Lecture Notes in Civil Engineering

José C. Matos · Paulo B. Lourenço ·
Daniel V. Oliveira · Jorge Branco ·
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18th International Probabilistic Workshop

IPW 2020

Springer

Lecture Notes in Civil Engineering

Volume 153

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ISSN 2366-2557 ISSN 2366-2565 (electronic)
Lecture Notes in Civil Engineering
ISBN 978-3-030-73615-6 ISBN 978-3-030-73616-3 (eBook)
https://doi.org/10.1007/978-3-030-73616-3

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Preface

The need to handle uncertainty and to make informed decisions renders evident the importance of the probabilistic and reliability topics. This can be seen in the most recent advances on the topic of the existing infrastructure maintenance and management, especially those related to safety and security under extreme events. Additionally, it is well-known that climate change issues are becoming even more relevant, with an impact on society, mostly affecting the likelihood and consequences of some natural hazards. Indeed, there is a need to develop deeper studies on data science, as well as on its application to system analysis, combining probabilistic and reliability tools to face the huge uncertainty.

The International Probabilistic Workshop (IPW) series started in 2003 as the Dresden Probabilistic Symposium at the Technical University of Dresden, repeated in 2004. In 2005, the 3rd edition held in Vienna was renamed as International Probabilistic Workshop. The previous IPWs took place in Berlin (2006), Ghent (2007), Darmstadt (2008), Delft (2009), Szcecin (2010), Braunschweig (2011), Stuttgart (2012), Brno (2013), Weimar (2014), Liverpool (2015), Ghent (2016), Dresden (2017), Vienna (2018) and Edinburgh (2019).

The IPW2020 (18th edition) was planned to take place in September 2020 at the University of Minho, Guimarães, Portugal. Unfortunately, the worldwide COVID-19 pandemic forced the postponement of the event to May 2021 and the adoption of an online format. Nevertheless, the scientific value and quantity of contributions (65 papers from 27 countries covering different probabilistic calculation methods) ensure the high quality of this Workshop, keeping the same scientific level as the previous ones.

The editors would like to thank all authors, keynote speakers, organizers of special sessions and participants for their valuable contributions, members of the Scientific

Committee for their meticulous work and the Workshop Secretariat for the dedicated teamwork, particularly during this exceptional pandemic period.

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Contents

Keynote Papers

Papers

Keynote Papers

Decision Analysis Applied to Natural Hazards

Herbert H. Einstein and Rita L. Sousa

Abstract Formal methods to handle decision-making under uncertainty that have been created for business management lend themselves to applications in many other areas, in which uncertainties play a major role. Hence, the authors and their co-workers have applied decision analysis to landslides since the 1980′s but many other approaches to landslide assessment and management have in principle done so. The keynote lecture itself will illustrate the application of decision analysis with many examples. For this reason, we concentrate in this paper on the principles of decision-making under uncertainty and the concept of using these principles in hazard and risk analysis of natural threats. We also like to note that what we present here is a summary of our past work. The paper starts with an introduction to the decision-making process and its application to natural threats. Risk management of natural threats is then demonstrated in detail with decision trees and Bayesian networks. This leads to sensitivity analyses to determine which risk management action is most effective.

Keywords Natural threats · Landslides · Decision making · Bayesian networks

1 Introduction

Uncertain events can be formally handled by decision-making under uncertainty that was developed for business management [1]. Given the uncertainty of many natural events, it is, therefore, quite logical to apply methods of decision-making under uncertainty to natural threats such as landslides, floods and wildfires, for instance. The authors of this paper have developed and applied these decision-making processes to landslides (e.g. [2, 3]). This involved the use of classic decision tree procedures that were extended to include warning systems. Very importantly, an alternative approach

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J. C. Matos et al. (eds.), *18th International Probabilistic Workshop*, Lecture Notes in Civil Engineering 153, https://doi.org/10.1007/978-3-030-73616-3_1

using Bayesian networks was then developed [4]. This paper, therefore, will first introduce the reader to the principles of decision-making under uncertainty (Sect. 2) and then comment on the formalization of the threat assessment process and how to incorporate it in the decision-making process (Sect. 3). This will be followed by showing examples of decision trees (Sect. 4), the use of Bayesian networks (Sect. 5) and end with conclusions (Sect. 6).

2 Decision-Making Under Uncertainty

Figure 1 is a schematic of decision-making under uncertainty based on the original development at the Harvard Business School [1]. As can be seen, the process can lead directly to the result of accepting the risk or to an updating cycle. The updating cycle on the left side relates to obtaining and using additional information or to managing the risk. The information model on the right side can be used to decide if it is worthwhile to collect additional information or not. Sousa et al. [5, 6] have

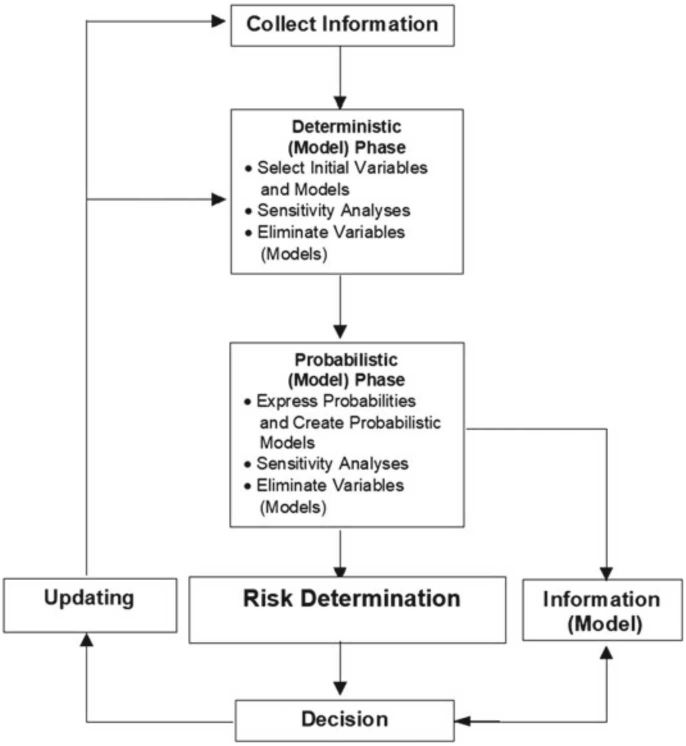


Fig. 1 Decision analysis cycle | Decision: accept risk or "Update" | Update: collect more information and/or manage risk

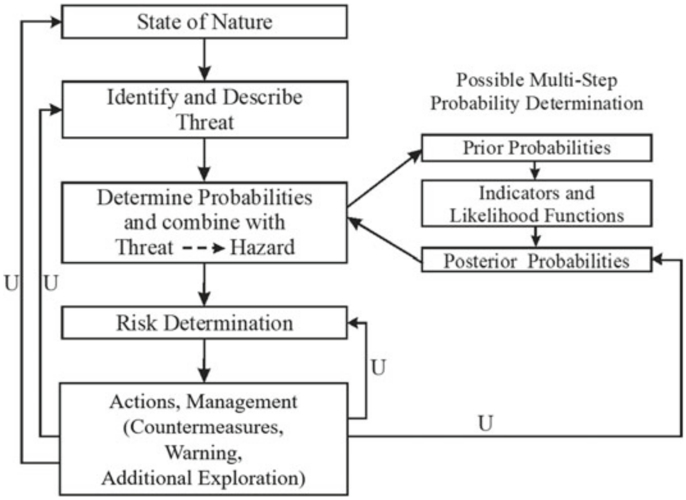


Fig. 2 Decision analysis cycle applied to natural threats | U = Updating

applied and explained the use of such information models in the context of natural hazards and tunneling.

The decision process of Fig. 1 can be expanded and adapted to dealing with natural threats as shown in Fig. 2. The expansion contains details on the decision in form of different actions in the context of risk management.

3 Formalization of the Threat Assessment Process

The terms threat, hazard and risk have already been used in Fig. 2, and they need to be formally defined. This is first done through the verbal expressions of Table 1 that lists the definitions as formulated by the Technical Committee No. 32 of the

Table 1 Definitions (Based on glossary of TC 32 of the ISSMGE)

Term	Definition
Threat (Danger)	Natural phenomenon that could lead to damage. Described by geometry, mechanical and other characteristics. Can be an existing one, or a potential one, such as a rockfall. No forecasting
Hazard	Probability that a particular threat (danger) occurs within a given period of time
Risk	Measure of the probability and severity of an adverse effect to life, health, property, or the environment Risk = Hazard × Potential Worth of Loss

Table 2 Other important concepts

Concept	Definition
Consequence	Result of a hazard being realized
Damage	Another way of expressing detrimental consequences
Vulnerability	– Often expressed on a scale of 0 (no loss) to 1 (total loss) – Expresses the fact that even if a threat materializes, it is not necessarily 100% certain that the consequences materialize – Can be formulated as a conditional probability

ISSMGE. In addition, several other concepts (terms) need to be used, and they are listed in Table 2.

The expressions in Table 1 and Table 2 can be used in the formal decision-making process discussed in Sect. 4.

4 Decision-Making Process

The intent is to make a decision in the context of risk management (recall Fig. 2). Before doing so, it is important to point out that very often it is better to work with hazard than with risk. The latter requires that one expresses the consequences with a value. Although this value can be qualitative or quantitative it can be often problematic e.g. if one deals with lives. Hazard to lives can be dealt with the so-called FN charts [7, 8] as shown in Fig. 3 for Hong Kong. The frequency (F) of events is the hazard and it is subjectively related to the number of fatalities (N).

If one goes all the way to risk (see also Table 1):

$$\begin{aligned}\text{Risk} &= \text{Probability of Threat} \times \text{Worth of Loss}\\ &= \text{Hazard} \times \text{Worth of Loss}\\ &= \text{Hazard} \times \text{Consequences}\end{aligned} \tag{1}$$

This can be expressed as:

$$\mathrm{R} = \mathrm{P[T]} \times \mathrm{u}(\mathrm{X_i}) \tag{2}$$

where

R Risk
P[T] Probability of Threat = Hazard
$u(\underline{X_i})$ Utility of the consequence, where $(\underline{X_i})$ is a vector of attributes if one uses a multiattribute approach [9, 10]

As indicated in Table 2 the fact that the consequences are uncertain is reflected by vulnerability, which can be expressed by the conditional probability $P[X_i|T]$ and

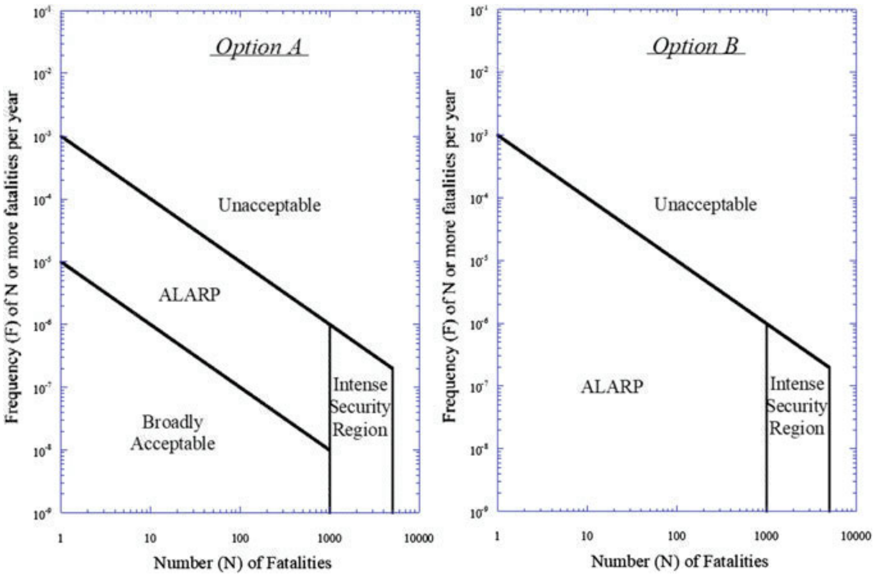


Fig. 3 Consideration of life losses with F-N charts. Example from Hong Kong [7] | ALARP = As Low As Reasonably Practical

thus risk is:

$$R = P[T] \times P[X_i|T] \times u(X_i) \tag{3}$$

One can manage risk in the following manner:

- No action
- Active countermeasures reduce P[T] i.e. the hazard
- Passive countermeasure reduce $P[X_i|T]$ i.e. the vulnerability
- Warning systems also reduce $P[X_i|T]$ i.e. the vulnerability.

Clearly combinations of all the above are possible.

5 Decision Trees

The management actions and their “cost” will produce what we term as “modified risk”. If the modified risk is smaller than the original one, it is worthwhile to take the management action. All this will now be shown in detail with decision trees related to the typical management actions. Figure 4 shows the overall decision tree that includes all actions.

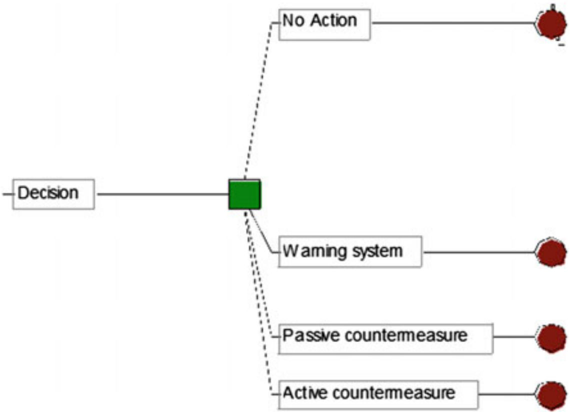


Fig. 4 Decision tree tool showing possible actions

The first possibility is "no-action" for which the decision tree is shown in Fig. 5. With this tree we also introduce some basic concepts and assumptions: The hazard model represents the probability P[T] that the threat occurs. The specific numbers (20.7, 79.3%) can be obtained e.g. with a probabilistic slope stability analysis. The vulnerability model provides the probability $P[X_i|T]$ that a consequence materializes if the threat occurs. The numbers used here are subjective estimates. Finally, one needs to associate costs with consequences, which is done in the consequence model. It is important to realize that vulnerability and consequence depend on each other. This is expressed here by having smaller vulnerability (40%) for the higher consequence costs (−20,000). These costs are here in terms of utilities. The total risk of no action is then obtained by multiplying and summing $[(0.5x - 10{,}000) + (0.4x - 20{,}000)] \times 0.207 = -2691$.

This "no action risk" is the "original risk" R that will be compared to modified risks R′ reflecting active or passive management actions. These management actions have a cost that needs to be included when determining the modified risk, as will be seen in the following.

With *active countermeasures* one reduces the probabilities of the threat from P[Threat] (20.7%) to P′ [Threat] (5.2%). This reflects, for instance, the effect of stabilizing a slope.

The stabilizing measures do have a cost that need to be considered. The modified risk will then be:

$$R' = u(C_{ac}) + P'[\text{Threat}] \times P[X_i|\text{Threat}] \times u(X_i) \tag{4}$$

where C_{ac} = cost of countermeasures.

Figure 6 presents the decision tree for active countermeasures. Different from the tree for no action it now includes the cost of countermeasures "-2000" and the lower probability of the threat. The multiplying and summing is as before leading to a slightly lower modified risk R′ = - 2672.75 compared to the original (no action) risk R = −2691.

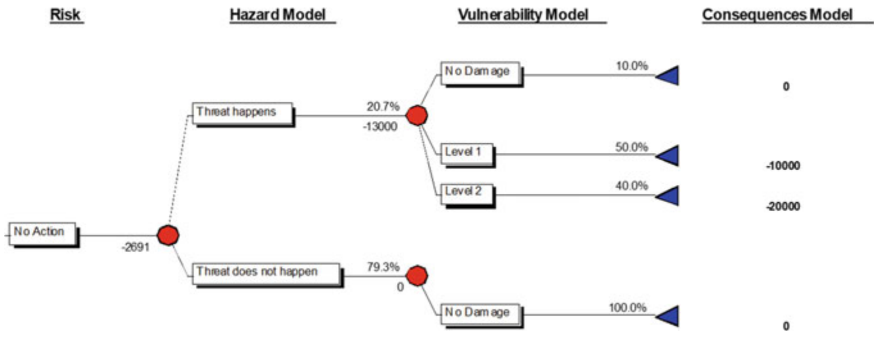


Fig. 5 Decision tree—no action

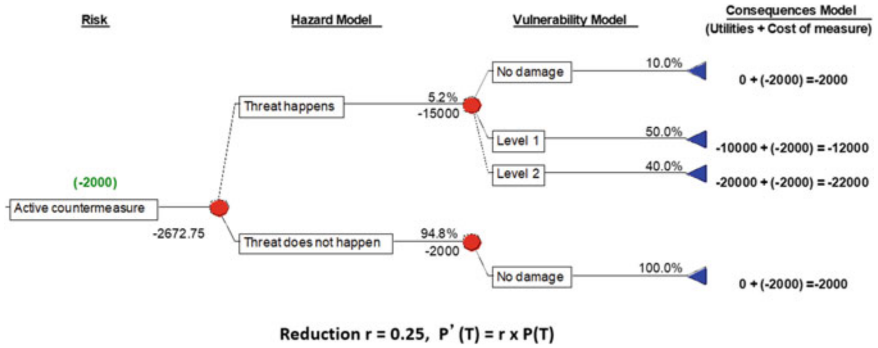


Fig. 6 Decision tree—active countermeasures.

Passive countermeasures reduce the vulnerability e.g. a protective shed against rockfall consequences. In the modified risk R', the hazard P[T] will be the same as for no action but the vulnerability will change to $P'[X_i|Threat]$ and thus R' will be:

$$R' = u\left(C_{pc}\right) + P[\text{Threat}] \times P'[X_i|\text{Threat}\} \times u(X_i) \tag{5}$$

where C_{pc} = cost of passive countermeasures. In the corresponding decision tree (Fig. 7) the vulnerabilities reflect the fact that the countermeasures reduce the probability of damage occurring and correspondingly increase the probability of no damage. With the numbers shown in Fig. 7 one obtains a modified risk of $R' = 2864.6$ that is higher than what resulted from active countermeasures.

Warning systems are also a kind of passive countermeasures. Many such systems exist, notably the tsunami warning systems in Japan and the Caribbean as well as avalanche warning systems in Switzerland [11] and Norway. Figure 8 shows how such systems fit into the overall decision-making process. The important component of warning systems is the trigger and this also complicates the decision-making process. Specifically, the reliability of the warning system that can be expressed

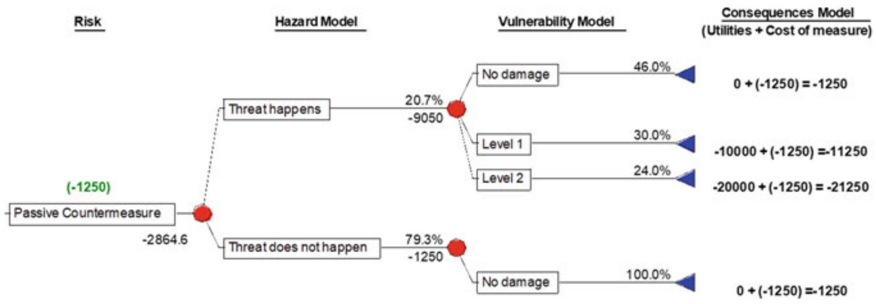


Fig. 7 Decision tree—passive countermeasures.

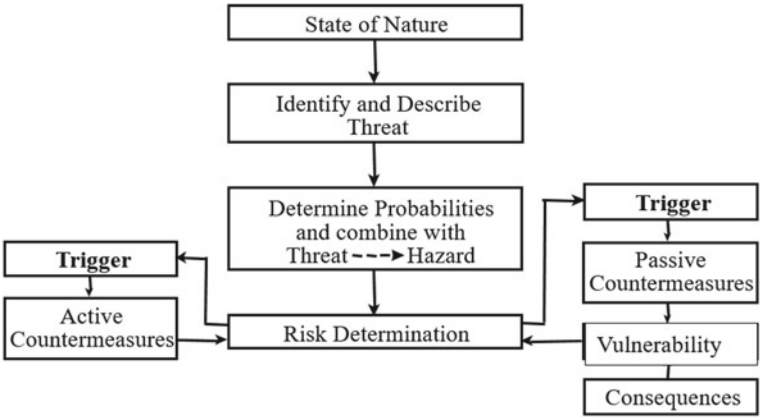
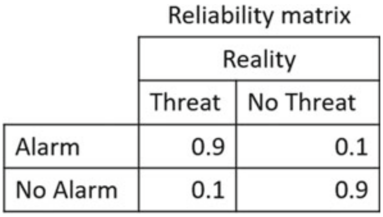


Fig. 8 Decision cycle for natural threats with warning system. | The "trigger" initiates countermeasures

in form of a reliability matrix (Fig. 9) needs to be included. In all decisions with countermeasures (active, passive, warning systems) it is also possible to include the effectiveness of countermeasures.

The decision trees show that there are sets of branches for each decision model. In the complete tree and going from right to left these models are "consequences", "vulnerability", "hazard", and "reliability". The number of trees increases if other models such as "effectiveness of countermeasures and multiple dependent hazards (e.g. earthquake or rainfall causing landslides) are included. In the extreme case one may thus end up with tens of branches. While informative since one can follow the decision process, it becomes visually difficult to fully capture the process.



Reliability matrix

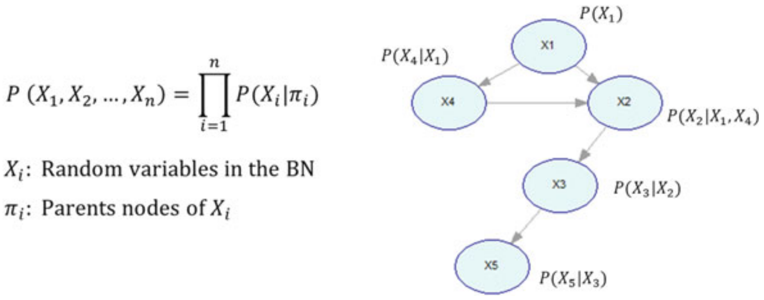
	Reality	
	Threat	No Threat
Alarm	0.9	0.1
No Alarm	0.1	0.9

Fig. 9 Reliability matrix: shows probability that alarm is triggered if threat occurs

6 Bayesian Networks

This can be remedied by using Bayesian networks [4], a probabilistic graphical model, that represents a set of random variables and their conditional dependencies via a directed acyclic graph. Figure 10 represents a generic **BN**. In this BN one has 5 random variables: X1, X2, X3, X4 and X5, represented by the nodes of the graph, and several edges that represent the conditional dependencies between variables. For example X2 has two parent nodes X1 and X4, so X2 conditionally depends on X1 and X4. On the other hand, for example, the random value X3 is conditionally independent of X4. Attached to each node of the BN are prior probability distributions (in the case of random variables without parent nodes) and conditional probability distributions for all the other nodes. Bayesian networks represent joint probability distributions in a compact and factorized way, by taking advantage of conditional independence, considering that not all variables depend on each other (i.e. do not have edges connecting all variables). In Fig. 11 the results of using Bayesian networks for the previously described cases using decision trees are given in table form and the results are summarized in Fig. 12.

In the discussion so far we assessed probabilities to demonstrate what can be done in decision-making under uncertainty. What is particularly interesting is the possibility to conduct sensitivity analyses to determine how the results i.e. the risk expressed in utilities will change if the underlying probabilities change. An example is shown in Fig. 13 in which P[T] the hazard is varied. For low P[T] no action results while warning systems are recommended for higher P[T].

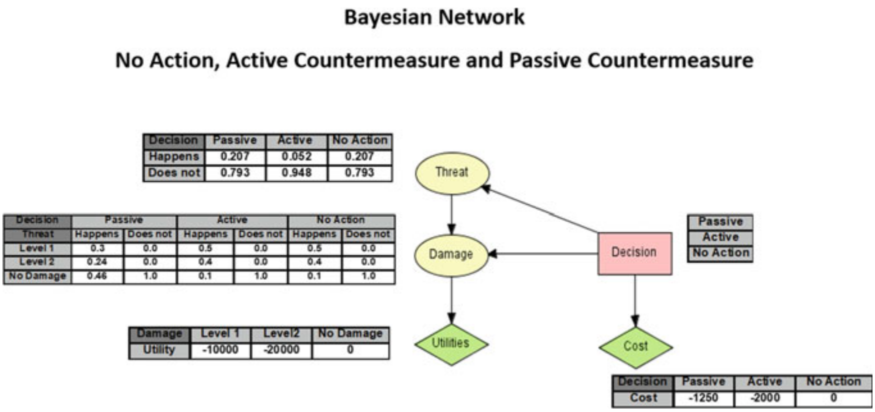


$$P\,(X_1, X_2, \dots, X_n) = \prod_{i=1}^{n} P(X_i|\pi_i)$$

X_i: Random variables in the BN

π_i: Parents nodes of X_i

Fig. 10 Bayesian networks are a concise representation of joint probability



Bayesian Network

No Action, Active Countermeasure and Passive Countermeasure

Decision	Passive	Active	No Action
Happens	0.207	0.052	0.207
Does not	0.793	0.948	0.793

Decision	Passive		Active		No Action	
Threat	Happens	Does not	Happens	Does not	Happens	Does not
Level 1	0.3	0.0	0.5	0.0	0.5	0.0
Level 2	0.24	0.0	0.4	0.0	0.4	0.0
No Damage	0.46	1.0	0.1	1.0	0.1	1.0

Damage	Level 1	Level2	No Damage
Utility	-10000	-20000	0

Passive
Active
No Action

Decision	Passive	Active	No Action
Cost	-1250	-2000	0

Fig. 11 Bayesian network applied to management of risk caused by natural threats

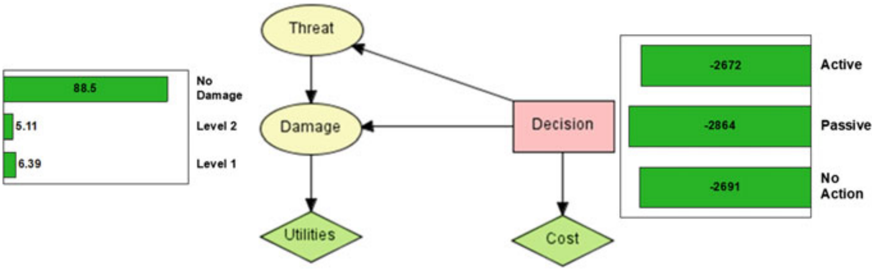


Fig. 12 Bayesian network applied to management of risk caused by natural threats-results

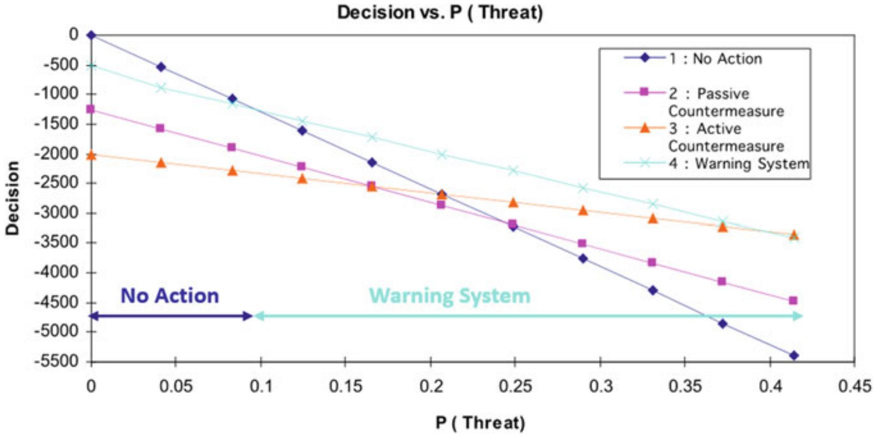


Fig. 13 Sensitivity analysis—different actions depending on probability of threat

7 Conclusions

Natural threats are characterized by uncertainty regarding temporal occurrence, spatial extent and many other aspects. Using probabilistic methods to describe the uncertainties is therefore common. It is then also logical to use methods of decision-making under uncertainty to assess and manage the threats and their consequences. Over the years the authors of this paper have developed decision-making approaches mostly regarding landslides. The keynote presentation and this paper summarize these approaches, which use decision trees and Bayesian Networks. This paper in essence provides a succinct guideline on how to use the decision-making approaches. The keynote presentation will then build on this with applications to practical cases mostly involving landslides but also other natural threats.

References

1. Pratt, J., Raiffa, H., & Schlaifer, R. (1965, 2008). *Introduction to statistical decision theory.*
2. Einstein, H. H., & Sousa, R. L. (2012). Risk in slopes. In L. Ribeiro e Sousa, E. Vargas Jr., M.M. Fernandes, & R. Azevedo (Eds.), *Innovative Numerical Modelling in Geomechanics, Chapter 11* (pp. 201–210). CRC Press. ISBN 9780415616614.
3. Einstein, H. H., Sousa, R., Karam, K., Manzella, I., & Kveldsvik, V. (2010). Rock slopes from mechanics to decision making. Keynote paper. In *Proceedings of the ISRM International Symposium—EUROCK 2010*, 15–18 June, Lausanne, Switzerland. ISRM-EUROCK-2010-001.
4. Sousa, R. L. (2010). *Risk analysis for tunneling projects* (Ph.D. dissertation). Massachusetts Institute of Technology. https://hdl.handle.net/1721.1/58282.
5. Sousa, R. L., Karam, K., & Einstein, H. H. (2014). Exploration analysis for landslide risk management. *Georisk, 8*(3), 155–170. https://doi.org/10.1080/17499518.2014.958174soli.
6. Sousa, R. L., Karam, K., Costa, A. L., Einstein, H. H. (2016). Exploration and decision-making in geotechnical engineering—A case study. In *10th Anniversary Special Issue of Georisk* (Vol. 11, No. 1, pp. 129–145).
7. Ho, K., Leroi, E., & Roberts, B. (2000). Quantitative. In *Proceedings of International Conference on Geotechnical and Geological Engineering GEOENG 200. Melbourne Risk Assessment—Applications, Myths and Future direction.*
8. Health and Safety Executive (HSE). (1984). *Control of Industrial Major Hazards.*
9. Keeney, R. L., & Raiffa, H. (1976). *Decision analysis with multiple conflicting objectives.* Wiley.
10. Baecher, G. B. (1981). *Risk screening for civil facilities* (20 p). Department of Civil Engineering, Massachusetts Institute of Technology CER-81-9.
11. Bründl, M.**,** Etter, H. J, Steiniger, M.**,** Klingler, Ch.**,** Rhyner, J.**,** & Ammann, W. J. (2004)**.** IFKIS (Interkantonales Frühwarn und Kriseninformationssystem)-a basis for managing avalanche risk in settlements and on roads in Switzerland. *Natural Hazards and Earth Sciences, 4.*

Probabilistic Seismic Risk Assessment of School Buildings

Ricardo Monteiro

Abstract The inadequate behavior of existing school buildings observed during past earthquakes in Italy have underlined the need to accurately understand their seismic performance. In order to do so, different metrics can be adopted to characterize their seismic response, either more focused on structural aspects or economic variables. This paper assesses the seismic risk level for three case study school buildings, representing the main typologies found within the Italian school building stock, and comments on the eventual need for retrofitting. A probabilistic-based earthquake engineering (PBEE) performance assessment is carried out using detailed numerical models, analyzed under ground motion records of increasing intensity, to quantify risk-based decision variables, such as expected annual loss and mean annual frequency of collapse. As an alternative to the detailed PBEE framework, a simplified seismic risk classification framework, recently applied in Italy, was also implemented. Different uncertainty parameters are included in the risk estimation frameworks, with a view also to future large-scale implementation of cost-benefit analyses. Lastly, one of the school buildings is further analyzed to understand the impact of the structural modelling uncertainty in the risk estimates and the consequent need for its proper consideration. The results show how the simplified risk classification framework is, as expected, conservative with respect to the detailed component-based approach, as well as the need for retrofitting of some of the building structural systems.

Keywords Risk assessment · Seismic retrofit · Cost-benefit analysis · Loss estimation · Modelling uncertainty

1 Introduction

Extensive damage and structural collapse observed in Italian school buildings during past seismic events have pointed out the need for seismic risk mitigation programs.

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J. C. Matos et al. (eds.), *18th International Probabilistic Workshop*, Lecture Notes in Civil Engineering 153, https://doi.org/10.1007/978-3-030-73616-3_2

These should identify the most vulnerable building typologies and reduce the earthquake-related economic losses and casualties through adequate seismic retrofit strategies. The collapse of a school in San Giuliano di Puglia during the 2002 Molise earthquake in Italy, which caused 30 fatalities, is a key example of the seismic vulnerability of the Italian existing school building stock [1]. Recent studies have also pointed out the importance of non-structural elements in achieving adequate seismic performance levels for an entire building system [2–4]. De Angelis and Pecce [5] reported the death of a student caused by the collapse of a classroom ceiling on November 22nd, 2008 at the Darwin High School in Rivoli, Italy and proposed a simplified methodology to assess the safety of non-structural elements installed in school buildings. Based on these considerations, the need for a seismic risk identification scheme for Italian school buildings comprising both structural and non-structural elements appears evident. Grant et al. [6] developed a risk-management framework to prioritize rehabilitation interventions for Italian school buildings; once the more vulnerable structures are identified. Furthermore, the seismic risk classification guidelines recently introduced in Italy [7] provide a simplified method that classifies existing buildings before and after strengthening interventions. The use of these guidelines may result in tax deductions as an incentive to improve the seismic safety of the existing Italian school building stock, leading to increased awareness of seismic safety and the importance of adequate seismic retrofit among citizens.

To contribute to this important issue, the European Centre for Training and Research in Earthquake Engineering (EUCENTRE) conducted “Progetto Scuole”, a research project aimed at investigating the seismic vulnerability of Italian school buildings. A comprehensive database was developed for approximately 49,000 school buildings in Italy by Borzi et al. [8]. Data related to structural behavior, as well as other features concerning school organizations, was collected. From the database, it was observed that approximately 80% of school buildings in Italy are made of unreinforced masonry (URM) and reinforced concrete frames with masonry infill (RC), whereas the remaining 20% are characterized by other typologies, such as precast structures (PC), steel constructions or mixed assemblies [9]. The knowledge of the main features of the existing school building stock allowed the identification of representative case study school buildings in order to perform detailed loss estimation studies, to be used in future identification of adequate retrofit strategies.

The well-known performance-based earthquake engineering (PBEE) methodology, proposed by Cornell and Krawinkler [3], and subsequently developed by the Pacific Earthquake Engineering Research Center (PEER) in California as the PEER-PBEE methodology, is applied in a systematic fashion in this study to perform the seismic loss assessment [4] of three case study school buildings, representative of different structural typologies, namely RC frames with masonry infill, URM buildings and PC structures. As reported by Taghavi and Miranda [10], the initial monetary investment in non-structural elements for office/schools, hotels, and hospitals buildings can reach up to 60–90% of the total building value.

In this study, the complete seismic loss assessment of the aforementioned three case-study school buildings, belonging to the most common typologies of the Italian existing school building stock, is presented. A detailed inventory of structural and