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Research Article

A Computing Model for Quantifying the Value of Structural Health Monitoring Information in Bridge Engineering

Baoquan Cheng [1,2] Lijie Wang,[3] Jianling Huang,[1] Xu Shi,[4] Xiaodong Hu,[1] and Huihua Chen [1]

[1]*School of Civil Engineering, Central South University, Changsha, Hunan 410083, China*
[2]*Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Kowloon, Hong Kong, China*
[3]*Department of Architecture, Shijiazhuang Institute of Railway Technology, Shijiazhuang, Hebei 050041, China*
[4]*College of Optoelectronic Engineering, Chongqing University, Chongqing 400044, China*

Correspondence should be addressed to Huihua Chen; chh24770@163.com

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Structural health monitoring system can provide valuable information for improving decision-making process in maintenance and management of bridges. However, managers usually lack understanding of value of structural health monitoring information. This paper developed a computing model for quantifying the value of structural health monitoring information based on Bayesian theory. Then, the model was demonstrated and validated using a simple case and the key factors (i.e., system accuracy, reparation cost, prior probability of structural failure, and manager's behavior pattern) influencing the value of structural health monitoring information were identified and discussed. Findings from this study help to answer the question of whether a structural health monitoring system should be installed and run, thus enriching the knowledge body of structural health monitoring.

1. Introduction

With the sustained economic development, the traffic volume particularly the overloading vehicles increased rapidly. This seriously threats the structural safety of bridges particularly those constructed as early as the 19th~the mid-20th century whose extended service lives have caused dangerous accumulation of structural damages in long-term use [1–3]. In fact, it is reported that structural accidents such as sudden bridge breakages occurred frequently in recent years. Once the structural failure occurred, there would be huge social-economic losses and human casualties. Therefore, how to ensure structural safety of bridges especially at the background of such a huge traffic volume has become the great challenge nowadays. In fact, if in-time judgements and alarms are made before structural failure, managers can take corresponding urgent measures to avoid future damages and accidents [4]. This requires managers regularly measure and assess the degree of cumulative structural damage [5]. Structural health monitoring (SHM) therefore emerged as times need and caught attention from both scholars and industrial stakeholders.

SHM can be defined as the strategies and process for identifying and characterizing structural damages. A completed SHM system usually consists of 6 modules including sensory system, data acquisition and transmission system, data processing and control system, structural health evaluation system, structural health data management system, and inspection and maintenance system [6–8]. It can provide real-time information about structural conditions of bridges (environmental loads and status, operation loads, bridge features, and structural responses) by integrating various state-of-art technologies such as sensory technology, deep learning, big data, and machine vision [9, 10]. These valuable information can provide decision-making references for managers in maintenance and management of bridges.

Nowadays, SHM has been conducted on more and more famous bridges such as Jiangyin Bridge (Jiangsu, China), Tsing Ma Bridge (Hong Kong), and Faroe Bridge (Denmark) in the global [11]. However, it is reported that many bridge managers in the real life are still reluctant to invest on SHM. Sometimes, even though the structural health monitoring information is available, they still make decisions based on their common sense and prior experience instead of actions suggested by the SHM system. The embarrassing situation actually results from a principle which goes beyond the scope of the bridge managers. Firstly, there exit many uncertainties affecting the quality of structural health monitoring information such as system accuracy and stability, environmental noise, and errors in data process. Bridge managers therefore usually cannot completely believe in the SHM system. They will weigh the actions suggested by SHM combining with their prior experience and common sense. At the same time, bridge managers are very concerned about results caused by wrong actions. They will consider all potential impacts of possible actions before making a decision, which also drives their preference to experience-based instead of SHM-suggested action [12]. In summary, lack of understanding of value of structural health monitoring information decrease managers' interests in SHM in the real life. To promote and improve application of SHM in future, the question of whether a SHM system should be installed and run must be addressed. This means that a rational model to evaluate the value of structural health monitoring information is urgently needed.

Current studies on SHM mainly focus on optimization of hardware system development, sensory system placement, and damage identification algorithms [13–18]. However, limited attention was paid to the value of structural health monitoring information [19–21]. To address this research gap, this paper aims to develop a computing model for quantitatively assessing the value of structural monitoring information based on Bayesian theory. Through scenario simulation and sensitivity analysis based on the developed model, the main influencing factor of value of structural health monitoring information is identified and discussed. This study can deepen managers' understanding of value of SHM and thus eliminate their doubt on reliability of SHM.

2. Method and Materials

2.1. Basic Assumptions. Many uncertainties are usually involved in the decision-making process. To make the best decision, the manager should collect related information of these uncertainties to decrease and eliminate them. These information that helps to reduce decision-making risks is of certain value to some extent. However, the process of information collection has to consume resources including time, manpower, and money. This means managers often face a difficult question, that is, if it is worthwhile to collect information. To answer this question, a standard should be developed, which means managers should convert all investment on information collection into monetary value and compare it with the value of information (VOI). Therefore, the quantitative assessment of VOI is of great significance for decision making.

To develop the computing model for quantifying VOI of SHM, some basic assumptions were made in advance as follows:

Assumption 1. A bridge must be at one of n possible structural states (e.g., undamaged, slight damage, serious damage, and structural failure) labeled as S_1, $S_2, \cdots$, S_n, of which possibilities are assumed to be mutually exclusive and exhaustive.

Assumption 2. The bridge manager has m action choices (e.g., do nothing, repair, and rebuild), and he has to choose one. We labeled these actions as $a_1, a_2, \cdots, a_m$.

Assumption 3. The manager's decision will cause a cost that depends on the bridge's actual structural state. c_{ij} indicates the expected cost for action a_i when the bridge is at state S_j. It should be noted that this cost includes many aspects such as financial losses, delayed transportation time, environmental impacts, and accident casualty caused by structural failure. It is assumed that all costs can be expressed by a monetary value.

Assumption 4. The manager is assumed to be a rational agent. This means the manager will always choose the most economic action with the minimum cost.

Based on above assumptions, a general model for quantifying the value of structural health monitoring information can be developed, which consists of 3 steps, i.e., (1) cost-benefit analysis, (2) prior decision analysis, and (3) preposterior decision analysis.

2.2. Cost-Benefit Analysis. The expected cost for every action when the bridge is in every structural state c_{ij} including both direct cost and indirect cost is evaluated in this step. This is the basis of accurate quantification of value of structural health monitoring information. Indirect cost (e.g., delayed transportation time, environmental impacts, and accident casualty caused by structural failure) can be converted into monetary value through value transfer approach [22].

2.3. Prior Decision Analysis. If there is not an SHM system, information about structural conditions of the bridge is not available. Therefore, the manager can only estimate the expected cost C_i of action a_i based on his prior experience and common sense by the following equation:

$$C_i = \sum_{j=1}^{n} c_{ij} P(S_j). \tag{1}$$

In which, $P(S_j)$ represents the prior probability that the bridge is at structural state S_j.

As a rational agent, the bridge manager will choose the most economic action a_{opt} that minimizes the expected cost as follows:

$$a_{\text{opt}} = \arg\min C_i = \arg\min \sum_{j=1}^{n} c_{ij} P(S_j). \tag{2}$$

The corresponding expected management cost without SHM can thus be calculated as follows:

$$C = \min C_i = \min \sum_{j=1}^{n} c_{ij} P(S_j). \tag{3}$$

2.4. Preposterior Decision Analysis. When an SHM system is installed and run, the manager can obtain a set of observation y such as deflection, stress, acceleration, and strain. The information can modify the bridge manager's knowledge of structural state S_j from $P(S_j)$ to $P(S_j \mid y)$, reducing the uncertainties and risks in the decision-making process. Equation (1) can therefore be rewritten as

$$C_i' = \sum_{j=1}^{n} c_{ij} P(S_j \mid y). \tag{4}$$

In which, the mark $'$ is a reminder that it is the expected cost posterior to the observations of y.

The posterior probability $P(S_j \mid y)$ can be calculated using the Bayesian rule:

$$P(S_j \mid y) = \frac{p(y \mid s_j) P(s_j)}{p(y)}. \tag{5}$$

In which, the probability of observations $p(y)$ can be estimated using the law of total probability:

$$p(y) = \sum_{j=1}^{n} p(y \mid S_j) P(S_j). \tag{6}$$

Thus, with structural health monitoring information y, equations (2) and (3) can be rewritten as equations (7) and (8):

$$a_{\mathrm{opt}}' = \arg\min C_i' = \arg\min \sum_{j=1}^{n} c_{ij} P(S_j \mid y), \tag{7}$$

$$C'(y) = \min C_i'(y) = \min \sum_{j=1}^{n} c_{ij} P(S_j \mid y). \tag{8}$$

Equation (8) represents the minimum expected cost with an individual observation set y. If the monitoring continues, the corresponding cost can be calculated with the probability distribution of y using

$$C' = \int_{\Omega_y} C'(y) p(y) \mathrm{d}y = \int_{\Omega_y} \min \left\{ \sum_{j=1}^{n} c_{ij} P(S_j \mid y) \right\} p(y) \mathrm{d}y. \tag{9}$$

In which, Ωy represents the domain of y.

Substituting equation (5) into equation (9), equation (9) can be rewritten as

$$C' = \int_{\Omega_y} \min \left\{ \sum_{j=1}^{n} c_{ij} p(y \mid S_j) P(S_j) \right\} \mathrm{d}y. \tag{10}$$

Then, the VOI of an independent SHM can be calculated using

$$\begin{aligned} \mathrm{VOI} &= C - C' \\ &= \min \sum_{j=1}^{n} c_{ij} P(S_j) - \int_{\Omega_y} \min \left\{ \sum_{j=1}^{n} c_{ij} p(y \mid S_j) P(S_j) \right\} \mathrm{d}y. \end{aligned} \tag{11}$$

3. Scenario Simulation

The developed computing model is demonstrated and validated by a simple example. For simplification, it is assumed that there are only two possible structural states for the bridge, i.e., undamaged (U) and damaged (D). The bridge manager has only two action choices: do nothing (DN) and repair (R). It will cost nothing if the manager does nothing when the bridge is undamaged whereas making this decision when structure fails will result in a huge cost C_F. In addition, choosing to repair the bridge will cause a cost C_R. We assumed that C_R is independent of the actual structural state of the bridge and $C_R \ll C_F$. The results of cost-benefit analysis are summarized in Table 1.

The bridge manager will estimate the expected cost of each action. The reparation cost is identically equal to C_R no matter what the actual structural state is. The cost of doing nothing then depends on the manager's knowledge of structural failure.

When there is not an SHM system, he can only estimate the cost of doing nothing C_{DN} based on his prior experience and common sense through the following equation:fd12

$$C_{DN} = C_F \cdot P(D). \tag{12}$$

In which, $P\ (D)$ represents the prior probability of the structural failure.

Based on rational agent assumption, the manager will only repair the bridge when $C_{DN} > C_R$; otherwise, he will accept risks and do nothing. Thus, the expected cost C without SHM can be got throughfd13

$$C = \min(C_R, C_F \cdot P(D)). \tag{13}$$

Next, the impacts of SHM on the manger's decision are investigated. For simplification, it is assumed that the SHM has only two outcomes (i.e., Silence (S) and Warning (W)). The outcome of SHM is probabilistically related to the actual structural state of bridges. If the observation exceeds the threshold, a warning will be given by the SHM system. Otherwise, it keeps silence. To model the system accuracy, two parameters are introduced: the probability of a false warning when a warning is given but the bridge is undamaged $P_{FW} = P(W \mid U)$, and the probability of false silence when the SHM system keeps silence but the structure fails $P_{FS} = P(S \mid D)$. Thus, the probabilities of SHM outcomes at each structural state are summarized in Table 2.

Generally, $P_{FW} \neq P_{FS}$. When a higher threshold is set, P_{FW} tends to go up while P_{FS} tends to decrease. The lower the P_{FW} and P_{FS} are, the more reliable the SHM is. More reliable structural health monitoring information has higher

Table 1: Temperature and wildlife count in the three areas covered by the study.

	U	D
DN	0	C_F
R	C_R	C_R

Table 2: Conditional probability of SHM outcomes and structural states.

	U	D
S	$1 - P_{FW} = P(S \mid U)$	$P_{FS} = P(S \mid D)$
W	$P_{FW} = P(W \mid U)$	$1 - P_{FS} = P(W \mid D)$

corresponding VOI. Only the situation in which P_{FW} and P_{FS} are both below 0.5 is taken into consideration in this study because SHM with too high rate has no values. Based on equation (6), the probability of each SHM outcome can be estimated through the following equations:

$$P_W = P(W \mid U) \cdot P(U) + P(W \mid D) \cdot P(D), \tag{14}$$

$$P_S = P(S \mid U) \cdot P(U) + P(S \mid D) \cdot P(D). \tag{15}$$

Then, equation (5) can be rewritten as equations (16) and (17) for assessing the probability of damage:

$$P(D \mid W) = \frac{P(W \mid D) \cdot P(D)}{P(W)}, \tag{16}$$

$$P(D \mid S) = \frac{P(S \mid D) \cdot P(D)}{P(S)}. \tag{17}$$

Thus, the structural health monitoring information enables the manager to update their knowledge of structural state and estimate the expected cost through the following equations again:

$$C'(W) = \min\left(C_R, P(D \mid W) \cdot C_F\right), \tag{18}$$

$$C'(S) = \min\left(C_R, P(D \mid S) \cdot C_F\right). \tag{19}$$

Therefore, the expected cost with SHM can be calculated through:

$$C' = C'(W) \cdot P(W) + C'(S) \cdot P(S). \tag{20}$$

Then, following the same criterion in equation (11), the VOI can therefore be evaluated through:

$$\begin{aligned} \mathrm{VOI} = C - C' &= \min\left(C_R, C_F \cdot P(D)\right) \\ &\quad - \left(C'(W) \cdot P(W) + C'(S) \cdot P(S)\right). \end{aligned} \tag{21}$$

It can be found that the value of structural health monitoring information depends on the specific values of cost of each action C_F and C_R, the prior probability of structural damage $P(D)$, and the error rates of the SHM system P_{FW} and P_{FS}.

4. Results and Discussion

4.1. VOI and System Accuracy. Figure 1 describes the contours of VOI (K\$) in which C_R = 10K\$, C_F = 1000K\$, and $P(D)$ = 0.5%. When the SHM can always offer completely precise information defined as perfect information (i.e., $P_{FW} = P_{FS} = 0$), the manager can always judge the actual structural state of the bridge accurately. Thus, he will only repair the bridge when it is damaged; otherwise, he will do nothing. In fact, structural failure will be prevented in either cases when perfect information is available. In this case, the value of perfect information $\mathrm{VOPI} = C - C' = 5000 - 50 = \$4950$. It is also the upper limit of the VOI. No matter how state-of-art SHM technologies are adopted, the corresponding VOI can never exceed this boundary. The ratio of actual VOI and VOPI can be used to present the efficiency of the SHM system. The other extreme condition is $P_{FW} = P_{FS} = 0.5$. This means the SHM outcome is absolutely independent of the actual structural state. Under this condition, $C = C' = \$5\mathrm{K}$ and corresponding VOI = 0. It proves that the SHM system with too high error rate has no values. It is also the lower limit of VOI. Between these two limit values, the VOI goes down with the decreasing system accuracy. In addition, the VOI is more sensitive to P_{FW} than P_{FS}. This can be validated by the fact that the VOI in S2 ($P_{FW} = 0.1$, $P_{FS} = 0.2$) is 5000 higher than that in S1 ($P_{FW} = 0.2$, $P_{FS} = 0.1$).

4.2. VOI and Reparation Cost. Figure 2 describes impacts of reparation cost CR on the VOI of the SHM system in which cost of structural failure C_F = 1000K\$ and the prior probability of damage $P(D)$ = 0.5%. We assume that $P_{FW} = P_{FS}$. In each lime, the VOI increases with the increasing reparation cost CR until reaching the peak at CR = 5K\$. Then, the VOI turns to decrease until VOI = 0 if reparation cost CR continues to increase. This is consistent with our common sense. When the reparation is very cheap, the manager will always repair the bridge to eliminate risks of structural failure no matter what structural health monitoring information is provided. When the reparation cost goes up, the expected cost with SHM C' goes down, leading to growth in VOI. At the point of CR = 5K\$, the expected cost with SHM C' decreases to the bottom and the VOI reaches the peak. After that, with the continuously incensing reparation cost, the bridge manager is likely to accept risks of structural failure, causing decreases in VOI. After the VOI reduces to 0, the manager will never repair the bridge due to the high cost. By comparing three limes, it can be found that the higher the SHM system accuracy is, the higher the VOI of SHM is. A higher SHM system accuracy also expands the effective range of SHM towards reparation cost.

4.3. VOI and Prior Probability of Damage. Figure 3 describes impacts of the prior probability of damage $P(D)$ on the VOI of the SHM system in which cost of structural failure C_F = 1000K\$ and reparation cost C_R = 5K\$. We still assume that $P_{FW} = P_{FS}$. In each lime, the VOI increases with the prior

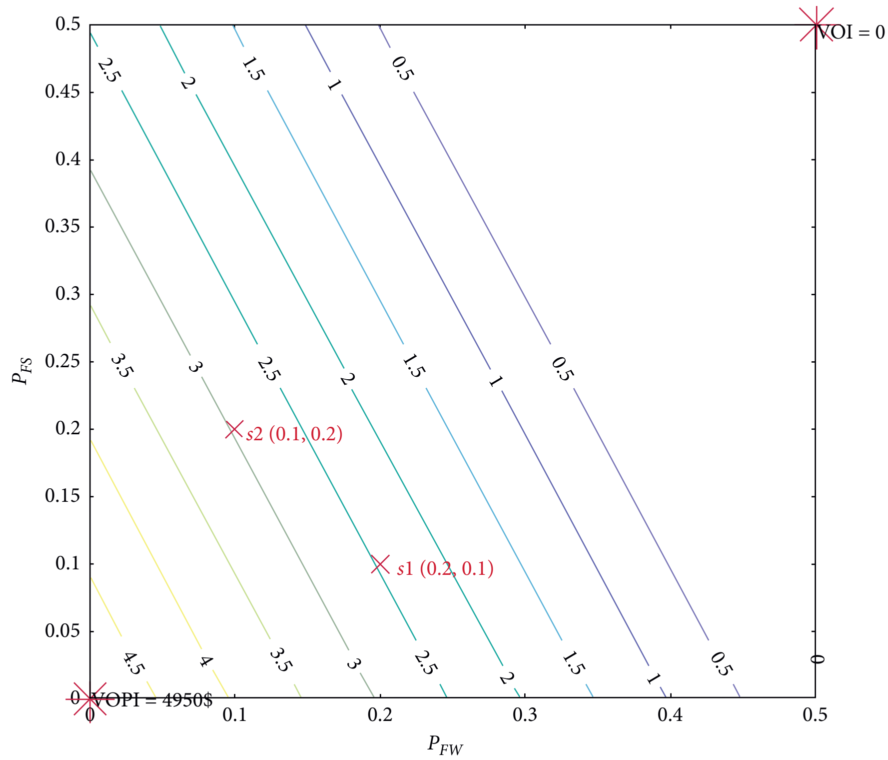

Figure 1: Contours of VOI (K$) as a function of the failure probability of the SHM system P_{FW} and P_{FS} when $C_R = 10$K$, $C_F = 1000$K$, and $P(D) = 0.5\%$.

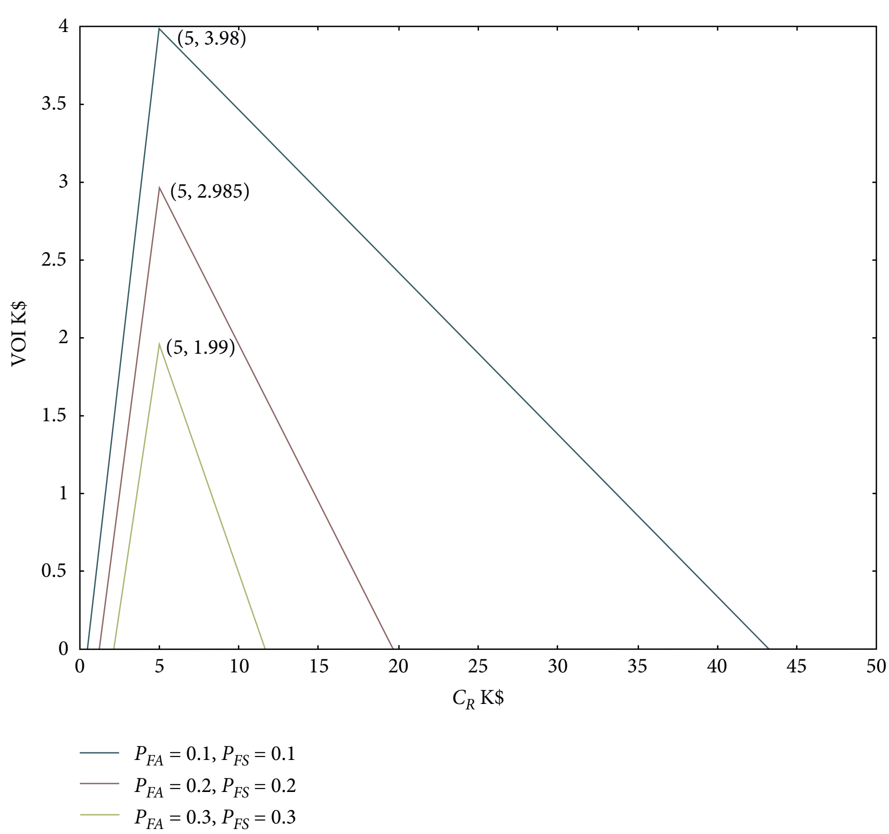

Figure 2: VOI as a function of the reparation cost CR when $C_F = 1000$K$, $P\ (D) = 0.5\%$, and $P_{FW} = P_{FS}$.

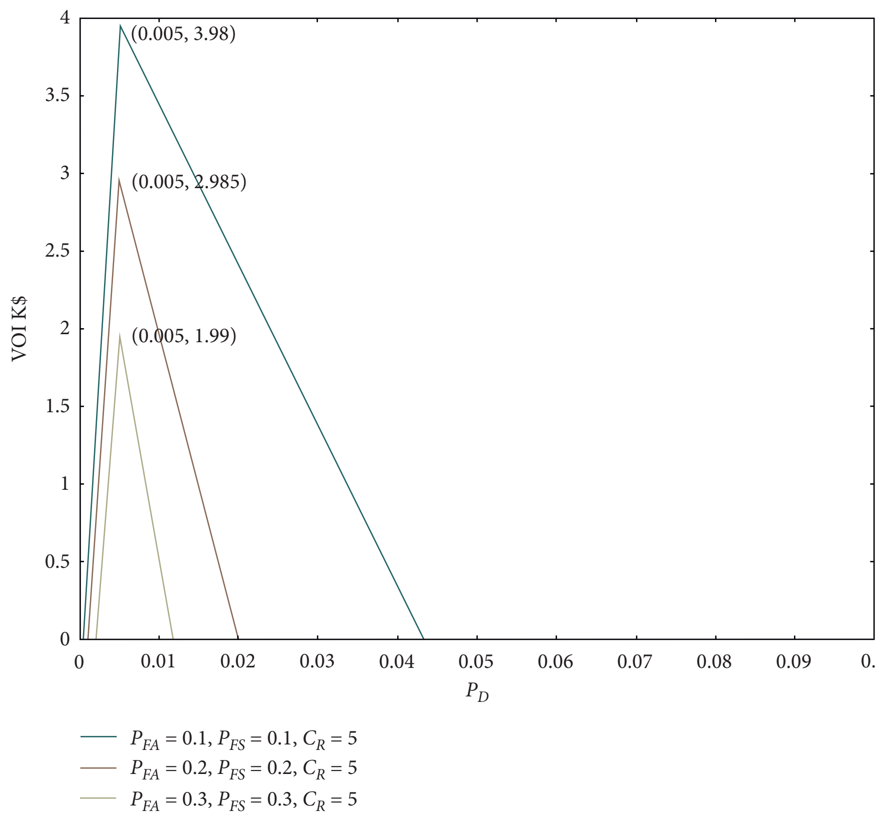

Figure 3: VOI as a function of the prior probability of damage $P(D)$ when $C_F = 1000$K\$, $P\ (D) = 0.5\%$, and $P_{FW} = P_{FS}$.

probability of damage $P(D)$ until reaching the peak at $P(D) = 0.005$. Then, the VOI turns to decrease until VOI $=$ 0 if the prior probability of damage continues to go up. This can be explained by the fact that when the probability of structural failure is too low, the bridge manager is really confident in structural safety and he will accept risks of structural failure and do nothing. SHM information helps little. When the prior probability of damage increases, uncertainties and risks in decision-making process as well increase. VOI helps to decrease these uncertainties and risks, and the VOI grows correspondingly. At the point of $P(D) = 0.005$, the expected cost with SHM C' decreases to the bottom and the VOI reaches the peak. After that, with the continuously incensing prior probability of damage, the bridge manager is likely to repair the bridge. In fact, uncertainties of the bridge structural state decrease, causing decreases in VOI. After the VOI reduces to 0, the manager will always repair the bridge to avoid high loss due to structural failure. By comparing three limes, it can be found that the higher the SHM system accuracy is, the higher the VOI of SHM is. A higher SHM system accuracy also expands the effective range of SHM towards prior probability of damage.

4.4. VOI and Manager's Behavior. The bridge manager's behavior pattern also influences the actual value of structural health monitoring information. It is assumed that the manager is a completely rational agent. This means in the developed model, the manager will always pursue the minimum expected economic cost in the decision-making process. This is not completely consistent with the reality. Two extreme situations are presented in this section. Firstly, if the manager is completely a risk-oriented agent, he will never accept the risk of structural failure. In this situation, he will select to repair the bridge. The other extreme situation occurs when the manager is a completely adventure agent. In this situation, he will do nothing for the largest interests. In above both extreme situations, the structural health monitoring information is not applied in the decision-making process and creates no value. Therefore, VOI = 0. This result proved that the manager's behavior is also an important influence factor of VOI of SHM.

5. Conclusions

This study was to quantify the value of structural health monitoring information. This aim has been achieved by developing a computing model based on Bayesian theory including three steps: (1) cost-benefit analysis, (2) prior decision analysis, and (3) preposterior decision analysis. The developed model was demonstrated and validated using a simple example. Simulation results show that VOI of SHM depends on system accuracy, the specific values of cost of each action, and the prior probability of damage. However, this study only considers a very ideal case with only two possible structural states and two feasible actions. However, the situation is much more complex in the real life. The value of structural health monitoring information in a more complicated situation that is closer to the real world should be assessed in the further studies.

Data Availability

All datasets generated for this study are included in the article.

Disclosure

This paper is based on the master dissertation of Baoquan Cheng at HK PolyU.

Conflicts of Interest

All authors declare no conflicts of interest.

Authors' Contributions

All authors contributed equally to this paper.

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