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Incorporation of Seismic Considerations in Bridge Management Systems

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Abstract: *The objective of this paper is to incorporate seismic hazard and risk analysis considerations, which are concerned with the occurrence of earthquakes and the vulnerability of structures, into bridge management systems. We develop a decision model for optimizing bridge maintenance, repair, and reconstruction (MR&R) policies that takes into account the occurrence of earthquake events. The model presented in this paper is not meant to be very detailed or comprehensive, but rather to allow us to obtain qualitative implications of including seismic considerations in bridge management systems. Based on four different case studies, we found that accounting for the probability of earthquake occurrence in a bridge MR&R decision-making model had a significant impact on the probability distribution of the bridge condition state, the optimal policies, and their total cost. Furthermore, we found that ignoring the probability of destruction due to earthquakes would lead to errors in budgeting.*

1 INTRODUCTION

The objective of a bridge management system is to assist highway agencies in selecting maintenance, repair, and reconstruction (MR&R) policies for networks of bridges. Systems, such as PONTIS (FHWA, 1993) or BRIDGIT (NET, 1994), solve for optimal MR&R policies at the network, bridge, or component level. In such systems, component deterioration is represented by Markov transition probabilities. Facility deterioration is a gradual process that is caused by mechanisms such as corrosion of the reinforcing bars in concrete components, or fatigue of steel elements. Current bridge management systems do not take into account the possibility of failure due to natural phenomena, such as earthquakes, which have the potential to cause the destruction of bridge structures.

The objective of this paper is to incorporate seismic hazard and risk analysis considerations, which are concerned with the occurrence of earthquakes and the vulnerability of structures, into bridge management systems. While this paper focuses specifically on seismic hazard, our approach can be generalized to damage from other natural phenomena, such as bridge scour due to flooding.

We develop a decision model for optimizing bridge MR&R policies that takes into account the occurrence of earthquake events. The model presented in this paper is not meant to be very detailed or comprehensive, but rather to allow us to obtain qualitative implications of including seismic considerations in bridge management systems.

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We begin with a quick review of the most relevant bridge management systems that have been developed to date. In the subsequent section, the main concepts of seismic risk analysis are presented. We follow with a description of the method used for the calculation of the annual probability of exceeding a given damage level. We then present the mathematical formulation of an MR&R decision model that accounts for seismic considerations. The conclusions of this paper are drawn from four case studies that explore several different scenarios.

2 BRIDGE MANAGEMENT SYSTEMS

The Inter-modal Surface Transportation Efficiency Act of 1991 (ISTEA) required state highway agencies to implement six types of infrastructure management systems by the year 1995. Although various state departments of transportation as well as the US DOT had developed some of these systems previously, this legislation provided the impetus for the adoption of bridge management systems (BMS). Two BMS have been developed at the national level in the U.S.: PONTIS (FHWA, 1993) and BRIDGIT (NET, 1994). Moreover, a number of states, such as Alabama, Connecticut, Indiana, North Carolina, and Pennsylvania, have developed their own systems (TRB, 1994).

All BMS must include realistic bridge deterioration models in order to predict the consequences of different possible corrective actions that are available to decision-makers in highway agencies. PONTIS and BRIDGIT use Markov transition probabilities to represent deterioration between the different deterioration states of the bridge components. These transition probabilities are developed using either expert elicitation or data from condition surveys. In either case, the emphasis is on modeling the gradual deterioration of bridge components from factors such as steel corrosion or fatigue. Perhaps as a result of this reliance on historical data or expert judgment, existing BMS do not account for the possibility of exceptional events, such as earthquakes.

PONTIS is certainly the most widely used bridge management system in the U.S. today. Moreover, the theoretical foundations of the underlying MR&R decision-making model are clear and rigorous. For this reason, our proposed model is mainly inspired by PONTIS. We now briefly describe the main concepts behind this BMS.

PONTIS considers the main elements (decks, girders, etc.) of all bridges as independent networks. It solves for optimal steady-state MR&R policies for each network. A steady-state policy causes the network-wide distribution of each element among its deterioration states to remain constant over time. The optimal policy is sustainable and minimizes the total cost. The optimal policies are obtained by solving the following linear program:

$$\min \sum_r \sum_i w_{ri}(c_{ri} + u_{ri})$$

$$\textit{subject to} \quad \begin{aligned} & w_{ri} \geq 0, \quad \forall r, \forall i \\ & \sum_r \sum_i w_{ri} = 1 \\ & \sum_r \sum_i w_{ri} P_{rij} = \sum_r w_{rj}, \quad \forall j \end{aligned} \tag{1}$$

where

- w_{ri} are the decision variables, the fraction of elements in deterioration state i to which action r is applied
- c_{ri} are the MR&R costs associated with state i and action r
- u_{ri} are the user costs associated with state i and action r
- P_{rij} are the transition probabilities from state i to state j after one period if action r is taken.

The first two constraints define the range of the decision variables; the fractions must be positive and must sum to one. The third constraint indicates the sustainability of the policy; this is the Chapman-Kolmogorov equation. Other constraints, such as a budget range or minimum quality requirements, may be added to this basic model.

With PONTIS, the development of optimal transient policies—how to take a given network condition-state distribution to the optimal steady state—is not obvious. There have been different approaches proposed to deal with this problem, such as introducing a "penalty" related to the distance to the steady state, and reaching the steady state in a given number of years (Guignier and Madanat, 1999).

3 SEISMIC RISK CONCEPTS

The damages caused by an earthquake primarily result from ground shaking, liquefaction, landslides, and differential fault deplacement. Moreover, indirect effects, such as fire and inundation, can lead to additional destruction (Kiremidjian, 1994). In this paper, we only consider the hazards from ground motion, for which several models have been developed. While ground shaking can be quantified by different indices, we use the peak ground acceleration, in units of gravity acceleration g.

Let us consider all earthquakes of engineering interest; these are earthquake events with magnitude M greater than a given value M_0 (for example, 4 on the Richter scale). We model these quakes as a Poisson process, defined by a parameter ν. This is a reasonable model for events that are rare and statistically independent. The ground motion at one site is a function of the magnitude of the earthquake M, the distance from the epicenter R, some site-specific conditions S, and a random term γ, as described by the attenuation law: $a = A(M, R, S, \gamma)$.

For each quake of engineering interest, the ground motion at one site can be considered as a random variable A, with a cumulative distribution function (cdf) $F_A(a)$. The result of a site hazard analysis is frequently presented as a hazard curve. It is defined as the probability that the peak ground acceleration exceeds a given level a at least once in a period $(0, t)$:

$$G_A(a) = P[A > a, (0, t)] \quad (2)$$

Figure 1 presents a hazard curve for 50 years for the city of Berkeley, CA (zip code 94702). It was obtained from the three risk levels (0.10, 0.05, and 0.02 probability of being exceeded in 50 years) given on the U.S. Geographical Survey web site in April 1999 (http://geohazards.cr.usgs.gov/eq/). The best fitting type I extreme value distribution was used. We therefore assume a hazard curve for $t = 50$ years of the form:

$$G_A(a) = 1 - \exp[-\exp(-\alpha a - \beta)] \quad (3)$$

where α and β are the parameters of the Type I extreme value distribution.

Using the Poisson process definition, it is possible to relate $G_A(a)$ to the cdf of ground motion by the following expression:

$$G_A(a) = 1 - \exp[-\nu t \cdot (1 - F_A(a))] \quad (4)$$

This is simply one minus the probability of zero earthquake with ground motion greater than a during a period of t years.

This allows us to find the expression of the hazard curve for 1 year:

$$H_A(a) = 1 - \exp\left[-\frac{1}{t} \cdot \exp(-\alpha a - \beta)\right] \quad (5)$$

Let us now explore the relation between ground motion and damage to a given bridge. This can be defined through a damage probability matrix (DPM) or a fragility curve.

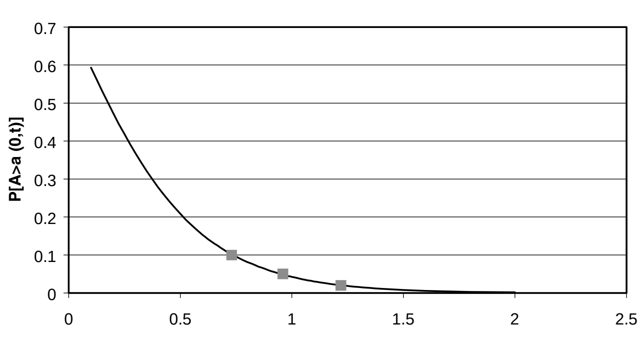

Fig. 1. Hazard curve.

A DPM describes the probability that the structure is in a particular damage state given the ground motion. It may be derived from p.d.f $f_{D|a}(d)$ for a continuous damage random variable d. A fragility curve can be defined as the probability of exceeding a given damage level d for a given ground motion:

$$Y_d(a) = P[D > d|a]$$

Figure 2 shows fragility curves used in the HAZUS software (National Institute of Building Sciences, 1997) for extensive damage (left curve) and complete damage (right) incurred by a seismically designed simply supported bridge (class HBR5). These curves are lognormal, with respective median value of ground motion 0.39 and 0.85 and lognormal standard deviation 0.5 and 0.6.

In HAZUS, damage states are defined by an empirical description. Extensive damage for a bridge includes "any column degrading without collapse [. . .], any connection losing some bearing support, or major settlement of the approach," while complete damage is characterized by "any column collapsing and connection losing all bearing support, which may lead to imminent deck collapse." The damage states are also related to a damage ratio of repair to replacement cost, as well as a restoration curve that describes bridge serviceability.

There are currently only two classification schemes available in the literature that are relevant for the seismic response of bridges to quakes (Basoz and Kiremidjian, 1996).

- The Earthquake Engineering Facility Classification (Applied Technology Council, 1985) contains only three classes for bridges. The structures are characterized by their sizes, structural systems, and types.
- The technical manual prepared for the National Institute of Building Sciences (Risk Management Solutions, 1995) classifies bridges into six groups with similar criteria, with a "high risk" modifier giving a total of 12 classes. This classification is the one used in the HAZUS software.

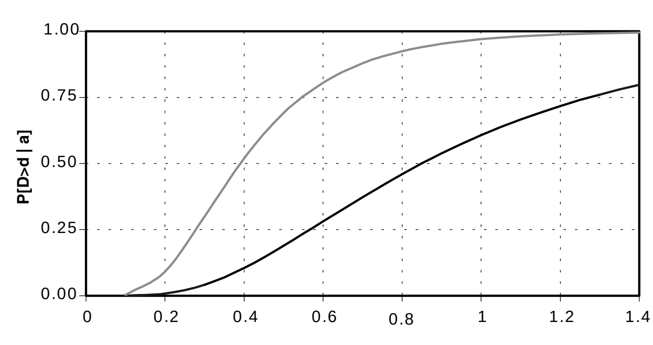

Fig. 2. Fragility curves.

Basoz and Kiremidjian (1996) emphasize the limitations of the existing classifications, which group in the same class bridges with significantly different seismic responses. They propose a new classification to give a better understanding of the behavior of bridges during earthquakes. However, the seismic responses of these new classes have not been established yet, while both DPMs and fragility curves are available for existing systems.

4 ANNUAL PROBABILITY OF DAMAGE

We now derive an expression for the risk that a given bridge incurs a seismic damage greater than a given level at least once in a year.

For a given bridge, there is a certain minimum level of peak ground acceleration a_l that will lead to this level of damage d_l. If we knew a_l, then the annual probability of damage of level d_l would simply be

$$P = H_A(a_l) \tag{6}$$

However, due to our incomplete knowledge of the structure's response to peak ground acceleration, the capacity of the bridge is not precisely known, but is a random variable A_l, in units of ground acceleration. This uncertainty is embedded in the fragility curve.

$$Y_{d_l}(a) = P[D > d_l|a] = P[A_l < a] \tag{7}$$

Equation 7 simply says that the probability of a damage level d_l given a peak ground acceleration of magnitude a is the probability that the structure's capacity A_l is less than a. The probability distribution function of A_l is therefore $dY_{dl}(a)/da$.

Finally, the probability of exceeding the damage level d_l at least once per year is

$$P = \int H_A(a)dY_{d_l}(a) \tag{8}$$

We used Equation 8 to compute the probabilities of two levels of damage, extensive and complete, for the 12 classes of bridges considered in HAZUS (National Institute of Building Sciences, 1997). The corresponding fragility curves and the data for the city of Berkeley were used. The results are presented in Table 1.

Ideally, we would want to compute different probabilities of damage, corresponding to the different deterioration states that the bridge may be in during its life cycle. Unfortunately, with their very limited number of classes, the current classifications cannot capture any difference in damage probability due to the deterioration of structural elements. For example, the class HBR1 of HAZUS is defined as bridges with a span at least 500 ft (major bridges) seismically designed/retrofitted, while HBR6 groups any conventionally designed simply supported bridge less than 500 ft long. The only reference to the deterioration of the facility may be that bridges built before 1960 are considered "high risk," and moved for example from class HBR6 to HBR12.

Table 1
Annual probabilities of extensive and complete damage

Bridge class	*HBR1*	*HBR2*	*HBR3*	*HBR4*	*HBR5*	*HBR6*
D> extensive	0.39%	0.46%	0.45%	0.54%	0.68%	1.00%
D> complete	0.10%	0.14%	0.13%	0.25%	0.24%	0.44%
Bridge class	*HBR7*	*HBR8*	*HBR9*	*HBR10*	*HBR11*	*HBR12*
D> extensive	0.52%	0.60%	0.60%	0.70%	0.86%	1.17%
D> complete	0.15%	0.21%	0.20%	0.35%	0.35%	0.57%

The new classes proposed by Basoz and Kiremidjian (1996) are defined on primary structural attributes, independent of the deterioration state. However, secondary attributes can intervene as "modifiers" and shift the fragility curve. Some of these attributes, namely "year built," "year of reconstruction," and "remaining service life" are undoubtedly related to the deterioration state of the bridge.

5 MR&R DECISION MODEL WITH SEISMIC CONSIDERATIONS

We list below the different assumptions made in formulating the MR&R decision model that accounts for the possible damage caused by earthquake events.

First, we simplify the damage states in which a bridge can be. We only consider the 'destruction' of the facility, and ignore any lower damage states. Destruction signifies a level of damage that requires replacement by a new bridge, with a cost comparable to the initial cost. As we integrate in our model some events with a small probability, it seems logical to consider only the cases where they have a high cost. A more detailed approach would take into account for example the five damage states of HAZUS: none, slight, moderate, extensive, complete. The complete (damage ratio 1.0) and at least part of the extensive (damage ratio 0.7) damage of HAZUS could be considered as our 'destruction' state.

We consider the annual probability of bridge destruction as a result of an earthquake. We implicitly neglect the probability of the bridge being destroyed several times in the same year. For a given bridge, the probability of destruction is well defined and can be calculated using Equation 8. As noted earlier, this probability is independent of the deterioration-state of the bridge, given the limitations of the existing classification. In most of this paper, we will assume a constant probability. As shown by Table 1, a reasonable order of magnitude is one percent probability of destruction per year. This estimation is probably on the lower side for Berkeley, as ground shaking is not the only earthquake hazard.

The other assumptions in the model are concerned with the costs of bridge destruction. There are two general categories of costs associated with bridge destruction. First, there are fixed costs, which are the costs to the users. These include possible loss of life and injuries when a bridge collapses during an earthquake. Moreover, high user delays can be expected at least in the first few days after destruction, before effective measures are implemented to manage traffic. Of course, the magnitude of these costs depends on the availability of alternate routes in the network. Such network considerations are not within the scope of this research. However, the expected cost is independent of the variables in our model. We therefore assume these costs to be the same whenever a bridge is destroyed.

The second category of costs consists of those incurred by the agency. The cost of reconstructing the bridge is fixed: we will assume that it is equal to the replacement cost. However, the economic impact of an earthquake is actually variable. It depends on the condition state in which the bridge was just before its destruction. Clearly, the loss is greater if the bridge was in a new condition than if it had to be replaced the following year anyway.

Our decision model is inspired by the formulation in PONTIS. We formulate a similar linear program and solve for a steady-state optimal policy. However, instead of using the individual bridge components as independent networks, we treat an entire bridge as a single element. This formulation simplifies the problem, as it removes the need to consider the deterioration of the different parts of the facility. If each component had to be represented separately, the problem would become more complex, as we would have to split the user costs after an earthquake among the different components, and thus the networks could not be considered independent.

Another major difference with the PONTIS formulation is that we solve for the optimal policy at the facility level, rather than at the network level. While the problem is formally the same, the interpretation of the decision variable, w_{ri}, changes. At the network level, w_{ri} was the proportion of a bridge component that was in state i and to which action r was applied. The number of facilities was assumed large enough so that the law of large numbers held and the proportions coincided with the probabilities.

At the facility level, w_{ri} is the probability that the bridge is in state i and receives action r. Therefore, if the recommended policy includes several possible actions for the same state, the agency should ensure that the proportion of actions taken over time corresponds to the steady-state optimal probability.

Let us finally explain the meaning of the budget constraint. We will assume that there is a limit to the average expenditure per year for a bridge, over a long period. This is the exact analog of having a network-wide budget constraint in PONTIS. More precisely, we will consider the constraint to apply only to the years when the bridge is not destroyed. In case of an earthquake, the agency has access to emergency funds, and it is therefore logical to assume that the budget constraint does not apply.

We represent condition by discrete states, ranging from 1 (best) to 4 (worst), in addition to a fifth state that is introduced to represent destruction. With the assumptions listed above, and in the case where there is a budget constraint and the probability of destruction is constant, the MR&R decision-making model that accounts for earthquake events is the linear program given below:

$$\min \sum_r \sum_i w_{ri}(c_{ri} + u_{ri})$$

$$\textit{subject to} \quad \begin{aligned} & w_{ri} \geq 0, \quad \forall r, \forall i; \quad \sum_a \sum_i w_{ai} = 1 \\ & \sum_r \sum_i w_{ri} P_{rij} = \sum_r w_{rj} \quad \forall j \\ & \frac{1}{1-P} \sum_r \sum_{i \leq 4} w_{ri} c_{ri} < B_{\max} \end{aligned} \tag{9}$$

where

w_{ri} are the decision variables, the probabilities that the bridge is in state i and receives action r
c_{ri} are the agency costs associated with state i and action r
u_{ri} are the user costs associated with state i and action r
P_{rij} are the transition probabilities from state i to state j after one year if action r is taken
P is the annual probability of destruction
$B_{\max}$ is the maximum average expenditure per year

The index of summation in the last constraint ($i \leq 4$) indicates that the budget constraint applies only to the cases when the bridge is in one of the four normal condition states.

6 EXAMPLES

The purpose of the examples is to evaluate the impact of the seismic considerations on the policies and costs of managing a hypothetical bridge. We solved the linear program in Equation 9, by using Microsoft Excel. Four different cases were studied, as described below.

6.1 Data

The transition probabilities for the different MR&R activities are shown in Table 2. In this table, the rows correspond to the bridge condition states before the MR&R activity is applied, whereas the columns refer to the condition states

Table 2
Transition probabilities

Do nothing: r = 1				
	1	*2*	*3*	*4*
1	0.7	0.3		
2		0.9	0.1	
3			0.5	0.5
4				1
Reconstruction: r = 3				
	1	*2*	*3*	*4*
1	1	0	0	0
2	1	0	0	0
3	1	0	0	0
4	1	0	0	0
Maintenance: r = 2				
	1	*2*	*3*	*4*
1	0.8	0.2		
2		0.95	0.05	
3			0.7	0.3
4				1

Table 3
Agency and user costs (in millions of dollars)

Agency	*r = 1*	*r = 2*	*r = 3*
1	0	5	150
2	0	5	150
3	0	5	150
4	0	5	150
5	150	150	150
Total	*r = 1*	*r = 2*	*r = 3*
1	0	5	200
2	5	10	200
3	15	20	200
4	30	35	200
5	400	400	400
Users	*r = 1*	*r = 2*	*r = 3*
1	0	0	50
2	5	5	50
3	15	15	50
4	30	30	50
5	250	250	250

in the year following the application of the activity. Three actions (do nothing, maintenance, and reconstruction) and four condition states are considered. The do-nothing probabilities are inspired by real data for bridge decks given in Guignier and Madanat (1999). Each year, the state may stay the same or decrease by one unit. Maintenance reduces the probability of transition to the lower state. Reconstruction creates a new bridge in state 1.

The matrices in Table 2 include the transition probabilities for bridge deterioration and repair without taking into account earthquake occurrence. To incorporate earthquake occurrence, a fifth state corresponding to destruction is defined. The transition probability from each state to state 5 is the annual probability of destruction (1%). The other transition probabilities are proportionally reduced. If the bridge is destroyed, the only possible action is reconstruction.

The costs corresponding to the states and actions are presented in the Table 3, decomposed into agency and user costs, and expressed in millions of dollars. These costs are hypothetical. What is important is that the ratios of their magnitudes are reasonable. In Table 3, the rows correspond to the bridge condition states.

For the agency, do-nothing has zero cost, while maintenance is very cheap ($5 million), compared to reconstruction ($150 million). For the users, the costs depend on the state of the facility (from $0 in state 1 to $30 million in state 4). If the bridge is rebuilt, traffic has to be detoured, which translates into high user costs ($50 million). If the bridge is destroyed during an earthquake (state 5), a very high cost ($250 million) represents loss of life, injuries and the high delays imposed on users due to the unexpected closure of the facility. Note that the magnitude of the user cost in case of destruction will not influence the optimal policy, as long as the probability of destruction is constant. This is because the user costs in state 5 are independent of the action taken.

6.2 Case #1

We first compare a scenario without earthquake occurrence to a scenario with a 1% probability of destruction. There is no budget constraint. A direct consequence is that the optimal policy is deterministic. A deterministic policy is one in which there is only one optimal action for each condition state of the bridge.

By inspecting Table 4, we can see that the possible occurrence of an earthquake has a significant impact on the probabilistic distribution of the bridge condition states. For example, the bridge will be in state 1 for 20.6% of the time instead of 17.9%. On the other hand, there is no influence on the optimal policy. In both cases, the optimal policy consists of maintenance for states 1 and 2, do-nothing for state 3, and reconstruction for state 4. Of course, the total cost per year is higher in the earthquake case.

Table 4
Results of case #1

0%			*Budget = $9.8 m.*
No Budget			*Total = $16.2 m.*
W_{ri}	*r = 1*	*r = 2*	*r = 3*
1	0.0%	17.9%	0.0%
2	0.0%	71.4%	0.0%
3	7.1%	0.0%	0.0%
4	0.0%	0.0%	3.6%
5	0.0%	0.0%	0.0%
1%			*Budget = $9.5 m.*
No Budget			*Total = $19.5 m.*
W_{ri}	*r = 1*	*r = 2*	*r = 3*
1	0.0%	20.6%	0.0%
2	0.0%	68.4%	0.0%
3	6.7%	0.0%	0.0%
4	0.0%	0.0%	3.3%
5	0.0%	0.0%	1.0%

6.3 Case #2

We now consider the same scenarios, but with a budget constraint: the average expenditure for the years without destruction is limited to $9 million (see Table 5). The effect is that the optimal reconstruction policy is randomized, because the agency does not have sufficient funds to systematically rebuild the bridge when it is in state 4. Note also that the optimal action in state 1 is to do nothing instead of maintenance.

With a budget constraint, the policies are quite different among the two scenarios. For the scenario without earthquakes, the optimal policy is to rebuild the bridge roughly 40% of the time when it is found in state 4, versus 75% of the time when there is a 1% probability of destruction.

6.4 Case #3

In the preceding case, we solved for the optimal policies assuming 0% and 1% chance of destruction per year. In the present case, we assume a 1% probability of destruction and we compare the optimal policy with the policy that assumes a 0% probability of destruction. In other words, we will solve the problem with the constraint that reconstruction is chosen 40% of the time, which is optimal for a 0% probability of destruction, and we compare the solution to the optimal solution for a 1% probability.

This comparison allows us to evaluate the benefits of accounting the possibility of earthquake while the MR&R are optimized. As can be seen in Table 6, accounting for seismic effects leads to a lower cost relative to the policy that ignores the possibility of earthquakes, by roughly 2.5%. Moreover, applying the suboptimal policy leads to error in budgeting, as the average expenditure during the years without destruction will be 4.5% lower than it should be.

6.5 Case #4

Finally we relax the assumption that the probability of destruction is independent of condition state. With a budget

Table 5
Results of case #2

0%			*Budget = $9 m.*
Budget < 9			*Total = $17.0 m.*
W_{ri}	*r = 1*	*r = 2*	*r = 3*
1	12.0%	0.0%	0.0%
2	0.0%	72.0%	0.0%
3	7.2%	0.0%	0.0%
4	5.2%	0.0%	3.6%
5	0.0%	0.0%	0.0%
1%			*Budget = $9 m.*
Budget < 9			*Total = $19.7 m.*
W_{ri}	*r = 1*	*r = 2*	*r = 3*
1	14.6%	0.0%	0.0%
2	0.0%	72.7%	0.0%
3	7.1%	0.0%	0.0%
4	1.1%	0.0%	3.5%
5	0.0%	0.0%	1.0%

Table 6
Results for case #3

1%			*Budget = $9 m.*
Budget < 9			*Total = $19.7 m.*
W_{ri}	*r = 1*	*r = 2*	*r = 3*
1	14.6%	0.0%	0.0%
2	0.0%	72.7%	0.0%
3	7.1%	0.0%	0.0%
4	1.1%	0.0%	3.5%
5	0.0%	0.0%	1.0%
1%			*Budget = $8.6 m.*
Forced			*Total = $20.2 m.*
W_{ri}	*r = 1*	*r = 2*	*r = 3*
1	14.0%	0.0%	0.0%
2	0.0%	70.0%	0.0%
3	6.9%	0.0%	0.0%
4	4.8%	0.0%	3.3%
5	0.0%	0.0%	1.0%

Table 7
Results of case #4

1% *Budget < 9*			*Budget = $9 m.* *Total = $19.7 m.*
W_{ri}	$r = 1$	$r = 2$	$r = 3$
1	14.6%	0.0%	0.0%
2	0.0%	72.7%	0.0%
3	7.1%	0.0%	0.0%
4	1.1%	0.0%	3.5%
5	0.0%	0.0%	1.0%
Variable % *Budget < 9*			*Budget = $9 m.* *Total = $19.6 m.*
W_{ri}	$r = 1$	$r = 2$	$r = 3$
1	14.6%	0.0%	0.0%
2	0.0%	73.5%	0.0%
3	7.1%	0.0%	0.0%
4	0.2%	0.0%	3.5%
5	0.0%	0.0%	1.0%

constraint, we compare our base scenario with a situation where P varies as follows:

State	1	2	3	4	5
P	0.5%	1%	2%	2%	2%

The mean probability of destruction remains approximately 1%. But the impact on the optimal policy is quite significant; the proportion of times that the agency should rebuild the bridge in state 4 increases from 75% to 95%. We can qualitatively explain this change: the higher probability of destruction in state 4 provides an incentive to decrease the proportion of time that the bridge is in this state, and this is achieved by rebuilding it earlier (see Table 7).

7 CONCLUSIONS

In this paper, we have demonstrated that accounting for the probability of earthquake occurrence in a bridge MR&R decision-making model had a significant impact. Accounting for seismic considerations led to the following changes:

- The probability distribution of the bridge condition-state was affected.
- When there is a budget constraint, the optimal policy was different.
- The difference in cost between the two policies was found not to be insignificant, and ignoring the probability of destruction due to earthquakes led to errors in budgeting.

In order to ensure the generality of these conclusions, this model should be implemented in different realistic situations, with real data for the probability of destruction, the transition probabilities, and the costs. A more refined model, for example, with more possible actions, could lead to more detailed conclusions. We would expect the maintenance policy to move toward less major rehabilitation and more regular maintenance.

An important point seems to be the variability of the probability of destruction with bridge condition state. We found that the optimal policy may be sensitive to these differences. Unfortunately, the current classifications do not capture the effect of condition state on the probability of destruction. There is a need for fragility curves developed for detailed bridge classes, such as those proposed by Basoz and Kiremidjian (1996). Moreover, the modifiers of the fragility curves should include explicitly the level of deterioration of the bridge, so that the different probabilities of destruction are directly available.

Finally, the most useful extension of this work would be to consider a whole network of bridges. This seems to be nontrivial. While the probability of destruction of a single facility is well defined, at the network level the damages of different bridges are strongly correlated. An earthquake event will lead to a deviation from the steady-state optimal policy, which is not easily handled. However, this problem should be explored in order to include seismic considerations in network-level bridge management systems.

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