable perspective is clearly inappropriate.

At an intra-generational level the characteristics of the system consist of the knowledge about the considered assets within a geographically bounded area and the surrounding world, the available decision alternatives and criteria (preferences) for assessing the utility associated with the different decision alternatives. The assets comprise in principle jointly and individually any value i.e. functionality, object, person and environmental quality which may be damaged or lost as a consequence of the natural hazards within the considered area. A very significant part of risk based decision making in practice is concerned about the identification of the characteristics of the assets, the interrelations with the surrounding world (i.e. how may consequences evolve outside of the considered geographical area) as well as the identification of acceptance criteria, possible consequences and their probabilities of occurrence. Managing risks is done by “buying” physical changes of the considered assets (e.g. protection, warning, strengthening, re-allocation) and by “buying” knowledge about the assets (how susceptible are they against natural hazards and how are they best safeguarded) and the surrounding world (the characteristics of possible hazards) such that the objectives of the decision making are optimized.

A system representation can be performed in terms of logically interrelated constituents at various levels of detail or scale in time and space. Constituents may be humans, physical components, procedural processes and human activities and thus partly include the assets, however, their interrelation in forming joint functions constitute additional assets. The appropriate level of detail or scale depends on the physical or procedural characteristics or any other logical entity of the considered problem as well as the spatial and temporal characteristics of consequences. The important issue when a system model is developed is that it facilitates a risk assessment and risk ranking of decision alternatives which is consistent with available knowledge about the system and which facilitates that risks may be updated according to knowledge which may be available at future times.

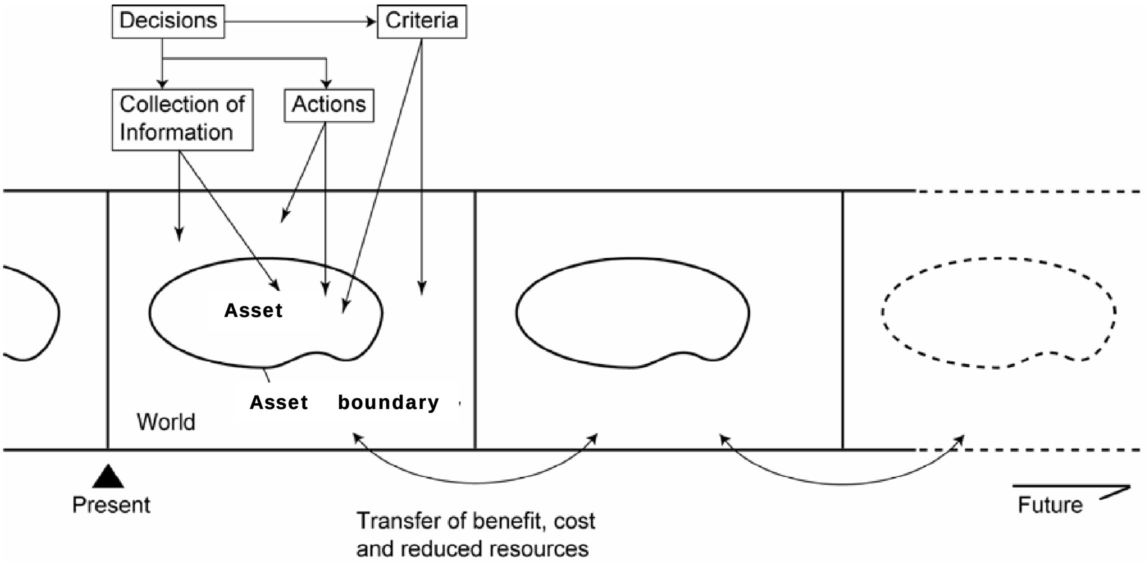

Fig.2 Main constituents of systems in risk based intra-/intergenerational decision analysis, (Faber and Nishijima, (2004))

3.5 Modelling of Consequences

The long term consequences of so-called disasters are sometimes wrongly assessed as being positive for society, due to the various positive effects caused by the forced renewal of societal infra-structure. The reason why this is a wrong assessment is due to the fact that societal losses including not least loss of lives would be smaller or even zero, if renewals are planned and organized instead of random and chaotic. Furthermore, whereas it might be true that some positive effect may arise even out of forced renewals this is conditional on the ability and economical capacity of the affected society to recuperate from the event. This may be the case in well developed countries, but constitutes a core problem in developing countries.

When considering the mechanism of consequences it is useful to differentiate between consequences associated with damages on the assets comprising constituents of the considered system, and losses going beyond these. First of all the immediate or direct consequences of natural hazards comprise loss of lives, damages to societal infrastructure and life lines as well as damages to the qualities of the environment. Follow-up or indirect consequences may include additional loss of lives caused by outbreak of epidemics or hunger. The indirect consequences may, however, also include losses of livelihoods, damages to the local and/or global economy as well as sociological effects. In risk management of systems such as societies of developing countries and ecosystems the possible consequences may not only be related to economical losses or losses of lives and habitants but as mentioned earlier may threaten the existence of the civilization in the considered geographical area itself.

The risk assessment for a given system is facilitated by considering the generic representation of the development of consequences shown in figures 3-4. Following Faber et al. (2007a) the hazards are represented as exposures to the asset and include any event acting on the constituents of the asset with the potential to damage these. The constituents of the asset can be considered as the first defense of the assets in regard to the exposures. The damages of the constituents are considered to be associated with direct consequences. Direct consequences may comprise different attributes of the asset such as monetary losses, loss of lives, damages to the qualities of the environment or just changed characteristics of the constituents.

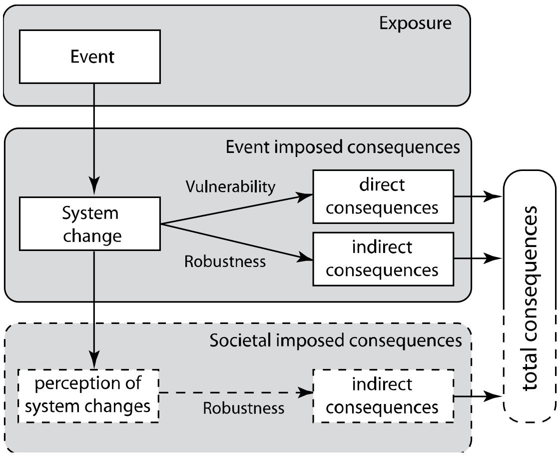

Fig.3 Representation of the mechanism generating consequences, (Faber et al., (2007a))

Based on the combination of events of constituent failures and the corresponding consequences indirect consequences may occur. Indirect consequences may be caused by e.g. the sum of monetary losses associated with the constituent failures and the physical changes of the asset as a whole caused by the combined effect of constituent failures. The indirect consequences in risk assessment play a major role, and the modeling of these should be given great emphasis, Faber and Maes, (2004). Typically the indirect consequences evolve spatially beyond the boundaries of the asset and also have a certain, sometimes even postponed development in time. It is clear that these characteristics must be accounted for in their assessment.

It is noted from Fig.3 that two types of indirect consequences are differentiated, namely the indirect consequences due to physical system changes and the indirect consequences caused by the societal or public perception of these. The reason for this differentiation is to indicate how risk management may efficiently be supported by risk communication. The better and more targeted risk communication undertaken before during and after events of natural hazards the smaller the consequences caused by perception will be. Often traditional risk assessments focus on the assessment of direct consequences and do not attempt to model the indirect consequences by rigorous modeling. Instead indirect consequences are included by somehow amplifying the direct consequences by means of a risk aversion function the characteristics of which generally are assessed subjectively. Indeed it is a little puzzling that the often more important contribution to consequences is commonly modeled by means of the simplest possible approximation, see e.g. Faber et al., (2007b) for a more thorough discussion on this issue. The approach suggested here where consequences are differentiated in to different components is meant to circumvent a too simplistic modeling, bringing the indirect consequences direct into focus and indicating the different ways they might be controlled.

Based on the system representation outlined in the forgoing it is now possible to introduce two system characteristics, namely the vulnerability and the robustness. The vulnerability of a given system characterizes the risk associated with the direct consequences and the robustness characterizes the degree the total risk is increased beyond the direct consequences. The three characteristics (exposure, vulnerability and robustness) which will be defined in the following are only unambiguous subject to a definition of the system.

In consistency with Haimes, (2004) it should be noted that very often the asset functionalities can be modeled as a logical system comprised by its own constituents. An asset could be a road network with constituents being e.g. bridges and segments of roads, see Fig.5. The bridges in turn could be modeled by logical systems with constituents being structural members. Depending on the level of detail in the risk assessment, i.e. the system definition, the considered geographical area, the exposure, constituents and consequences would be different.

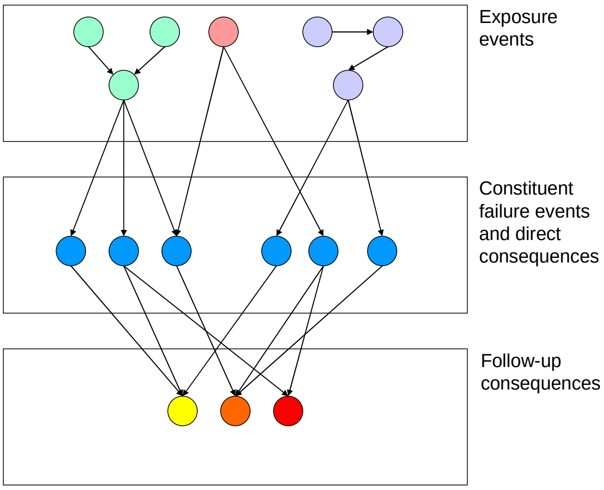

Fig.4 Logical representation of interrelation between exposures, constituent failures, sequences of constituent failures and consequences, (Faber et al., (2007a)

The hierarchical risk assessment framework is applicable at any level of scale for the assessment of a given system. It may be applied to components, sub-systems and the system as a whole; thereby the framework also facilitates a hierarchical approach to risk assessment. The definition of the system in this context becomes of tremendous significance in the definition of exposure, vulnerability and robustness.

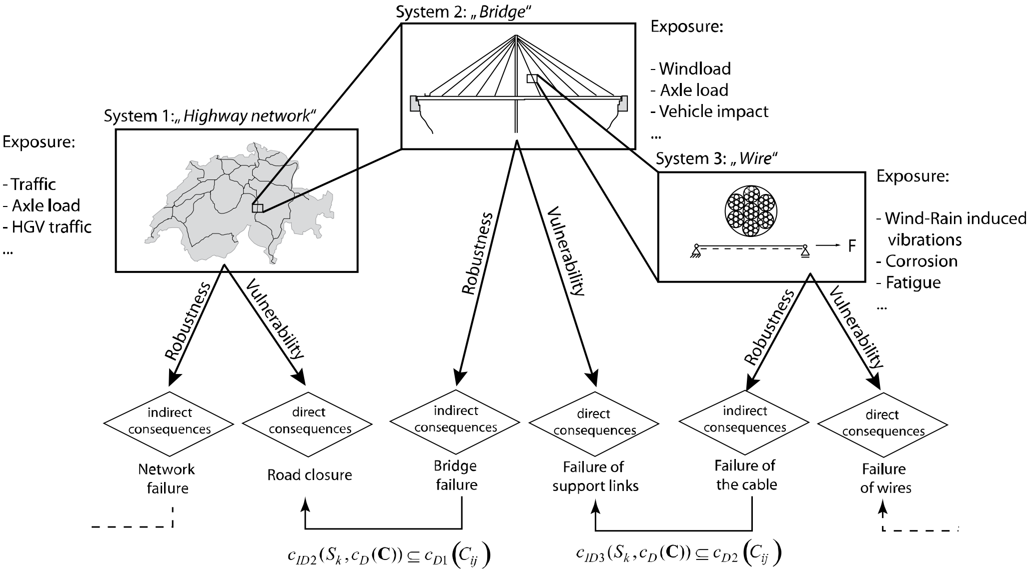

Fig.5 Generic system characterization at different scales in terms of exposure, vulnerability and Robustness, (Faber et al. (2007a)

4 REPRESENTATION OF KNOWLEDGE IN RISK ASSESSMENT

In the management of risks due to natural hazard the considered asset, exposure and consequences are all characteristics of the system with a pronounced dependency of time and space. Assets may be distributed or concentrated geographically and depending on this may be exposed to different hazards. Some exposure events like earthquakes and hurricanes are associated with a large impact area and may induce severe consequences for larger cities and even regions. Others exposures like avalanches and rock-falls are associated with a comparative much smaller impact area such as a few houses and roadway segments. However, not only the size of the impact area is of importance, also the possible dependencies between events at different locations and at different points in time play a role in the risk management. Severe precipitation which may be associated with a relatively large impact area is a precursor for a range of natural hazards such land slides, rock.-fall and avalanches which in turn all are associated with a small impact area. In managing risks over larger areas like regions and countries it is thus of large importance to account for the dependency introduced through e.g. the precipitation. In a similar way global oceanographic events like the el Niño effect introduces general climatic changes with changes in e.g. precipitation and frequencies of hurricanes. Due to such effects the risk pattern in a given geographical area in terms of exposure types, frequency and intensity may exhibit significant non-ergodic variations over time

Not only the exposure events require a careful treatment in the risk assessment but also the consequences of the exposure events and the activities of humans depend on spatial and temporal characteristics. Concentrated large assets may be less exposed to a certain natural hazard but at the same time increase the overall consequences should the hazard actually occur. As mentioned previously consequences also exhibit a temporal dependency; some consequences will depend on the season and time of the day when they occur. In addition consequences also may have delayed effects. Examples hereof are loss of arable land due to salination caused by Tsunamis and diseases' in the aftermath of floods. Such delayed effects depend on the specifics of a considered system and are difficult to categorize in general terms. However, the common feature is that the extent to which they will occur depends on a complex interrelation of several events and conditions.

Due to the hierarchical structure of the system representation and the temporally and spatially varying characteristics of exposure events and consequences the risk assessment is greatly supported by the Bayesian probability theory and modern risk assessment tools such as e.g. Bayesian Probabilistic Nets and Influence Diagrams, Pearl (1988).

The Bayesian probability theory facilitates the consistent representation of uncertainty independent of their source and type; purely subjectively assessed uncertainties, analytically assessed uncertainties and evidence as obtained through observations may be combined. It has become standard to differentiate between uncertainties due to inherent natural variability (aleatory/type I), model uncertainties and statistical uncertainties (epistemic/type II). This differentiation is useful for the purpose of setting focus on how uncertainty and risks may be reduced by collection of additional information. Furthermore, the understanding of the different types of uncertainty is required for the correct assessment of risks. However, if all relevant consequences have been included in the risk assessment a differentiated treatment in the decision analysis, is not appropriate, see Faber (2005).

4.1 Assessment of probabilities

In the assessment of risk the probabilities of the different events associated with consequences must be evaluated. In principle if the consequence inducing events are well defined methods of probability analysis such as crude Monte Carlo simulation, Engelund et al. (1993), allow for the accurate assessment of their probabilities. For a very large class of problems methods of modern reliability theory such as FORM/SORM and various variance reduction schemes for Monte Carlo sampling may readily be applied with significantly improved accuracy compared to crude Monte Carlos simulation (see e.g. Rackwitz (1991) and Rackwitz (2001). In the context of assessing probabilities for problems with temporal and/or spatial variability subject to both aleatory and epistemic uncertainty the appropriate probabilistic modeling necessitates that the assessment of probabilities is adapted accordingly. Probability assessment in temporally varying problems is discussed in e.g. Schall et al. (1991), Rackwitz (2001) and Bryla P. et al. (1991).

4.2 Quantification of risk

Following Faber et al. (2007) the asset which is considered subject to a risk assessment is assumed to be exposed to hazardous events (exposures EX) with probabilistic characterization $p(EX_k),\ k=1,\ n_{EXP}$, where n_{EXP} denotes the number of exposures. It is assumed that the considered asset includes n_{CON} individual constituents, each with a discrete set of damage states C_{ij} , $i=1,2..n_{CON}$, $j=1,2..n_{C_i}$. The probability of direct consequences $c_D(\mathbf{C}_l)$ associated with the l^{th} of n_{CSTA} possible different state of damage of all constituents $\mathbf{C}_l$, conditional on the exposure event

EX_k is described by $p(\mathbf{C}_l|EX_k)$ and the associated conditional risk is $p(\mathbf{C}_l|EX_k)c_D(\mathbf{C}_l)$. The vulnerability of the asset is defined as the risk due to all direct consequences (for all n_{CON} constituents) and may be assessed through the expected value of the conditional risk due to direct consequences over all n_{EXP} possible exposure events and all constituent damage states n_{CSTA}:

$$R_D = \sum_{k=1}^{n_{EXP}} \sum_{l=1}^{n_{CSTA}} p(\mathbf{C}_l|EX_k)c_D(\mathbf{C}_l)p(EX_k) \tag{1}$$

Using this definition of vulnerability in the context of management of risks due to natural hazards provides a clear representation of the expected value of immediate monetary losses, i.e. the amount of economical resources which should be allocated for renewal of societal infra-structure. It also provides an assessment of loss of lives and damages to the qualities of the environment on the short term, however, provides little information about how the consequences are contained over both time and geography. To assess these additional consequences the indirect consequences must be considered carefully.

The functionality of the considered asset depends on the state of the constituents. It is assumed that there are n_{SSTA} possible different states of the constituents S_m associated with indirect consequences $c_{ID}(S_m,c_D(\mathbf{C}_l))$. The probability of indirect consequences conditional on a given state of the constituents $\mathbf{C}_l$, the direct consequences $c_d(\mathbf{C}_l)$ and the exposure EX_k, is described by $p(S_m|\mathbf{C}_l,EX_k)$. The corresponding conditional risk is $p(S_m|\mathbf{C}_l,EX_k)c_{ID}(S_m,c_D(\mathbf{C}_l))$. The risk due to indirect consequences is assessed through the expected value of the indirect consequences in regard to all possible exposures and constituent states, as:

$$R_{ID} = \sum_{k=1}^{n_{EXP}} \sum_{l=1}^{n_{CSTA}} \sum_{m=1}^{n_{SSTA}} c_{ID}(S_m,c_D(\mathbf{C}_l)) \times p(S_m|\mathbf{C}_l,EX_k)p(\mathbf{C}_l|EX_k)p(EX_k) \tag{2}$$

The robustness of an asset is an indicator of the ability of the asset to limit total consequences to direct consequences and is defined through the ratio of risks due to direct consequences to the total risk. This characteristic may readily be quantified though the index of robustness I_R Baker et al. (2007) and Schubert and Faber (2007):

$$I_R = \frac{R_D}{R_{ID}+R_D} \tag{3}$$

which allows for a ranking of decisions in regard to their effect on robustness.

In the management of risks due to natural hazards the robustness may be seen as an indicator of the extent to which functionality losses and delayed effects of events of natural hazard exposures contribute to the overall risks. Furthermore, the robustness may be assessed conditional on the occurrence of particular exposure events as well as for parts of the considered asset in isolation then thereby provide important information on how the overall risks are may most efficiently be limited to direct consequences. Finally, information about the robustness of a considered system will also provide information on the resilience or the adaptive capacity of the system, i.e. the capability of the considered system with all available resources in regard to organization and economical resources to manage and recover the losses due to natural hazards.

In the foregoing no mention was made in regard to the time reference period to which the probabilities and consequently also the risks have to be related. A clear specification of this is of course necessary as this will influence the decision making.

4.3 Risk updating and risk indicators

Risk indicators may be understood as any observable or measurable characteristic of the considered system containing information about the risk. If the system representation has been performed appropriately, risk indicators will in general be available for what concerns both the exposure to the system, the vulnerability of the system and the robustness of the system, see Fig.6.

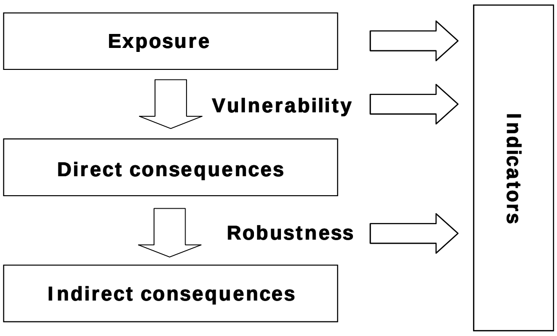

Fig.6 Risk indicators at different levels of the system representation (Faber and Maes, 2005)

In a Bayesian framework for risk based decision making such indicators play an important role. Considering the risk assessment of a load bearing structure risk indicators are e.g. any observable quantity which can be related to the loading of the structure (exposure), the strength of the components of the structure (vulnerability) and the redundancy, ductility, effectiveness of condition control and maintenance (robustness).

5 EXAMPLE-MANAGEMENT OF EARTHQUAKE RISKS

With the aim of illustrating selected aspects relating to the application of the framework presented in the foregoing an example is provided in the following based on recent research on risk management for larger geographical areas subject to earthquake hazards.

5.1 The Merci Project

Management of risks due to earthquakes is a research topic which has attracted broad attention from many different engineering disciplines and for very good reasons also the insurance industry. Whereas the treatment of this problem complex necessitates in depth knowledge of several disciplines of natural science and engineering an additional challenge lies in the interdisciplinary understanding required to interface these disciplines consistently for the assessment and the management of risks. Within the MERCI project Bayraktarli et al. (2004) management of earthquake risks is approached by considering the tree different decision situations; before, during and after the event of an earthquake, see Fig.1.

5.2 Utilizing GIS in the spatial representation of the system

The methodical idea in the MERCI project is to utilize the Bayesian decision theory in conjunction with generic risk assessment models; including important model components ranging from the modelling of the seismic event itself, over the behaviour of the soil to the response of structure categories and the further development of different types of consequences. Indicators of risk in terms of observations and data are achieved from satellite and aerial photographs and utilized by the generic risk models. The whole set of modules and data are managed by a Geographical Information System (GIS) which in the end is used for the optimization of strategies for the management of risks before, during and after an earthquake event, see Fig.7.

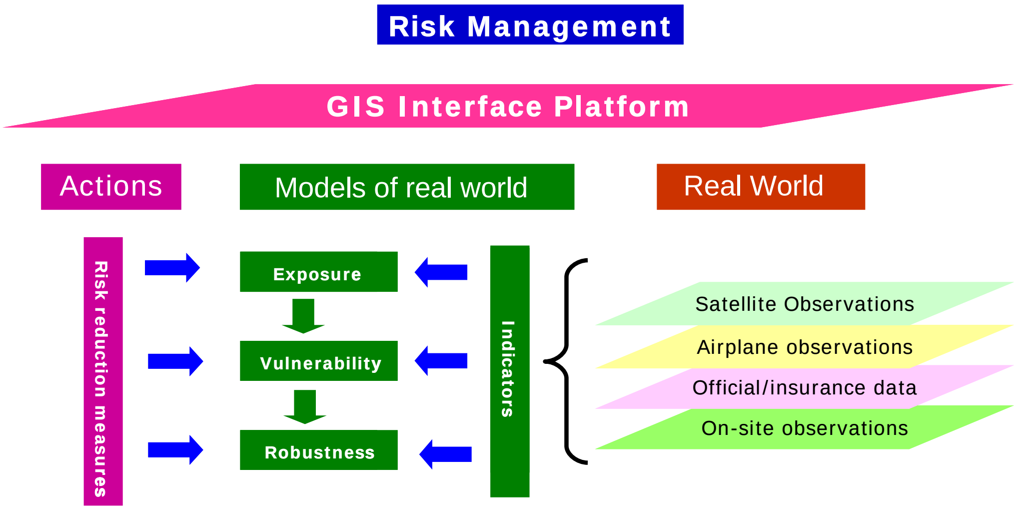

Fig.7 Illustration of the structure of the risk management in the Merci project

The management of earthquake risks involves a long series of challenges in which the temporal and spatial representation of uncertainties play important roles. This concern not least the modelling of the earthquakes themselves, the propagation of the earthquake waves through the stratum, the characteristics and the behaviour of the soil, buildings and infrastructures subjected to the earthquake excitation. The uncertainties involved in any model of these phenomena include model and statistical uncertainties as well as inherent natural variability. Information can be obtained in regard to the parameters which have influence on the assessment of risks; however, this information, whether it is achieved from visual surveys, by testing of building performance or soil samples or achieved through aerial or satellite photographs is also associated with often significant uncertainty. As the assessment of risks must take all these uncertainties into account the data are conveniently managed in GIS systems as illustrated in Fig.8.

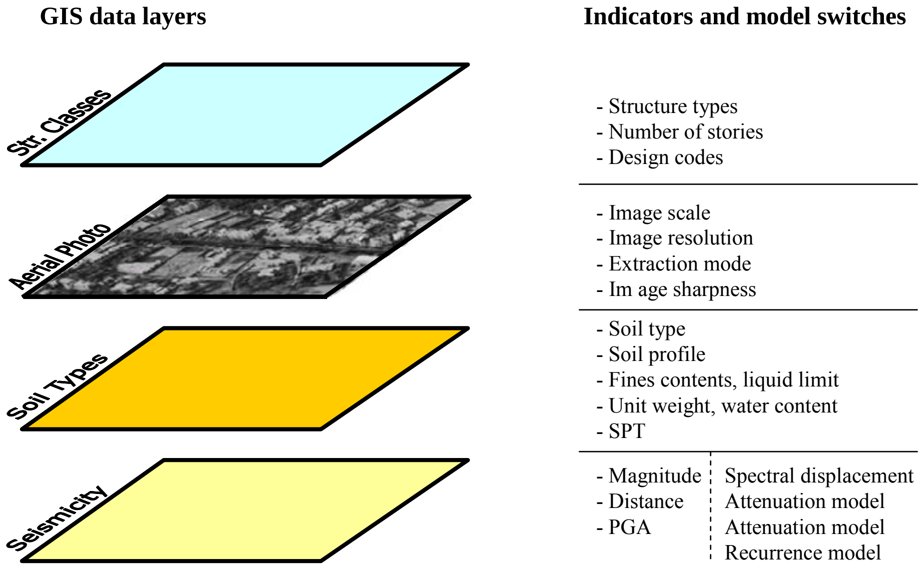

Fig.8 Illustration of the storage of geographical specific information in the GIS system

5.3 Generic indicator based risk models

As outlined in Bayraktarli et al. (2005) the risks as well as optimal decision options are identified through generic risk models utilizing hierarchical Bayesian modeling and utilizing BPN's.

Available information which has influence on the risks is represented through indicators. Indicators might be information characterizing the class of structures, the characteristics of the soils, the distance to the known fault lines, etc, see Fig.8.

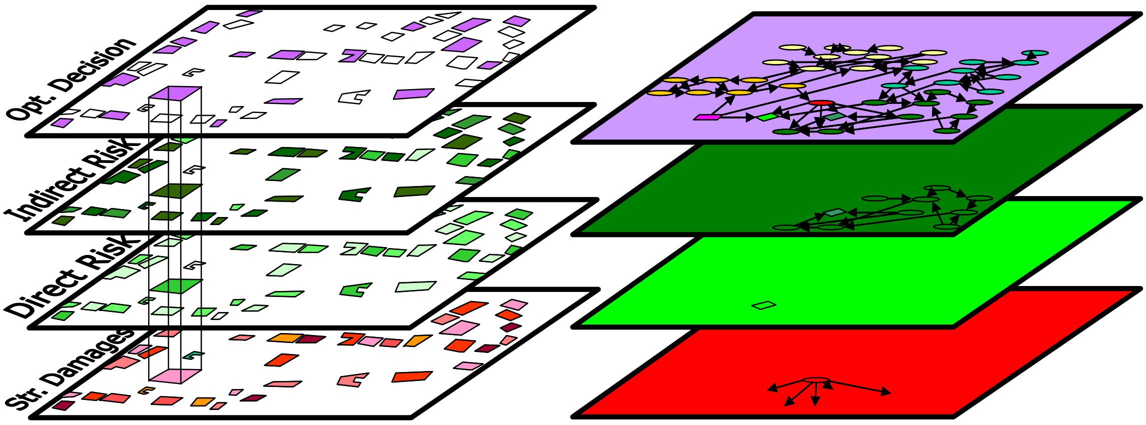

Fig.9 Illustration of the organization of the generic hierarchical Bayesian risk modelling in the GIS system

As an example of one of the applied risk models a BPN is shown in Fig.10 corresponding to the assessment of the liquefaction probability at any given location based on the indicators outlined in Bayraktarli et al., (2006) and Buchheister et al. (2006).

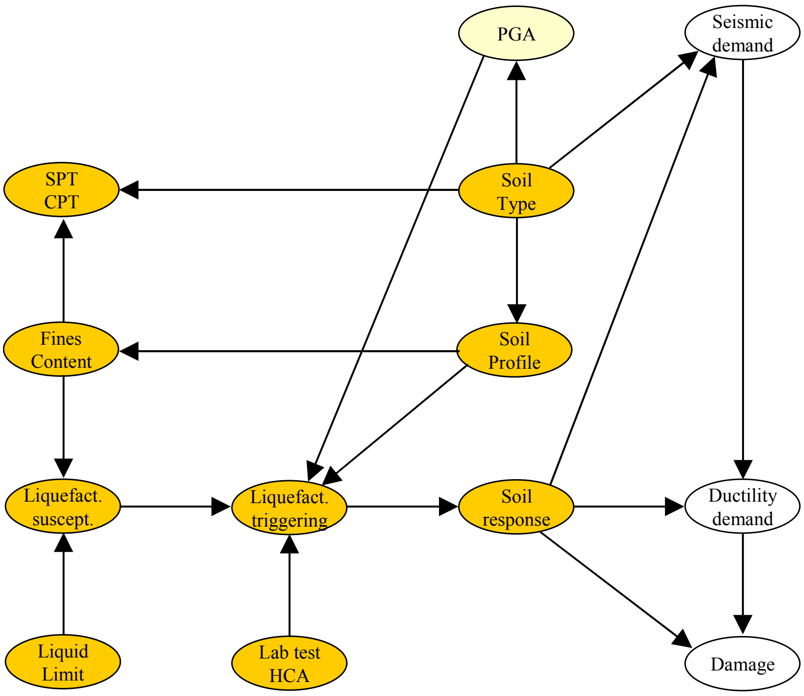

Fig.10 Illustration of the BPN applied for the assessment of the probability of liquefaction at any given location in the considered geographical area based on indicators

By coupling the BPN illustrated in Fig.10 with the indicators stored in the GIS database the probability of liquefaction for given earthquake scenarios is readily calculated as illustrated in Fig.11. The calculation of the conditional probability tables specifying the variables shown in the BPN is based on data as well as methods of modern reliability theory, see also Bayraktarli et al. (2006)

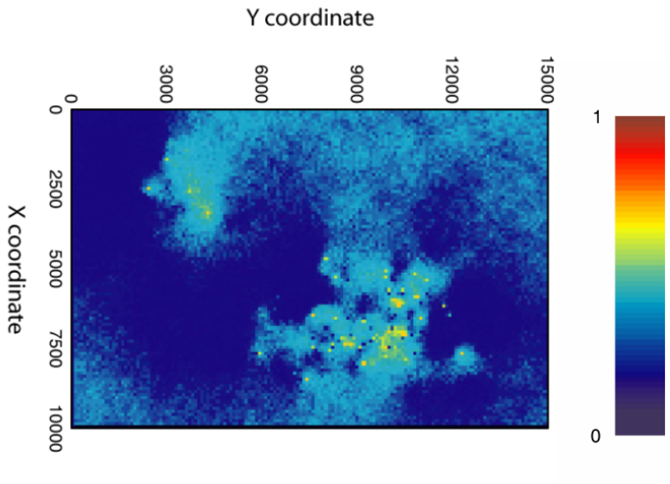

Fig.11 Calculated probability of liquefaction for an earthquake of magnitude 7.5 and a PGA of 0.3 m/s^2

5.4 Loss Estimation

The use of indicator based risk models facilitates that generic risk models are developed which through the indicators can be made specific for each individual building in e.g. a large city. In this way only a few risk models need to be developed to assess e.g. the expected losses due to damages of buildings; the same net can be applied for all buildings using the indicators which are stored in the GIS database for each building, see Fig.9.

As an example of the integral use of the proposed framework for risk assessment consider the illustration given in Fig.12 illustrating a typical distribution of losses corresponding to direct consequences for the building structures in a given area.

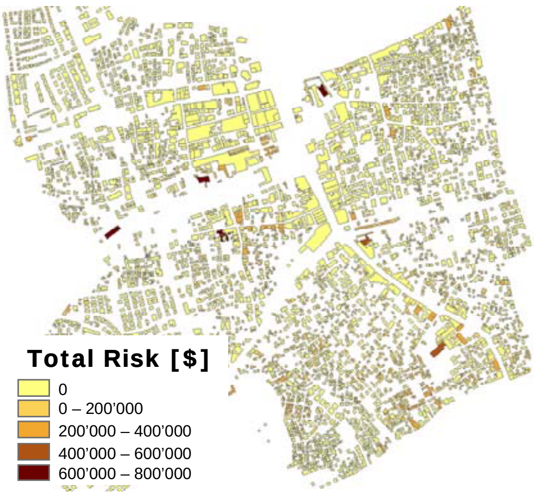

Fig.12 Typical distribution of expected losses over the structures in a given geographical area

Integral risk assessment and management utilizing a system where all available information is represented in terms of indicators provides not only the basis for identifying in which way earthquake risks might be reduced most efficiently in terms of soil improvements or retrofitting of different classes of structures in accordance to different schemes. Moreover, such an integral framework facilitates that optimal decisions can be identified for the cost efficient improvement of knowledge, see Bayraktarli and Faber (2007).

6 CONCLUSIONS

The present paper addresses risk assessment in the face of natural hazards. Basis is taken in presently ongoing work by the Joint Committee on Structural Safety (JCSS) on the development on a guideline for risk based decision making in engineering. The approach proposed in this guideline is adapted to the specifics of management of risks due to natural hazards and various specific aspects of importance are outlined and discussed. The proposed approach does not focus on the procedure of risk based decision making but rather on the system representation, i.e. the engineering modeling ranging from the mechanisms generating consequences over the modeling of knowledge and uncertainties and the hierarchical structure of how individual system constituents interrelate in a causal manner in supporting functionality. The framework, furthermore, suggests representing the considered systems in terms of exposures, vulnerability and robustness, where vulnerability is linked to the magnitude of direct risks and robustness the degree to which direct risks are amplified. The proposed framework is hierarchically structured in regard to how exposures, consequences and knowledge interact in the generation of risks and this suggests that Bayesian hierarchical models are utilized to support the risk assessment. Finally the suggested framework has a generic characteristic which suggests that generic risk models are established and adapted to a given specific situation by means of indicators.

The framework is illustrated on an example considering management of earthquake risks at large geographical scales utilizing generic indicator based risk models and data management supported by Geographical Information Systems. It is shown how the GIS system facilitates management of specific information of relevance for the assessment of risks for a give geographical location and it is outlined how this framework facilitates the assessment of risks for large portfolios of assets.

The consistent representation of uncertainty in time and space in all steps of the risk assessment in the management of risks due to natural hazards constitutes a major challenge in bringing the methods of the modern structural reliability theory, risk assessment and decision analysis into practice. Each practical problem has its own specifics, but it is also important to realize the similarities. Over time it would be a great benefit for the engineering profession to establish as certain level of standardization in the probabilistic modeling of events and their consequences. Significant contributions in this direction are collected in (JCSS, 2001) but there are still many important amendments and improvement to be made.

It is a great challenge for the engineering profession to provide methods and tools enhancing decision making for the purpose of efficient management of natural hazards. Considering the tremendous effects which may be associated with changing climate in general it seems evident that much more research and developments is needed in the coming years to support decision making on how to cope with increased occurrences of strong wind storms, floods and droughts and their associated consequences for the population around the earth.

ACKNOWLEDGEMENTS

The author greatly acknowledges financial support by the Swiss National Science Foundation (SNF) in the framework of the interdisciplinary research project “Management of Earthquake Risks using Condition Indicators” (MERCI).

REFERENCES

Alwang, J., P. Siegel and S. Jorgensen (2001), ‘Vulnerability: a View from Different Disciplines’, Social Protection Unit, Human Development Network, World Bank, May, 2001.

AS/NZS 4360 (1999), Risk Management, Standards Australia, Sydney.

Baker, J. W., Schubert, M. and Faber, M. H. (2007). "On the assessment of robustness." Journal of Structural Safety, in press

Bayraktarli, Y.Y., Ulfkjaer, J.-P., Yazgan, U. and Faber, M.H. (2005), On the Application of Bayesian Probabilistic Networks for Earthquake Risk Management, Proceedings ICOSSAR'05, ed. G. Augusti, G.I. Schuëller, M. Ciampoli, 9th International Conference on Structural Safety and Reliability, Rome, June 19-23, 2005. pp. 3505-3512.

Bayraktarli, Y.Y., Faber, M.H., Laue, J., Grün, A., Dazio, A., Schalcher, H.-R. and Hollenstein, K. (2004), Management of Earthquake Risks using Condition Indicators Proceedings 14th International Conference on Engineering Surveying, Zurich, Switzerland, March 15-19, 2004.

Bayraktarli, Y.Y., Yazgan, U., Dazio, A. and Faber, M.H. (2006), Capabilities of the Bayesian probabilistic networks approach for earthquake risk management, Proceedings of ECEES, First European Conference on Earthquake Engineering and Seismology, Geneva, Switzerland, September 3-8, 2006.

Bayraktarli, Y. and Faber, M.H. (2007), Value of information analysis in earthquake risk management. 10th International Conference on Applications of Statistics and Probability in Civil Engineering, The University of Tokyo, Kashiwa Campus, JAPAN.

Brooks, N. (2003), Vulnerability, risk and adaptation: A conceptual framework, Tyndall Centre for Climate Change Research and Centre for Social and Economic Research on the Global Environment, School of Environmental Sciences, Working Paper No. 38, http://edcintl.cr.usgs.gov/SEMSOC/uploads/File/Brooks_Vy_risk_adapt.pdf, 2003.

Bryla, P., Faber, M. H. and Rackwitz, R. (1991). Second Order Methods in Time Variant Reliability Problems. Proceedings OMAE'91, 10th International Conference on Offshore Mechanics and Arctic Engineering, Stavanger, Norway.

Buchheister, J., Bayraktarli, Y.Y., Laue, J. and Faber, M.H. (2006), Uncertainties in a deterministic and probabilistic approach on liquefaction susceptibility, Proceedings of ECEES, First European Conference on Earthquake Engineering and Seismology, Geneva, Switzerland, September 3-8, 2006.

Engelund, S. and Rackwitz, R. (1993). "A benchmark study on importance sampling techniques in structural reliability." Structural Safety 12(4): 255-276.

Faber, M.H, (2005) On the Treatment of Uncertainties and Probabilities in Engineering Decision Analysis, Journal of Offshore Mechanics and Arctic Engineering, Trans. ASME, 127(3), August 2005, pp. 243-248.
Faber M.H. and Stewart M.G. (2003). "Risk Assessment for Civil Engineering Facilities: Critical Overview and Discussion." 80(2): 173-184.

Faber, M.H. and Maes, M.A. (2004), Modeling of Risk Perception in Engineering Decision Analysis, Proceedings 11th IFIP WG7.5 Working Conference on Reliability and Optimization of Structural Systems, eds. M.A. Maes and L. Huyse, 2004, pp. 95-104.

Faber, M.H. Nishijima, K. (2004), Aspects of Sustainability in Engineering Decision Analysis, In proc. to the 9th ASCE Specialty Conference on Probabilistic Mechanics and Structural Reliability, Albuquerque, New Mexico, ASU, July 26-28, 2004.

Faber, M. H., Maes, M. A., Baker, J. W., Vrouwenvelder, T., and Takada, T. (2007a). Principles of Risk Assessment of Engineered Systems. 10th International Conference on Applications of Statistics and Probability in Civil Engineering, The University of Tokyo, Kashiwa Campus, JAPAN.

Faber, M.H., Schubert, M. and Baker, J. (2007b), Decision making subject to aversion of low frequency high consequence events, Special Workshop on Risk Acceptance and Risk Communication, March 26-27, 2007, Stanford University.

Haimes, Y.Y. (2004), Risk Modeling, Assessment, and Management, Wiley-IEEE, 2004.

JCSS (2001). Probabilistic Model Code, The Joint Committee on Structural Safety, www.jcss.ethz.ch.
Klein J.T., Nicholls, R. J., Thomalla, F. (2003), Resilience to natural hazards: How useful is this concept?, Global Environmental Change Part B: Environmental Hazards, 5(1-2), pp. 35-45.

Pearl, J. (1988), Probabilistic Reasoning in Intelligent Systems: Networks and Plausible Inference, San Mateo, California, USA,: Morgan Kaufmann.

Rackwitz, R. (1991). Structural Reliability Methods-Solutions and Problems in Probability Integration. Proceedings of ICASPG, Mexico City.

Rackwitz, R. (2001). "Reliability analysis--a review and some perspectives." Structural Safety 23(4): 365-395.

Schall, G., Faber, M. H. and Rackwitz, R. (1991). "The Ergodicity Assumption for Sea States in the Reliability Assessment of Offshore Structures." Journal of Offshore Mechanics and Arctic Engineering, Trans. ASME 113(3): 241-246.

Schubert, M. and Faber, M. H.(2007), Robustness of Infrastructures Subject to Rare Events. 10th International Conference on Applications of Statistics and Probability in Civil Engineering, The University of Tokyo, Kashiwa Campus, JAPAN.

Raiffa, H. & Schlaifer, R.: (1961), Applied Statistical Decision Theory, Harward University Press, Cambridge University Press, Cambridge, Mass.

Von Neumann, J. & Morgenstern, O. (1944). Theory of Games and Economical Behavior. Princeton University Press (also: 3rd Edition, 1953, John Wiley & Sons).