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The benefit of permanent monitoring for seismic emergency management

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Abstract

In this paper, a framework based on Value of Information (VoI) theory from pre-posterior Bayesian decision analysis is applied to the case of post-earthquake emergency management of traffic restrictions for a bridge. The decision context is the following: the operator of a bridge is concerned about the use of the structure in post-earthquake scenarios and wishes to know if it is worth to install a Structural Health Monitoring (SHM) system which gives information about the state of the bridge. The possible choices about traffic restrictions after the seismic event are *Open* or *Close* the bridge. The benefit of SHM is computed based on VoI and the influence of significant variables involved in the decisional framework is investigated.

1. Introduction

The correct functioning of transportation networks is necessary to avoid isolation of entire urbanized centers or delays in emergency operations following calamities. However, transportation networks may be affected by severe events. This is particularly true for the weakest links of transportation networks such as roadways bridges. The consequences associated to the decision about traffic restrictions relate to user safety and to the disturbance and economic losses caused to drivers and rescue vehicles by the loss of functionality of the bridge. Operators of transportation networks and bridges can base their decision either on prior information they have on the infrastructure or on new data, including SHM information. Ideally, the cost of new knowledge should be balanced by the benefit it brings in relations to risk reduction. The VoI from the Bayesian decision theory (Raiffa & Schlaifer, 1961) is a suitable method to quantify this benefit. Recently, the attention of the scientific community has been focusing on the quantification of the VoI from SHM using the pre-posterior Bayesian decision analysis (Faber et al., 2015). The aim of this work is to carry out a VoI analysis for SHM in the context of emergency management of a motorway bridge under seismic hazard. The investigated structure is a roadway bridge located in Sicily, Italy. The VoI is computed for a SHM system that provides information about the maximum displacement induced by an earthquake at the top of the central pier.

2. Decision scenario and VoI analysis

In the situation considered herein, the *decision maker* is the bridge operator that has to decide about the installation of a permanent SHM system on a bridge located in a seismic-prone area. Additional stakeholders are the users of the bridge. The aim of the SHM system is to support decisions about traffic restrictions in the emergency period following an earthquake. An additional decision is involved, i.e the traffic restrictions to issue after an earthquake. The reference period for the decision about the installation of the SHM is 50 years whereas the reference period for the decision about the traffic restrictions is 2 weeks. The event of interest is the collapse of the piers of the bridge due to traffic loads. The probability of failure of each pier depends on its structural state after the earthquake. Traffic restrictions may generate Direct Consequences (DC) - due to the collapse of the bridge and to the possible casualties and fatalities - and Indirect Consequences (IC) - related to the loss of functionality of the bridge such as pollution, downtime, and fuel consumption. Consequences are expressed as monetary costs. It is noted that IC exist only in the case of closure of the bridge whereas DC costs are associated to bridge failure induced by the traffic loads on the open bridge bridge after the earthquake. The performance indicator chosen to describe the bridge state is the maximum displacement at the top of the central pier. The decision about the installation of an SHM able to provide this indicator is made based on a VoI analyses. The VoI is defined as the difference between the expected consequences of the decision about traffic restrictions made using a) only prior information and b) with the further knowledge from SHM. This difference must be evaluated considering the range of possible seismic events at the location of the bridge. One branch of the decision tree describing the decision problem for one of the possible seismic events is provided in Figure 1. The entire decision tree is obtained considering several branches, one for each possible (discretized) intensity of the seismic event, each associated with its probability of occurrence. The following variables define the decision problem: the set of actions $A = \{Open, Close\}$ related to traffic restrictions; the set of structural states $D = \{d_1, d_2, \ldots., d_5\}$, the set of actions $E = \{Do\ not\ use\ SHM, Use\ SHM\}$ related to selection of SHM strategy; the set of observations $Z = \{z_1, z_2, \ldots\}$ from SHM. The structural states d_i have a prior probability $P'[d_i]$ and a posterior probability $P''[d_i|z_k]$. The latter is computed by means of the Bayes' theorem using the likelihood functions $P[z_k|d_i]$ that express the distribution of the SHM output z associated to the structural state d_i. The probability of failure in the state d_i under traffic restriction a_j is indicated as $P(F|d_i, a_j)$. The terminal costs are indicated as DC and IC in Figure 1. If the action *Close* is selected, the probability of failure is zero, since there is no traffic that can induce the collapse, therefore in this case the expected cost only IC. When the action *Open* the bridge keeps its functionality therefore there are only DC that, for each damage state, must be multiplied by the relevant probability of failure. The following sections report the computation of the variables affecting the decision problem for the considered case study.

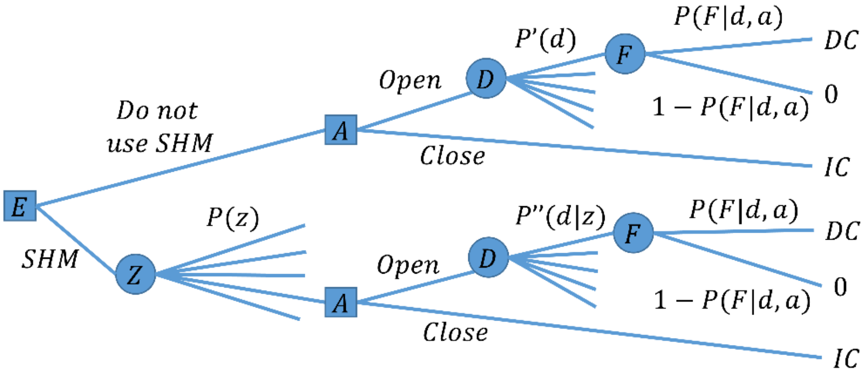

Figure 1 Decision tree for the case study

3. Description of the case study

The case study is the Cusumano bridge which is located on the SS114 road between the cities of Augusta and Catania (southeast Sicily) in a medium-high seismic zone. (Figure 3). The bridge is part of the national network of the Seismic Observatory of Structures (OSS) of the Italian Civil Protection Department (Dolce et al., 2015). The mechanical and geometric characteristics of the materials have been determined through in-situ investigations and are available online in the Italian

Civil Protection database (Protezione Civile, 2019). A finite element model of the bridge has been created and calibrated based on the values of natural frequencies and modal shapes retrieved from ambient vibration test.

Figure 2 West side elevation of the bridge (Protezione Civile, 2019)

Figure 3 Bottom surface of decks (Protezione Civile, 2019)

4. Components of VoI analysis

The general framework for the calculation of VoI in the case of emergency management of roadway bridges has been presented in (Limongelli et al., 2018). Five structural states d_i, corresponding to increasing damage levels after the earthquake, are defined, namely: no damage (d_1); achievement of the 2‰ strain in compressed concrete in one pier (d_2); achievement of the 2‰ strain in compressed concrete in all pier (d_3); bending failure of one pier (d_4); bending failure of all piers (d_5). Only structural states that cause loss of resistance, therefore a change of the failure probability, are considered.

Prior probabilities of system states can be obtained from fragility functions $F(S_a)$ that have been computed using the method proposed by Mander (Mander, 1999):

$$F(S_a) = \Phi\left[\frac{1}{\beta_c} ln\left(\frac{S_a}{A_i}\right)\right] \tag{1}$$

where $\Phi[\cdot]$ is the standard log-normal cumulative distribution function; S_a is the spectral acceleration amplitude at period $T = 1$ sec; A_i is the median spectral acceleration necessary to cause the i-th structural state to occur; β_c normalized composite log-normal standard deviation is assumed equal to 0.6. S_a is obtained from the response spectrum at the site of the bridge (NTC, 2018). Given the spectral acceleration, the only unknown parameter is the median acceleration A_i that induces the i-th structural state. These values of A_i can be obtained from the results of a pushover analysis in correspondence of the achievement of each structural state d_i.

Due to P-Δ effects, the post-earthquake traffic load capacity of the bridge is affected by the magnitude of the residual displacement induced by the seismic event. A value of the residual displacement Δ_r and of the residual bending moment capacity M_r are associated with each structural state d_i of the bridge. In absence of detailed modeling, M_r and Δ_r are computed using simplified empirical relation. Specifically, the residual displacement is assumed equal to 40% of the maximum displacement and the residual moment is computed assuming that at reload – after the residual displacement is achieved – the slope of the bending moment-displacement relationship is equal to the unload branch. The capacity M_r is assumed as the value of the bending moment

corresponding to an incremental displacement, with respect to the residual value, equal to the yielding displacement (Ardakani & Saiidi, 2013).
The probability of failure of the bridge is computed considering the bridge composed by three independent components (three piers) in series. The probability of collapse of each pier under traffic load depends on its structural state after the earthquake. The limit state corresponds to the achievement of the bending capacity at the base of one of the piers. The distribution of the maxima road traffic load on the reference period (2 weeks) has been assumed as Log-Normal distribution (LN) $LN(0.53T_k, 15\%)$ (Sykora, 2019) corresponding to a Gumbel distribution of the annual maxima with mean $0.7T_k$ and coefficient of variation 7.5% (Fib, 2016) where the characteristic value T_k is the *infrequent load* applied according to Eurocode 2 (CEN, 2003).
The likelihood functions $P[z_k|d_i]$ of the displacement z describe its distribution in the different structural states ($d_i, i = 1,2,\ldots,5$) accounting for all the uncertainties that affect this parameter. A deterministic value of the displacement Δ_i for each structural state has been obtained through the pushover analyses. The value of the displacement provided by the SHM system is affected by uncertainties that depend on its magnitude (e.g. those related to the non-linear structural behavior) and others that are independent on it (fixed uncertainties) such as environmental effects, approximation introduced by signal processing (e.g. truncation and integration). Model and instrumental (due to sensors) uncertainties may belong to both classes (Trapani, 2015). In order to account for the two types of uncertainties the following model is assumed for $P[z_k|d_i]$:

$$P[z_k|d_i] = \Delta_i + \Delta_i\sigma_D\varepsilon + \sigma_F\varepsilon \tag{2}$$

where Δ_i is the displacement associated to the state d_i , σ_D is the standard deviation of the uncertainties that depend on the displacement magnitude, σ_F is the standard deviation of the fixed uncertainties, ε is a standard Gaussian random noise. As mentioned, the considered structural states correspond to different magnitudes of the displacement, independent on its sign. Therefore, the Folded Normal distribution, different from zero only for positive values of the displacement, has been used hereafter to model the likelihood functions.
IC and DC are estimated considering costs related to pollution, fuel consumption and user time delay (Limongelli et al., 2018) and for the case study considered herein are equal to 1.20E+06 € and 1.74E+07 €, respectively based on the assumptions in reported inTable 1.
The VoI must is computed considering the occurrence of all the possible seismic events – each with its probability of occurrence - given the reference period (50 years). Assuming independent seismic events, the VoI is computed as the sum of the VoI computed for each – discretized – magnitude of the seismic event, times its probability of occurrence. The probabilities of occurrence have been calculated using the seismic hazard curve of the geographical area where the bridge is located (Panzera et al., 2011).

Table 1 Data used to compute ID and DC

Variable	*Value*	*Variable*	*Value*
Length of the bridge	*172 m*	*Cost of fuel*	*1.5 €/l*
Daily number of vehicles	*11700*	*Cost of travel time*	*5.76 €/person/h*
Mean number of people per vehicle	*2*	*Cost of fatality*	*1,649,877 €*
Mean velocity of vehicle	*80 km/h*	*Cost of injury (long term assistance)*	*216,359 €*
Cost of demolition and new bridge	*16,757,038 €*	*Total number of fatalities*	*100*
Length of diversion due to limitation	*10 km*	*Fatalities due to delay*	*1 %*

5. Results and discussion

The evolution of the prior expected costs related to the considered traffic restrictions *Open* and *Close* with the intensity of the seismic event (represented by S_a) is reported in Figure 4, left up. The variation of the VoI with S_a and with the accuracy of the monitoring system (depending on the uncertainties σ_F and σ_D) is reported in Figure 4, lower left. The values of the standard deviations σ_F and σ_D are dependent being both related to model and instrumental uncertainties. In this example, it is assumed that $\sigma_F = \sigma_D/2$.

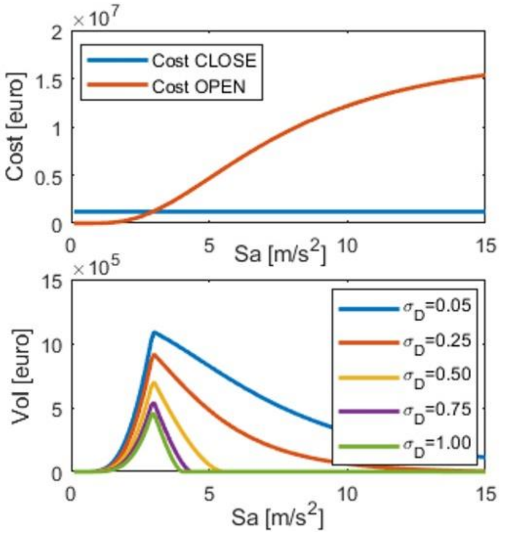

Figure 4 VoI as a function of the spectral acceleration amplitude S_a and likelihood uncertainty σ_D.

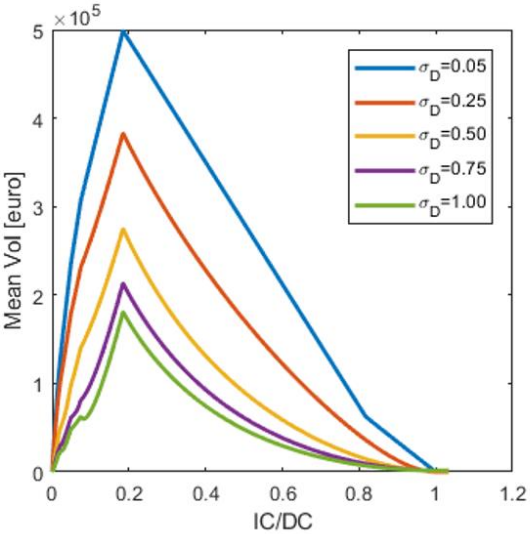

Figure 5 VoI as a function of IC/DC and likelihood uncertainty σ_D.

The comparison of the two pictures on the left of Figure 4 shows that the maximum value of the VoI corresponds to the point of intersection between the curves of prior expected costs. At this point, the costs of the two decisions (*Open* or *Close*) made basing only on prior information are equal. The prior information do not support the decision maker in the choice of one of the two actions. Therefore, this is the situation the VoI reaches its maximum value. For the same value of the seismic intensity the VoI decreases with the accuracy of the monitoring system (at the increase of σ_F and σ_D). In Figure 5, it is reported the mean VoI of SHM for all the possible seismic events (each weighted with its probability of occurrence) as a function of the uncertainty σ_D and of the ratio between indirect and direct costs IC/DC. The VoI tends to zero for low values of IC/DC and for values higher than 1. In the first case the operator selects the action *Close* and in the second case the action *Open* - that is the action corresponding to the minimum cost - irrespective of the outcome of the SHM that, for this reason, has a null VoI.

6. Conclusions

The benefit of permanent SHM for the seismic emergency management has been quantified resorting to the concept of VoI from Bayesian decision analysis. A roadway bridge in a seismic - prone area in Sicily, Italy, is considered as case study. The methodology presented herein can be used by operators of transportation systems to estimate the advantage of using a SHM system before installing it. The critical elements of the VoI analysis are the computation of the prior probabilities of structural states, the likelihood functions, and the estimation of consequences, which can be direct or indirect. It has been shown that the VoI decreases when the uncertainty associated to the output of SHM increases. The ratio between Indirect and direct costs has a strong influence on the VoI that vanishes when one of the two costs sharply exceeds the other, making the information from the SHM uninfluential on the behavior of the decision maker.

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