On the Application of Bayesian Probabilistic Networks for Earthquake Risk Management

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ABSTRACT:

The present paper considers the application of Bayesian Probabilistic Networks (BPN's) in risk management for portfolios of structures subject to earthquake hazards. The BPN's facilitate that risks are assessed in a generic framework using indicators to relate the generic representation to the specific condition prevailing a given site, soil conditions, structure class, occupancy, etc. Initially a summary of previous work in the area of earthquake risk management is provided. Thereafter the general problem framework for management of earthquake risks is introduced for three different decision situations; before, during and after an earthquake. Following this, a basic introduction on BPN's is provided and it is outlined how the concept of indicators provides an efficient means of representing risks generically and for updating generic models in accordance with site specific information. A generic structural modelling framework is described which facilitates the automatic generation of input files for non-linear structural response analysis using the open source finite element software OpenSees. This framework makes it possible in a straight forward manner to analyse and generate vulnerability curves for several structure classes with a minimum use of man-hours.

The application of the methodology is illustrated considering the decision problem of whether or not to retrofit a specific class of structures. The structures within the considered class represent low-rise, bare frame reinforced concrete structures located on a site close to the western part of the North Anatolian Fault in Turkey. The example describes how vulnerability curves are produced for both original and retrofitted structures and based on a simplified consequence model illustrates how the BPN's can be used to support decision making.

1 INTRODUCTION

Efficient management and consistent quantification of risks due to earthquakes is increasingly becoming an issue of societal concern. Sustainable societal decision making requires that a framework for risk management is developed, which, at a fundamental level allows for the consistent comparison of risks from different hazards such as earthquakes, flooding and draughts but also and equally important allows for a consistent assessment of the cost efficiency of different strategies for controlling the associated risks.

Significant efforts have been allocated in the past to assess the seismic risk related to existing structures subject to earthquake hazards. One of the first major projects concerning the assessment of the seismic risk is the ATC-13 project (see ATC, 1985). The ATC-13 report provides a set of vulnerability functions in the form of damage probability matrices (see Whitman et al., 1973) to be used in the assessment of the seismic vulnerability of a stock of structures located within the same region.

In the 1990's, the period designated as the International Decade for Natural Disaster Reduction (IDNDR) by the UN (UN, 1987), a number of seismic risk assessment studies were carried out around the world. One of the major projects within this period is the RADIUS (Risk Assessment Tools for Diagnosis of Urban Areas against Seismic Disasters) project (GHI, 2004). In this project, practical tools for a preliminary estimation of the possible damage scenarios and for the preparation of a risk management plan for nine case study cities are developed.

Another important earthquake loss estimation methodology, called HAZUS (Whitman et al., 1997), is developed by the Federal Emergency Management Agency through the National Institute of

Building Sciences. Details are summarized in Kircher et al. (1997a) and Kircher et al. (1997b). HAZUS originally contained very general methods for estimating the earthquake losses at a regional scale. With the addition of the Advanced Engineering Building Module (FEMA, 2001) building specific damage estimation studies are made possible.

The approach in this paper to use Bayesian Probabilistic Networks (BPN's) for earthquake risk management has, unlike the aforementioned methodologies, the advantage of forming a basis for consistently integrating all aspects affecting the damage on structures located within a region subjected to the same earthquake exposure. The uncertainties which are influencing the functional chain of an earthquake from the source mechanism, the site effects, the structural response, the immediate consequences (damage) to the indirect consequences can be handled consistently. Furthermore, with new information at hand a consistent updating of the results can be performed. This facilitates the extension of the approach to decision problems related to risk management during and after earthquakes.

Bayesian probabilistic networks, alternatively called belief networks or probabilistic causal networks, have become popular during the last two decades in the research areas of artificial intelligence, probability assessment and uncertainty modelling (Pearl, 1988). The ideas and techniques have gained recognition also in other engineering disciplines and natural sciences, especially in problems involving high complexities and large uncertainties, see also Faber et al. (2002).

An application of causal networks for the purpose of aiding technicians to assess historical buildings subject to earthquake hazards is given in Salvaneschi et al. (1997). As an example the seismic vulnerability is evaluated by modelling the available knowledge in the form of logical trees in Miyasato et al. (1986), Ishizuka et al. (1981) and Pagnoni et al. (1989). Furthermore, in Zhang and Yao (1988) conceptual networks and frames are applied to map observable information into damage states.

The description and assessment of natural hazards and the quantification of their related risks appears to be a problem for which BPN's can be a helpful tool. In Hincks et al. (2004) BPN's are applied to forecasting volcanic hazards, in Antonucci et al. (2004) to assess hazards due to debris flow, and in Straub (2005) to natural hazards risk assessment.

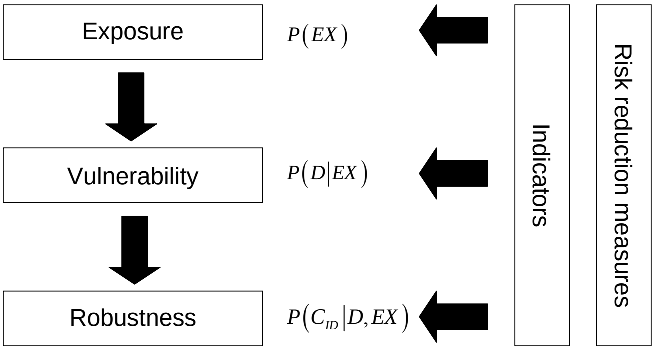

Figure 1. Illustration of risk assessment framework.

2 FRAMEWORK FOR RISK ASSESSMENT

Risk assessments may be facilitated by consideration of the framework illustrated in Figure 1, (see also Faizian et al., 2004). In this framework three levels are distinguished, namely the exposure, the vulnerability and the robustness. The exposure can be considered an indicator of the hazard potential for a given object or system of consideration. Considering earthquakes, the exposure *EX* is an inherently uncertain phenomenon with probabilistic characteristics usually provided in terms of earthquake ground motion intensities and corresponding return periods. The vulnerability, assessed through the probability $P(D|EX)$, can be considered an indicator of the immediate consequences (or damages D to the system) associated with a given exposure event. Considering an earthquake event the vulnerability is associated with significant uncertainty and is appropriately described by a probability distribution of different damage states of structures conditional on the exposure event, e.g. the earthquake magnitude, duration of the earthquake, source-to-site distance, etc.. The robustness, assessed through the complement of the probability $P(C_{ID}|D,EX)$, is an indicator of the indirect consequences C_{ID} due to the damages of the considered system. Considering again the event of an earthquake the robustness is associated with the conditional probability of losses of various degrees conditional on the exposure and a given damage state. For a system corresponding to a city or region societal losses including loss of lives as well as economical losses may depend strongly on e.g. the specific time of the year, week and day where an earthquake occurs. In this way the robustness of the system exposed to an earthquake will also be dependent on the specific time when an earthquake takes place. The modeling of uncertainty associated with the assessment of exposure and vulnerability may be based on well established frameworks such as the Joint Committee on Structural Safety Probabilistic Model Code, (JCSS, 2001).

The uncertainties involved in the assessment of the robustness contain significant epistemic uncertainty. One of the reasons for the significant subjective element of uncertainty in consequence modeling is the uncertainty of the decision maker in regard to appropriateness and completeness of the applied consequence assessment models. However, in correspondence with the risk assessment framework outlined in the above and consistent with Faber and Maes (2003) it is proposed to perform the risk assessment on the basis of the following expression for the risk R or the equivalent expected direct consequences C_D and indirect consequences C_{ID}:

$$R = E\left[C_D + C_{ID}\right] = \iint C_D\, p\left(D \middle| EX\right) p\left(EX\right) dD\, dEX + \iiint C_{ID}\, p\left(C_{ID} \middle| D, EX\right) p\left(D \middle| EX\right) p\left(EX\right) dC_{ID}\, dD\, dEX \qquad (1)$$

As will be outlined in more detail in the following chapter BPN's are applied to establish a generic model of the causal relations between the hazard event itself and the possible consequences. This model also involves a number of observable characteristics which comprise so-called indicators. Only retrofitting is considered in the following as a possible risk reducing measure and the risk associated with this measure will be compared with the risk associated with doing nothing. This comparison then constitutes the basis for the decision making.

3 BAYESIAN PROBABILISTIC NETWORKS FOR EARTHQUAKE RISK MANAGEMENT

The overall theoretical framework is the preposterior analysis from the Bayesian decision theory; see e.g. Raiffa and Schlaifer (1961). As mentioned previously BPN's constitute a flexible, intuitive and strong model framework for Bayesian probabilistic analysis. One of the BPN tools suitable for risk assessment and decision analysis is a special type of influence diagram as described in Jensen (2001). Due to their mind mapping characteristic, BPNs comprise a significant support in the early phases of a risk analysis, where the main task is to identify the potential hazard scenarios and the interrelation of events leading to adverse events.

The basic feature of BPNs may be described by the following steps, see also Figure 2:

- Formulation of causal interrelations of events leading to the events of interest (consequences). This is graphically shown in terms of nodes (variables) connected by arrows. Variables with ingoing arrows are called children. Variables with outgoing arrows are called parents.
- Assigning to each variable a number of discrete mutually exclusive states.
- Assigning probability structures (tables) for the states of each of the variables (conditional probabilities in case that the variables are children).
- Assigning consequences corresponding to the states represented by the BPN.

Having developed the BPN's, the required probability tables and consequences the risk assessment and the decision analysis is straightforward.

Furthermore, the BPN's provide a very strong tool for the updating of risks as information about any state represented in the BPN's can be introduced. This feature is especially valuable as knowledge may be provided in more or less precise form e.g. as indicators. Furthermore, BPN's also provide a tool for diagnosing a system, i.e. identifying the event scenarios which, with the largest likelihood lead to specific adverse events of interest.

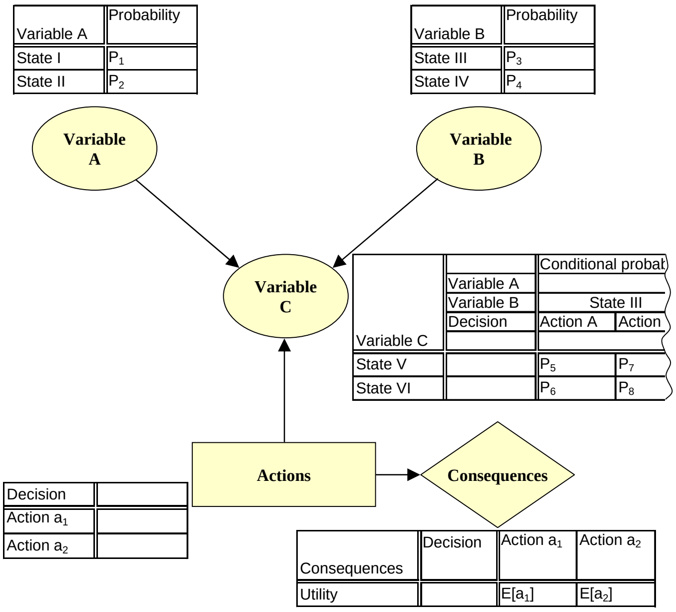

Figure 2. A principle BPN with states and probability tables.

In Figure 3 the BPN considered in the present paper is illustrated. In the following only the general idea behind the net is explained whereas details are provided in the subsequent example application.

In the example the seismic activity related to the source zone is considered as a point source. The probabilities for the occurrence of earthquakes with specific magnitudes are considered in the 'Earthquake Magnitude' node. The probability distribution of the distances of the structures is presented by the 'Earthquake Distance' node. The prevailing soil conditions at the considered location are represented by the 'Soil type' node. The 'Seismic demand' node is conditioned on these three nodes and on the 'Fundamental Period' node. The relative representation of the structural types within the structural class is considered by the 'Structural class' node. This node has an influence on the 'Fundamental Period' node, on the 'Number of People at Risk' node and hence also on the 'Number of Fatalities' node. Conditional on the seismic demand, the probabilities of being in a predefined damage state form the conditional probability tables in the 'Damage' node. For the 'Damage' node model uncertainties are taken into account and implemented by the 'Damage Assessment Uncertainty' node. All these nodes are regarded as indicators relevant for the decision situation.

For the identified decision situation possible activities are given in the 'Actions' node. Direct consequences, i.e. the 'Damage' node as well as indirect consequences, i.e. 'Number of Fatalities' node, are considered when implementing the table for the

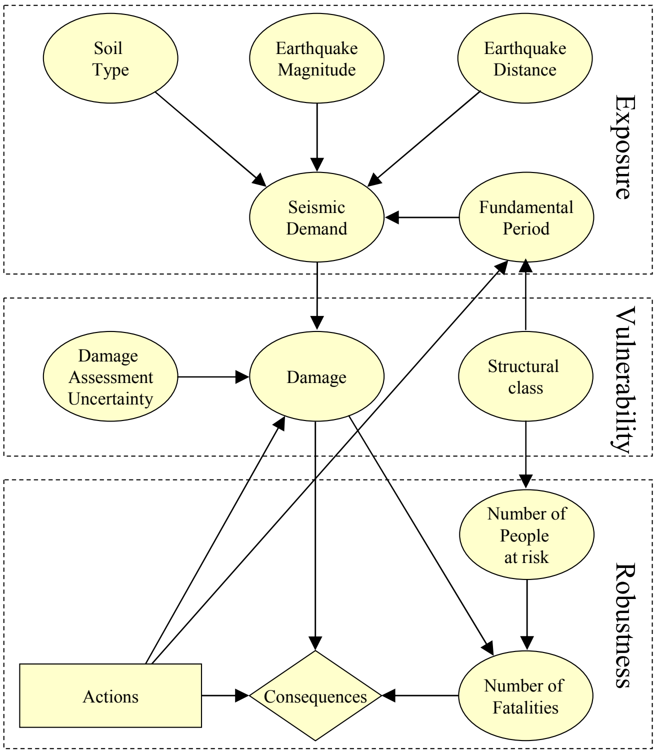

Figure 3. Bayesian network for the structure class.

'Consequences' node. The optimal decision is to be based on a comparison of the expected total consequences of the alternative actions.

4 PROBABILISTIC MODELING IN EARTHQUAKE RISK ASSESSMENTS

Based on Eq. (1) and consistent with the PEER performance-based earthquake engineering framework (Cornell and Krawinkler, 2000), the following expression is elaborated in the proposed methodology:

$$
\begin{aligned}
& E\left[C_D + C_{ID}\right] = \\
& \quad \iiiint C_D \, dP\left(D \middle| EDP\right) dP\left(EDP \mid IM\right) \\
& \qquad dP(IM \mid SE)\, p(SE)\, dSE \;+ \\
& \int\!\!\iiiint C_{ID} \, dP\left(C_{ID} \middle| D\right) dP\left(D \middle| EDP\right) \\
& \qquad dP\left(EDP \mid IM\right) dP(IM \mid SE)\, p(SE)\, dSE
\end{aligned}
\qquad (2)
$$

In Eq. (2), C_D, C_{ID} are the direct and indirect consequences, D is the damage state, EDP is the engineering demand parameter (i.e. maximum peak interstory drift ratio, dissipated energy, etc.), IM is the ground motion intensity measure (i.e. the spectral displacement, peak ground response, etc.) and SE is the seismic event. In the following sections the components of Eq. (2) are further explained.

4.1 *Assessment of the Exposure*

Exposure, in the context of this study, is represented by the probability that a specific ground motion intensity measure, IM, exceeds a specific value at a given site in a specific time interval. This probability is also denoted as the seismic hazard at the site. In Eq. (2), the terms $dP\left(IM \middle| SE\right)$ and $p\left(SE\right)$ are related to the assessment of the seismic hazard.

The main sources of uncertainties involved in evaluating the seismic hazard at a given site arises from the definition of seismic sources, recurrence relations, attenuation relationships, local site effects and soil-structure-interaction effects. Seismic sources are points, lines or areas with a uniform level of seismic activity and are defined on the basis of geological, geophysical and seismological data. Recurrence relations are defined for each source zone according to the assessed recurrence frequencies of earthquakes with different magnitudes. Attenuation relationships provide estimates of major characteristic parameters of a strong ground motion (i.e. peak ground acceleration, acceleration response spectra) at a given site due to a seismic event with given major characteristics, such as magnitude, distance and faulting mechanism. A review of the major developments in the field of seismic hazard analysis is available in Atkinson (2004). Particularly, the probabilistic approaches for estimating the seismic hazard provide a structured framework for explicit quantification of the uncertainties involved. The Probabilistic Seismic Hazard Analyses is one of the major studies in this field (Cornell, 1968).

It should be noted that explicit quantification of uncertainties involved in the estimation of seismic hazards in turn provides the possibility of evaluating the sensitivity of results to various uncertain parameters. Such information forms a valuable basis for allocating the available resources to gain more information for the improvement of the hazard estimates. As a result of the modular approach followed in this study, a number of seismic hazard models with varying levels of detail can be utilized.

4.2 *Vulnerability assessment*

The vulnerability of a structural system is expressed through the probability that a specific level of damage, D occurs when the structure is subjected to a specific loading intensity, IM. In Eq. (2), the terms $dP\left(D \middle| EDP\right)$ and $dP\left(EDP \middle| IM\right)$ are directly related to the assessment of the seismic vulnerability of a structure.

The methods for obtaining the vulnerability functions for structures can mainly be categorized as: methods based on expert opinion, methods based on observed damage distributions after earthquakes and methods based on structural response analyses. A review of the major approaches related to seismic vulnerability assessment of structures is available in Porter (2003). Methods based on structural response analyses, such as Mosalam et al. (1997), Singhal & Kiremidjian (1997), provide the advantage of investigating the effect of individual parameters on the structural response in an analytical manner. Due to the term $dP\left(D\middle|EDP\right)$, the dependency between D and EDP also plays an important role in the evaluation of the usefulness of EDP's. In many of the available vulnerability assessment studies this link is established based on empirical methods, such as experiments and post-earthquake damage observations.

The updatability of BPN's makes them an efficient tool, provided that the selected EDP's can be updated. The use of residual deformations observed after earthquakes as EDP might form a basis for such applications (Mackie & Stojadinovic, 2004). The technologies being developed in the field of photogrammetry can be utilized to provide such information (Bayraktarli et al., 2004).

4.3 *Robustness assessment*

Robustness, i.e. the complement of $dP(C_{ID}|D)$, is an indicator of the indirect consequences C_{ID} due to the damages D of the considered system. Considering seismic events, robustness is associated with the conditional probability of losses of various degrees conditional on the damage state. For a city, societal losses including loss of lives as well as economical losses depend strongly on e.g. the specific time of the year, week and day where an earthquake occurs.

To ensure consistent decision making the uncertainty of any type of economic impact due to earthquakes has to be included. These economic impacts are direct economic losses due to damaged structures, their contents and lifelines (Geipel, 1991), indirect economic losses due to business interruption (Benson and Clay, 2004), loss of revenues and increases of costs in the public sector, expenses and losses of individuals and loss of household incomes due to death, injury, or job interruption (National Research Council, 2004).

Loss of individuals may be quantified by the Societal Life Saving Cost (SLSC) (Rackwitz, 2003) or by the Implied Cost of Averting Fatalities (ICAF) (Skjong & Ronold, 1998), which are derived based on the Life Quality Index (Nathwani et al., 1997).

5 EXAMPLE APPLICATION

In the following the focus is directed to the problem of identifying adequate risk reducing measures for a class of structures subjected to earthquakes. It is assumed that the structures are located near the western part of the North Anatolian Fault in Turkey.

The BPN for this considered class of structures is given in Figure 3. This structural class comprises low story reinforced concrete moment resisting bare frames designed according to Eurocode 2 to resist gravity loads. The structures have regularity in the plane and vertical geometry (Figure 4).

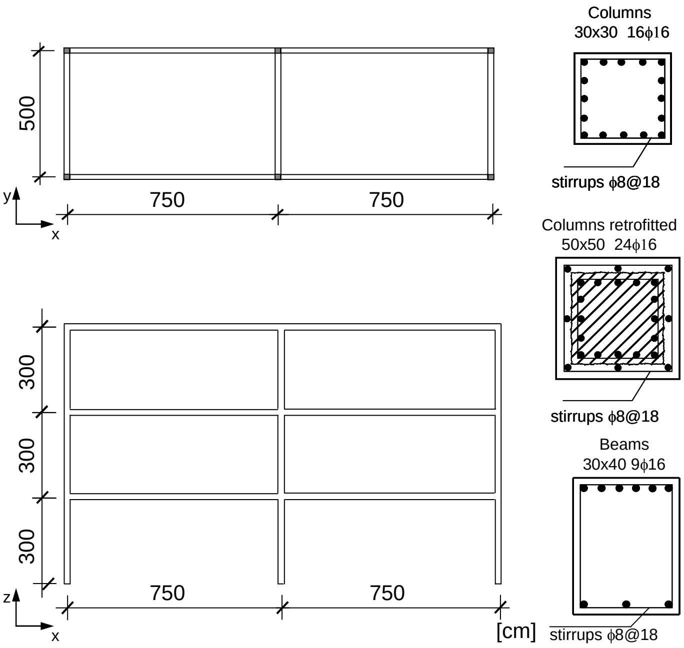

Figure 4. Plane, vertical view and details of the structures.

In the example one decision alternative, namely direct strengthening of all vertical load carrying components by column jacketing is considered (see Figure 4). It is assumed that the jacketed column behaves monolithically, with full composite action between old and new concrete and that the full axial load is applied on the entire jacketed column.

5.1 *Assessment of the Exposure*

The well known Gutenberg-Richter magnitude reccurrence relationship (Gutenberg and Richter, 1944), as recommended in the JCSS Code (JCSS, 2001), is applied in the example. Recurrence rate parameters corresponding to Anatolian Trough source zone, are taken from the study by Erdik et al. (1985). The seismic activity related to the source zone is considered as a point source and the occurrence of strong earthquakes is assumed to follow a stationary Poisson process.

For the earthquake demand modelling a set of acceleration time histories is generated. The Attenuation relationship proposed by Boore et al. (1997) for estimating the pseudo-acceleration response spectra for the random horizontal component at 5% damping, is used for the synthesis of the ground motion time histories. 16 pairs of moment magnitudes (5.5, 6.5, 7.0, 7.5), epicentre distances (10, 20, 40, 80 km) and site class (sand) are selected and using a modified version of SIMQKE (Gasparini and Vanmarcke, 1976) by Lestuzzi (2000) 20 samples of accelerogram time histories for each pair of these are generated, resulting in 320 simulations.

5.2 *Vulnerability Assessment*

For the calculation of the structural response parameters the open source finite element program OpenSees is applied (OpenSees, 2004). OpenSees is used to perform nonlinear dynamic analysis of the structures (with and without retrofitting).

The structures are subjected to the 320 ground motion time histories. 3200 input files for OpenSees are correspondingly generated and after the calculations a large amount of data must be analysed. In order to simplify the geometry generation, to minimize the risk of input and data analysing errors a generic software package is developed in MATLAB©.

Apart from special files defining some geometry parameters, all calculations are done using the same set of files. The program reads specific data from input files defining the structures in a generic way. These data are then assigned to an overall MATLAB data structure. The data are then used to construct the nodes, elements, constrains, masses, damping, loads as well as the analysis methods. Finally the data structure is written to a tcl-file, which serves as input to OpenSees. Also numerous visualisation and data analysis functions are developed. The MATLAB program code controlling the analysis procedure consists of more than 15'000 lines.

The beams and columns are modelled with nonlinear beam-column elements, which are based on the non-iterative force formulation and consider the distribution of plasticity along the element. The reinforced concrete cross sections are modelled using a fibre cross section model. Rigid diaphragms are used to model the slabs.

The concrete material is modelled after Park et al. (1972) with degraded linear unloading/reloading stiffness, based on the work of Karsan and Jirsa (1969), and assuming no tensile strength. The confined and unconfined concrete is modelled by applying two different sets of material parameters. The damping is modelled as Rayleigh damping, which implies a combination of the mass and the stiffness matrices at the current state. Masses are lumped in the rigid diaphragms. All material parameters are assumed to be deterministic. The columns on the ground level are fixed for all degrees of freedom. The ground acceleration is applied in the *y*-direction.

The solution algorithm is of the Newton type with a convergence criteria expressed in terms of the norm of the displacement increment vector. The integrator is of the Newmark type. The time step is set to 0.01 s and the length of the time series is 25 s, resulting in 2500 time steps for each series. It takes about 500 s to calculate one time series for the example structure on a Intel Pentium PC.

For this example, the maximum interstory drift ratio (MIDR) is selected as the engineering demand parameter (*EDP*) and calculated using OpenSees. The damage states and relevant MIDR values used, which are based on recommended engineering judgment and experimental observations (Huo and Hwang, 1996), are given in Table 1.

The MIDR's are classified into the damage states using Table 1. Assuming that the spectral displacement for the damage states are lognormally distributed, the parameters of the distribution are estimated using the Maximum Likelihood Method. In this approach a combined representation of the terms $dP\left(EDP|IM\right)$ and $dP\left(D|EDP\right)$ from Eq. (2) were utilised as a set of fragility curves. In Figure 5 fragility curves for the structures, with and without retrofitted columns, are given. It should be noted that the fundamental period of the structures reduce from 0.79 s to 0.67 s due to the retrofitting and hence the spectral displacement, S_d, is also reduced. It should be noted that in the structural response calculation leading to the MIDR's modelling uncertainties have not been taken into account.

Table 1. Damage state classification based on MIDR.

Performance State (S)	Response level	MIDR [%]
No damage	Elastic	< 0.2
Insignificant damage	Cracking	0.2-0.5
Moderate damage	Yielding	0.5-1.0
Heavy damage	General yielding	>1.0

5.3 *Robustness assessments*

In the decision problem identified for the present example only costs associated with retrofitting, rebuilding and loss of life are considered. For Turkey, the unit rebuilding costs are 175 USD/m^2 and the unit retrofitting costs are 250 USD/column (Has Inşaat, 2004). The loss of life is quantified by the SLSC. For Turkey, based on data for year 2004, the SLSC is estimated as 135'000 USD per fatality.

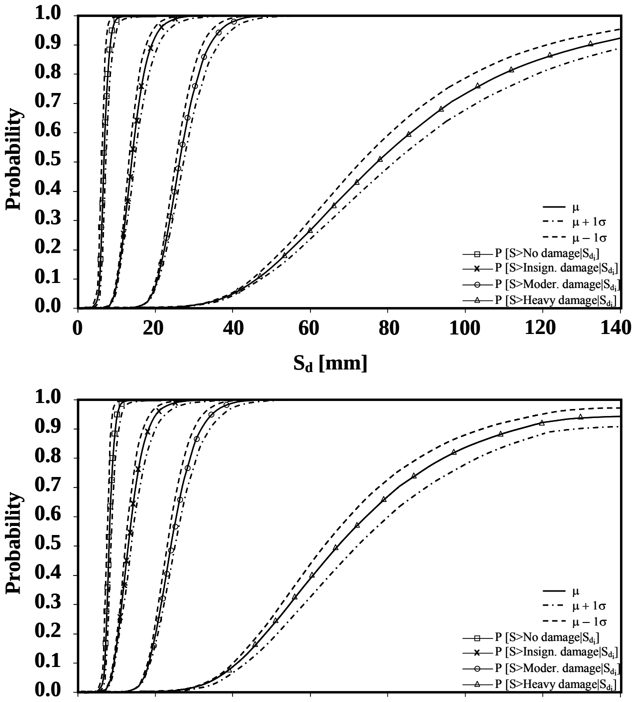

Figure 5. Fragility curves for the structures, without (top) and with retrofitted columns (bottom).

5.4 *BPN Analysis*

The BPN for the decision problem of retrofitting or not retrofitting the specified structures is given in Figure 3. In the following the probability tables of the nodes (i.e. indicators) in Figure 3 are discussed.

The annual probabilities for each M_w (M_w=5.5, 6.5, 7.0, 7.5) are calculated as described in Sec. 5.1 and form the probability tables for the 'Earthquake Magnitude' node. The structures are assumed to be uniformly distributed in the region with epicentre distances of R=10 km, 20 km, 40 km and 80 km. The prevailing soil type in the considered location is assumed to be dense sand. For all combinations of (M_w, R) and depending on the fundamental periods of the structures, the spectral displacement values are estimated as described in Sec. 5.1. The seismic demand node consists of these spectral displacement values. The probabilities of being in the defined damage states are read from the fragility curves for each seismic demand value. These values constitute the probabilities of the 'Damage' node.

In the 'Actions' node 'column retrofitting' and 'doing nothing' are considered as decision alternatives. The consequences of these actions are implemented in terms of costs, conditional on the damage and the number of fatalities. Damage can influence the cost directly, i.e. for the damage state "heavy damage" and "collapse" rebuilding costs are considered, or indirectly over the number of fatalities.

Having quantified the probability tables and consequences, the example BPN can be used for risk assessment and decision analysis. E.g. for the situation described in the foregoing, 'column retrofitting' is the optimal action.

A sensitivity analysis of the unit cost values for retrofitting on the optimal decision is also performed using the BPN by means of a parameter study. For the parameter study, unit retrofitting cost values from 50 USD/column to 650 USD/column are considered. The results are shown in Figure 6. Here it can be seen that the optimal decision is sensitive to the unit retrofitting cost.

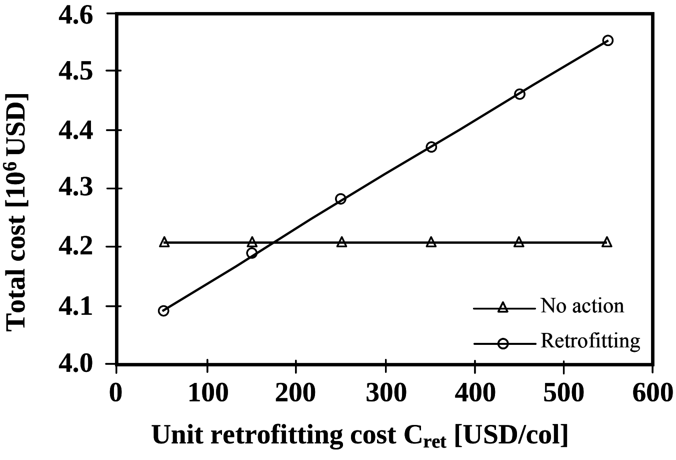

Figure 6. Influence of the unit retrofitting cost on the decision situation for the structures.

6 CONCLUSIONS

The application of Bayesian Probabilistic Networks (BPN) for earthquake risk management is considered. It is found that the uncertainties associated with all elements in the functional chain of an earthquake from the source mechanism, site effects, structural response, damage assessments and consequence assessment can be handled consistently using BPN's.

The application of BPN for earthquake risk management is illustrated on a decision problem on whether or not to retrofit low-rise, bare frame reinforced concrete structures assumed to be located on a site close to the western part of the North Anatolian Fault in Turkey.

The problem is formulated by considering a framework consisting of three levels: exposure, vulnerability and robustness. A BPN is constructed considering this modularity. The example also shows that BPN's can be used for conducting scenario studies or for performing sensitivity analyses.

BPN's also facilitate easy updating based on evidence on the indicators. Any kind of evidence, e.g. information about the earthquake magnitude, earthquake distance or soil type as well as information on the damage causing residual roof displacement measured by photogrammetrical technologies may be used. This enables the application of the approach to decision problems related to risk management during and after an earthquake.

It should be noted that as a result of the suggested modular approach more elaborate methods for estimating the exposure, the vulnerability and the robustness can easily be implemented.

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