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Engineering Structures 25 (2003) 903–912

ENGINEERING STRUCTURES

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Risk-based approach to the determination of optimal interventions for bridges affected by multiple hazards

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Received 8 August 2002; received in revised form 20 January 2003; accepted 21 January 2003

Abstract

Decision makers use bridge management systems to determine the optimal allocation of available resources. These systems are currently focused on the structural condition of deteriorating bridges with respect to traffic loads. Bridges, however, are affected by multiple hazards, such as flooding and earthquakes, and not only traffic loading. These multiple hazards should be considered in these management systems when determining the optimal intervention.

A risk-based approach can be used to determine the optimal intervention for a bridge subjected to multiple hazards. It requires the determination of the likely ‘levels of service’ to be provided by the bridge, (e.g. both lanes of traffic open, only one lane of traffic open or both lanes closed), the evaluation of the probability of having these levels of service due to the multiple hazards as well as the consequences of each of these levels of service, and selecting the interventions to minimise the risk of inadequate service.

This article gives the methodology to be used when determining the optimal intervention for a bridge affected by multiple hazards. The risk-based approach is illustrated using a simple example in which the optimal intervention of two interventions is found.

Keywords: Bridge management strategies; Multiple hazards; Optimal resource allocation; Risk-based approach

1. Introduction

Bridges are built to serve road users. The ability of bridges to provide an adequate level of service to the users may be compromised due to multiple hazards, such as traffic loading, flooding and earthquakes. Optimal bridge management strategies must be determined considering all of the hazards that may affect this level of service. By focusing on minimising the risk of having inadequate service, management strategies for bridges affected by multiple hazards, can be determined. This article gives the methodology to be followed for determining the optimal intervention for a bridge affected by multiple hazards.

2. Methodology

The risk of having inadequate service requires the estimation of the likelihood of inadequate levels of service as well as the consequences of having these inadequate levels of service. For example, on a two-lane bridge the risk of having inadequate service will require estimating the probability and consequences of closing one lane of traffic as well as the probability and consequences of closing both lanes of traffic.

The general methodology to determine the risk of having inadequate service is:

- *Identify hazards* that may result in inadequate service, such as traffic loading, flooding and earthquakes, by visual inspection and engineering judgement.
- *Identify failure modes* for each hazard that will result in specified levels of inadequate service, such as full or partial bridge closure, by visual inspection and engineering judgement. (A failure mode is defined as

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0141-0296/03/$ - see front matter © 2003 Elsevier Science Ltd. All rights reserved.
doi:10.1016/S0141-0296(03)00024-5

Nomenclature

A_{rebar}	area of tensile reinforcement
b	reinforcement bar number
B	total number of reinforcement bars
corr	rate of corrosion of the diameter of the steel reinforcement bar
d_{int}	initial diameter of reinforcement
$f'_R(r)$	prior resistance distribution
$f''_R(r)$	posterior resistance distribution
$F^t_S(r)$	distribution function of the maximum action effect experienced up until time t
FM	failure mode
G	difference between the structural resistance and the action effects
$g_R(t)$	change in structural resistance with respect to time
$g_S(t)$	change in the action effect with respect to time
$g_{\text{SDL}}(t)$	change in the action effect created by the dead load with respect to time
$g_{\text{SLL}}(t)$	change in the action effect created by the live load with respect to time
i	interval of time
I	total number of time intervals in investigated time period
k	levels of service
K	total number of levels of service
M_R	moment capacity
M_{SLL}	moment created due to traffic loading
M_{SLD}	moment calculated due to dead load
m_1	intervention 1
n_{FM}	number of relevant failure modes in hazard
$P(A)$	probability of having a specified limit state during the investigated time period
$P(A_i \mid B_{i-t})$	probability of having a specified limit state within each time interval given that the limit state has not occurred before this interval
$P(B_{i-1})$	probability of not having the specified limit state before time interval i
P_{FH}	probability of having a limit state due to a hazard scenario
$P_{s-\text{FM}}$	probability of not having the specified limit state due to failure mode, FM
R	structural resistance
S	action effects created in the structure
t	time
y_{R}	depth of the abutment foundations
y_{S}	depth of scour

the structural behaviour resulting in the exceedance of a defined limit state.)

- *Determine limit states equations* for each failure mode. The limit states equations take into consideration structural behaviour and the definition of the criteria that will result in specified levels of inadequate service. Resistance models are determined based on how the structure behaves and how this behaviour changes with respect to time. Action effect models are determined based on how the effects are created in the structure by the actions, considering when, where and the magnitude of the actions.
- *Estimate probability of the specified levels of inadequate service*, including determination of the appropriate probabilistic distributions to represent the variables to be considered as random in the limit states equations.
- *Determine consequences of the specified levels of inadequate service*. This requires modelling user behaviour when the bridge does not provide an adequate level of service.
- *Estimate risk of having inadequate service*. The summation of the probability of having specified levels of inadequate service multiplied by consequences of the levels of inadequate service.
- *Determination of the optimal intervention*: the optimal intervention minimises the risk associated with inadequate service for the least resources.

3. Hazards and failure modes

The relevant hazards and failure modes that may result in different levels of inadequate service are identified through visual inspection of the bridge and engineering judgement. There may be multiple failure modes for each hazard. As it is not possible to consider all hazards or failure modes, the ones most likely to occur should be selected. By doing this it is assumed that the risks of inadequate service due to the unconsidered hazards and failure modes are negligible. Analysis excluding these hazards and failure modes will not give an exact probability of a level of inadequate service but does permit an estimation of the risk of inadequate service.

4. Limit states equations

The limit states equations to be considered are those that will result in a level of inadequate service, such as a speed restriction, weight restriction, single lane closure or complete bridge closure. For example, if the depth of a river bed is lowered below the depth of an abutment due to scouring during a flood, the bridge will be closed immediately for safety considerations until a more in-depth analysis, or an intervention, can be performed, resulting in a level of inadequate service. The general form of a limit states equation is given in Eq. (1).

$$G = Rg_R(t) - Sg_s(t) \tag{1}$$

where G is the difference between the initial structural resistance, such as moment capacity, R that deteriorates with respect to time based on the type and speed of deterioration, $g_R(t)$, and the action effects, created in the structure, such as the maximum created moment, S that changes with respect to time, $g_S(t)$. If the structural resistance and action effects do not change with respect to time, i.e. the hazard is time independent, $g_R(t)$ and $g_S(t)$, are equal to 1.

4.1. Resistance

The resistance of a bridge ($Rg_R(t)$ in Eq. (1)) is based on its type of structural system, structural dimensions and material properties, and their rates of change. The changes in structural dimensions or material properties can be incorporated into limit states equations by taking into consideration the physical phenomena at work directly or by using best-fit polynomial functions representing the changes over time [1]. For example, to predict the reduction in moment capacity of a concrete T-beam (Fig. 1), the corrosion of steel reinforcement can be either directly incorporated into the limit states equation (Eq. (2)) or incorporated as a best-fit polynomial representing the deterioration of the initial resistance with respect to time.

$$A_{\mathrm{rebar}} = \sum_{b=1}^{B} (d_{\mathrm{int}}^{i} - \mathrm{corr}^{i} t)^{2} \frac{\pi}{4} \tag{2}$$

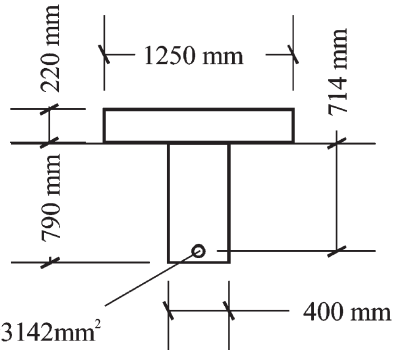

Fig. 1. T-beam.

where A_{rebar} is the area of tensile reinforcement, d_{int} the initial diameter of reinforcement, corr the rate of corrosion of the diameter of the steel reinforcement bar, b the total number of reinforcement bars, and t is time.

A comparison of the best-fit polynomial (Eq. (3)) and Eq. (2), over a 15-year period assuming a rate of corrosion, corr, of 0.05 mm/year, is shown in Fig. 2. In this case, the best-fit polynomial is linear due to the relatively small amount of deterioration that occurs in the selected time frame.

$$g_R(t) = 1 - 0.0048t \tag{3}$$

4.2. Action effects

The severest actions to which structures are subjected are used to determine the maximum action effects in bridges and therefore, the risk of inadequate service. For time independent hazards the severest action within the investigated time period may be used to estimate the probability of having the specified limit state [2]. For example, when investigating the probability of a bridge having a specified scour depth due to flooding in a 15-year period, it may be the largest flood discharge that will occur in this 15-year period is of interest. If the cost of the intervention in different time intervals cannot be

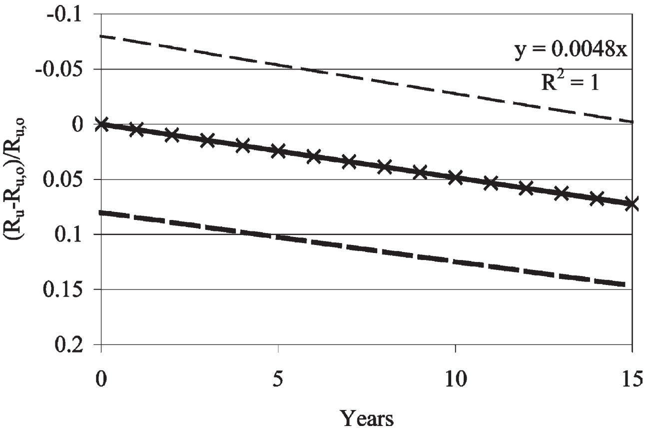

Fig. 2. Normalised loss of resistance with respect to time of a concrete T-beam.

approximated as constant, however, then it will still be necessary to determine the severest actions in smaller intervals of time, e.g. 1-year intervals [3,4]. For time dependent hazards, since the resistance of the bridge changes with respect to time, the severest actions within the investigated time period must be known continuously [5,6]. For example, when investigating the probability that a bridge will have unacceptable flexural cracks due to traffic loading, a load that will not cause the cracks in year 1 of a 15-year period may cause the cracks in year 15 due to deterioration of the structural resistance.

Estimating the severest action, such as a truck load and flood discharge, is not in itself sufficient to evaluate the probability of specified levels of inadequate service. The effects created by the action, such as maximum expected moment in a structural member, must be determined.

5. Probability of specified levels of inadequate service

After the limit states equations are determined, the probability of having the specified levels of inadequate service due to different failure modes can be evaluated. The variables to be considered as random in the limit states equations must be modelled using appropriate probabilistic distributions and parameters, e.g. on the resistance side—the strength of the tensile reinforcement in a concrete beam, or the stone size of riverbed material, on the action effect side—the maximum flow of water in a river during a flood. Non-destructive and destructive tests, as well as documented literature, can be used to help determine the appropriate distributions and parameters. The uncertainty in the models used to predict the structural resistance and action effects should be included in the risk analysis. The probability distributions of interest are often extreme distributions that must be determined from the initial variate. The asymptotic theory of statistical extremes can be used to find these distributions [7].

Once the appropriate probabilistic distributions are determined, the probability of the specified levels of inadequate service can be estimated. Two common methods used when the probability density functions representing the resistance and action effects can be assumed to be constant with respect to time are: (1) numerical integration and (2) the Monte Carlo simulation [8]. The probability of the specified levels of inadequate service due to time independent hazards is estimated using the probability density functions representing the resistance and action effects for the entire investigated time period.

When the overall time period to be investigated must be divided into smaller intervals as is the case for time independent hazards when the cost of intervention cannot be assumed to be constant, the probability of the bridge having the specified limit state during the investigated time period $P(A)$, can be determined using

$$P(A) = \sum_{i=1}^{n} P(A_i|B_{i-1})P(B_{i-1}) \tag{4}$$

where $P(A_i|B_{i-1})$ is the probability of having a specified limit state within each time interval given that the limit state has not occurred before this interval, and $P(B_{i-1})$ is the probability of not having the specified limit state before time interval i.

As the resistance and the action effects change with respect to time the probability of the specified level of inadequate service in each successive time interval changes (Eq. (5)), given that the bridge survives until this interval.

$$P(A_i|B_{i-1}) = P(Rg_R(t_i) < Sg_S(t_i)|Rg_R(t_{i-1}) > Sg_S(t_{i-1})) \tag{5}$$

Care must be taken in estimating the probability density function of the resistance in successive intervals so as not to progressively multiply the uncertainty in successive intervals. As the bridge survives successive intervals, and therefore, an increasing number of action effects, the probabilistic model of resistance must be updated to remove some of the initial uncertainty (Fig. 3) [6]. The mean of the resistance in Fig. 3 is assumed to deteriorate as a deterministic function of the initial resistance. The coefficient of variation of the resistance is assumed to remain constant. The prior service loads act as proof loads, i.e. it is known that the structure at the time of loading had a certain resistance [5,9]. Fig. 4 shows the effect of deterioration on the resistance probability density function in successive years, assuming, wrongly, that the resistance R, is independent in each interval. The updated distribution of structural resistance, $f'_R(r)$, at time t, to be used in the determination of the probability of the specified level of inadequate service [6] is given in Eq. (6).

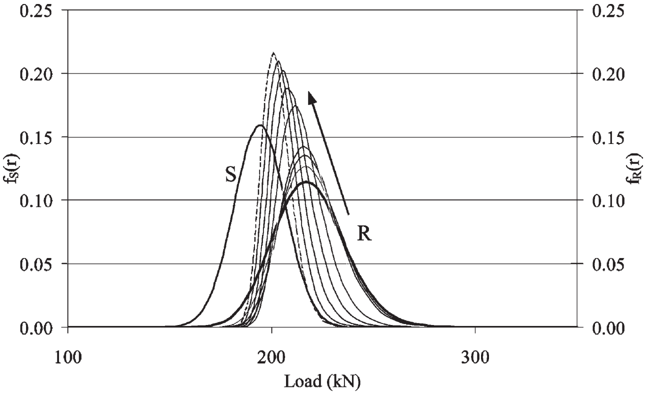

Fig. 3. The effect on $f_R(r)$ of prior service loads.

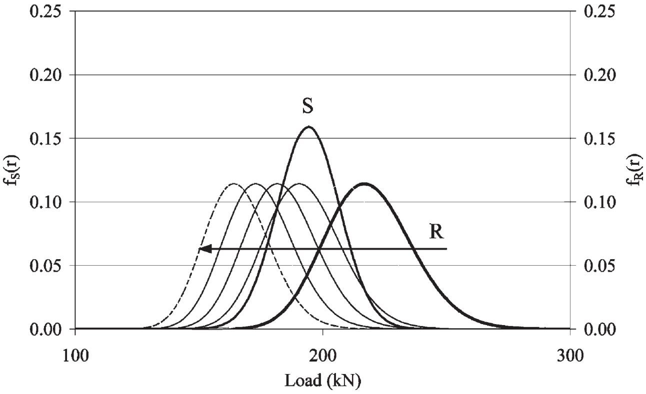

Fig. 4. Effect on $f_R(r)$ with deterioration.

$$f'_R(r) = \frac{F^t_S(r) f'_R(r)}{\int_{-\infty}^{\infty} F^t_S(r) f'_R(r)\,\mathrm{d}r} \tag{6}$$

The probability of surviving until each successive time interval is given in Eq. (7).

$$P(B_{i-1}) = P(Rg_R(t_{i-1}) > Sg_s(t_{i-1}) | Rg_R(t_{i-2}) > Sg_S(t_{i-2})) \tag{7}$$

To determine the probability of a specified level of inadequate service due to a hazard it is necessary to combine the probabilities of having the specified level of inadequate service due to each failure mode within the hazard (Eq. (8)).

$$P_{\mathrm{FH}} = 1 - \prod_{\mathrm{FM}=1}^{n_{\mathrm{FM}}} (P_{S-\mathrm{FM}}) \tag{8}$$

In Eq. (8) it is assumed that all failure modes are statistically independent for one bridge for one hazard. This assumption is not true in reality but is made for simplicity. Multiple failure modes are generally not independent because they tend to be functions of one or more common random variables, e.g. the same truck loads or positions. If there is any correlation between failure modes Eq. (8) will be too high. If they are perfectly correlated Eq. (8) will be equal the largest probability of the specified level of inadequate service due to one failure mode. Although the assumption of independent failure modes may be a significant source of error it is expected to give reasonable approximations for P_{FH} which are consistent with the level of accuracy needed for vulnerability assessment (i.e. an order of magnitude) and therefore the planning of optimal management strategies [10].

6. Consequences of levels of inadequate service

The consequences of inadequate service are user costs. These costs for each expected level of inadequate service must be estimated to evaluate the risk of inadequate service and therefore, to determine the optimal intervention. These costs may be grouped into two categories, the user costs of travelling and the user costs of not travelling.

The user costs of travelling are comprised of vehicle operating costs, travel time costs and accident costs. They can be approximated by simulating the flow of traffic on the transportation network assuming the bridge provides the specified levels of inadequate service and comparing the costs of travel with those incurred on the fully operational network. The magnitude of the user costs is affected by the interrelation between the traffic flow (number of vehicles travelling), the road condition on which the vehicles are travelling and vehicle speed. To estimate the user costs on a network over a period of time, the traffic flow over the network links must be predicted as well as the condition of the roads on which the vehicles travel and the vehicle speeds. The specifics of this interrelation are different for different types of vehicles. The following is an example of the interrelation (illustrated in Fig. 5). (1) Traffic causes the deterioration of road condition (an increase in traffic results in an increase in road deterioration and roughness, at the same vehicle speed). (2) A deterioration in road condition, i.e. increased roughness, causes the desired vehicle speed to drop and therefore, slower vehicles. (3) Slower vehicles can result in increased congestion, which means a reduced link capacity and potentially fewer vehicles on the link. (4) Increased congestion may lead to a further reduction in vehicle speed. (5) Slower vehicle speeds may result in a slower deterioration of the road condition. (6) Road condition affects the drivers' route choice and therefore, the number of vehicles travelling on the road, and so on. A good illustration of this interrelation can be found in Ref. [11].

The user costs of not travelling are the loss of the benefits of travelling minus the savings in travel costs. The maximum yearly monetary benefit from travelling on the transportation network cannot be more than the gross domestic product (GDP), and since not all of the

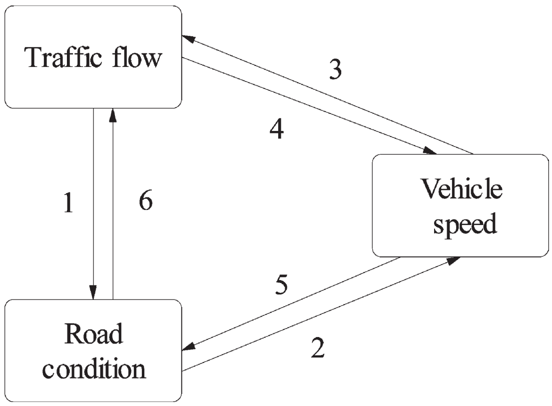

Fig. 5. Interrelation of traffic flow, road condition and vehicle speed.

GDP, however, relies on the use of the transportation network, it is reasonable to assume that the loss of not being able to use the network can be expressed as a percentage of GDP. GDP is a measure of a country's domestic production of goods and services over the course of a year, not directly including unreported activities, such as unpaid housework or unreported activities. An economic analysis is required to determine the percentage loss of GDP due to a level of inadequate service.

The expected user costs during an investigated time period due to inadequate service depend on when the level of inadequate service occurs as well as the duration of the inadequate service. For example, if a vehicle is detoured on a newly paved road the vehicle operating costs will be lower than if it is detoured on a paved road 15 years after it was paved. To consider the change in user costs with respect to road deterioration, the probability and cost of inadequate service for all intervals that may be considered constant throughout the investigated time period, must be determined.

7. Risk of inadequate service

The risk of inadequate service is the summation of the probability of having each specified level of inadequate service multiplied by the consequences of that level of service, in each time interval that may be considered as constant throughout the investigated time period (Eq. (9)).

$$\text{Risk of inadequate service} = \sum_{i=1}^{I}\sum_{k=1}^{K}(P\ (\text{level of service}_k)_i \times \text{Consequences (level of service}_k)_i) \tag{9}$$

8. Optimal intervention

Using a risk-based approach, the optimal bridge intervention is the one that collectively minimizes the risk of inadequate service and allocated resources. To determine the optimal intervention the costs and benefits, reduction of risks, associated with each possible intervention must be evaluated. Four methods that can be used to compare these interventions are: (1) the present worth method, (2) the equivalent uniform cost method, (3) the rate of return method, and (4) the benefit–cost ratio method [12,13]. Each of these methods reduces the costs over an investigated time period to a common base for comparison. Since the costs must be compared over an investigated time period, i.e. the costs in year 15 of an investigated time period must be compared with the costs in year 1, the value of money in each year must be considered. The change in the value of money with time is known as the discount rate.

9. Illustrative example

The example bridge has five simple spans of 12 m in length and traverses a perennial stream Fig. 6.

9.1. Hazards and failure modes

Two hazards are investigated: the traffic hazard (traffic loads may surpass the carrying capacity of the bridge), and the flood hazard (excessive scour during a flood may lead to foundation failure). The failure mode investigated for the traffic hazard is the yielding of tensile reinforcement in a concrete T-beam in one span. The failure mode investigated for the flood hazard is abutment scour at one abutment.

9.2. Limit states equations

The general limit states equation for the concrete T-beam flexural failure mode is

$$G = M_R g_R(t) - M_{\mathrm{SLL}} g_{\mathrm{SLL}}(t) - M_{\mathrm{SDL}} g_{\mathrm{SDL}}(t) \tag{10}$$

where M_R is the moment capacity, M_{SLL} the moment created due to traffic loading, M_{SLD} the moment created due to dead load, $g_R(t)$ the change in structural resistance with respect to time, and $g_{\mathrm{SLL}}(t)$ and $g_{\mathrm{SDL}}(t)$ are the changes in the moment created due to traffic loading and dead load, respectively.

Only the general form of the limit states equation is used in this example. The moment capacity of the beam M_R, over a 15-year period deteriorates as shown in Fig. 2. The maximum moment created in the beam is assumed to be constant, i.e. not time dependent.

The general limit state equation for abutment scour is

$$G = y_{\mathrm{R}} g_R(t) - y_{\mathrm{S}} g_S(t) \tag{11}$$

where y_{R} depth of the abutment foundations and y_{S} is the depth of scour

The bridge resistance to scour is the abutment depth. It is assumed that failure occurs when the scour depth equals the depth of the abutment. The abutment depth and the maximum flood, in this example, do not change with time. Determination of scour depth (action effect) depends on the magnitude of the expected discharge (action), the relationship between flow and river height (the river rating curve), and site characteristics, such as soil type, river direction and river gradient.

9.3. Probabilities of the specified levels of inadequate service

The distributions and parameters (mean, $\bar{x}$, and coefficient of variation, c.o.v.) for the variables in the limit

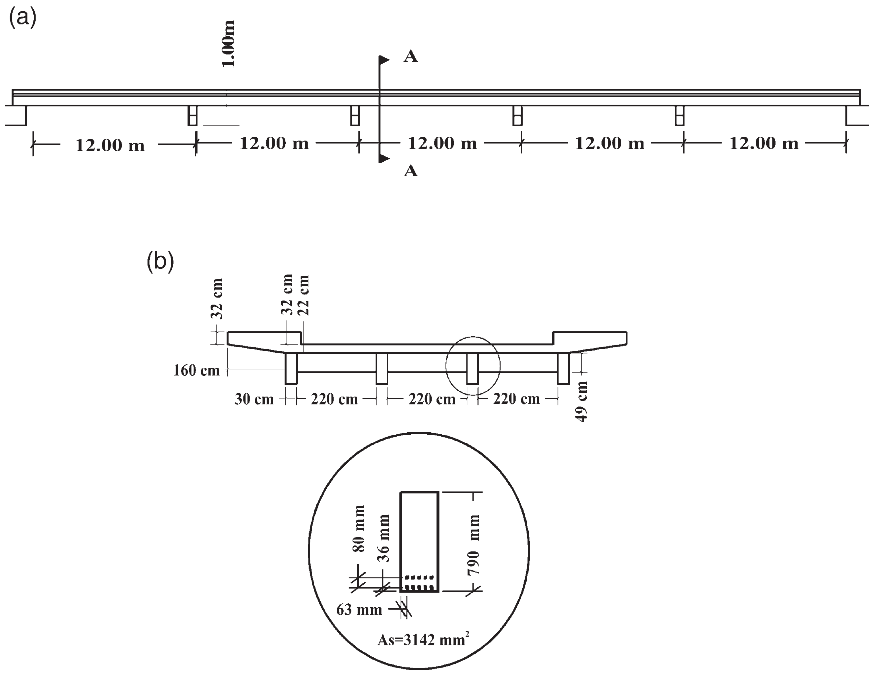

Fig. 6. Concrete T-beam bridge (a) profile, (b) cross section A-A.

states equations are given for the traffic and flood hazards in Tables 1 and 2, respectively. The distributions used represent the maximum expected action effects in a 1-year period. The probabilities of having inadequate service in each of the 15-year period for the example bridge due to the traffic and flood hazards are given in Figs 7 and 8, respectively. Since only one failure mode per hazard is considered, it is not necessary to combine failure modes to determine the probability of inadequate service due to a hazard.

Table 1
Parameter estimates and distributions for the traffic hazard

Variable	Definition	Mean, $\bar{x}$	c.o.v.	Distribution
M_R	Moment resistance (initial)	460 kN	0.08	Log-normal
M_{SDL}	Moment created in beam due to dead load	70 kN	–	Deterministic
M_{SLL}	Moment created in beam due to live load	200 kN	0.1	Normal
$g_R(t)$	Change in moment resistance in beam	$1-0.0048t$	–	–
$g_{\mathrm{SLL}}(t)$	Change in moment created in beam due to live load	1	–	Deterministic
$g_{\mathrm{SLL}}(t)$	Change in moment created in beam due to dead load	1	–	Deterministic

Table 2
Parameter estimates and distributions for the flood hazard

Variable	Definition	Mean, $\bar{x}$	c.o.v.	Distribution
y_{R}	Scour depth	3	0.1	Normal
y_{S}	Abutment depth	4	0.01	Log-normal
$g_{\mathrm{S}}(t)$	Change in scour depth with time	1	–	Deterministic
$g_{\mathrm{R}}(t)$	Change in abutment depth with time	1	–	Deterministic

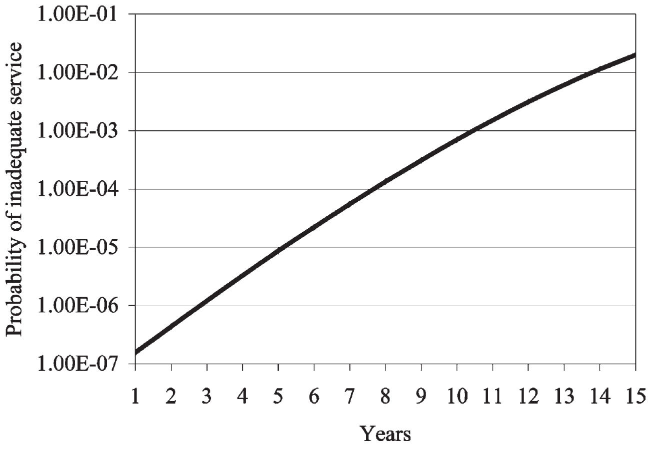

Fig. 7. The probability of inadequate service in each year during the 15-year period due to the traffic hazard.

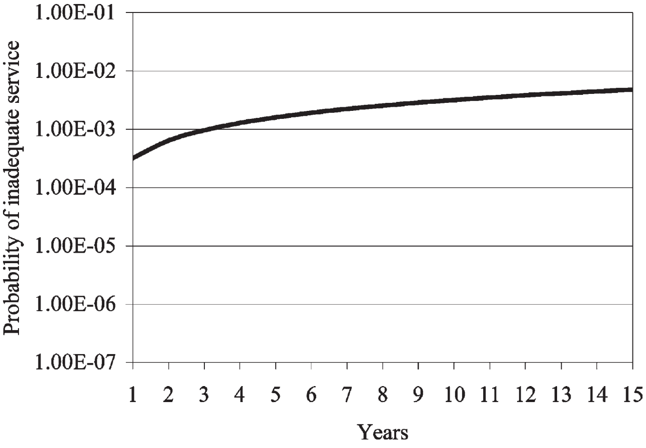

Fig. 8. The probability of inadequate service during the 15-year period due to the flood hazard.

9.4. Consequences of levels of inadequate service

If there is inadequate service due to the traffic hazard so that an intervention must be performed on the bridge, one lane will be closed for 1 month and then the other lane will be closed for 1 month, therefore, for 2 months following exceedance of the service criterion only one lane will be open to traffic. This will result in a restriction to traffic flow. This assumption can be made because interventions to strengthen the load carrying capacity of a bridge can be planned in such a way that complete closure of the bridge is not required. For this illustration it is assumed that closing one lane of traffic for 2 months will cost €2 million in the first year and will increase to €3.4 million as shown in Table 3.

If there is inadequate service due to the flood hazard, the entire bridge will be closed, i.e. both the lanes. Once the scour depth is greater than the abutment depth, the bridge will be closed immediately so further investigation can be done. This will result in forced detours for the users of the bridge. It is assumed that the bridge will be closed for 4 months while a new abutment is put in place. For this illustration it is assumed that the forced detours will cost €5 million in the first year and will increase to €7.8 million in the year 15 as shown in Table 3.

9.5. Risk of inadequate service

The risk of inadequate service is calculated as the probability of each specified level of inadequate service multiplied by the consequences of each specified level of inadequate service in each time interval throughout the investigated time period (Eq. (12))

$$\text{Risk of inadequate service} = \sum_{i=1}^{I} (\text{probability}_{m1} \times \text{consequences}_{m1} + \text{probability}_{m2} \times \text{consequences}_{m2}) \tag{12}$$

where the subscript 1 denotes having only one lane closed and subscript 2 denotes having both lanes closed. It is assumed that the bridge can only fail once in the investigated time period. This is a reasonable assumption because once closed for a major intervention, the bridge would be fixed with regards to all hazards. The risk due to the traffic and flood hazards are 142×10^3 and 262×10^3 €, respectively (Table 3).

Table 3
Probability of inadequate service in each year during 15-year period due to the traffic and flood hazards

Year	Traffic hazard			Flood hazard		
	Probability	Consequences (million €)	Risk probability × consequences (million €)	Probability	Consequences (million €)	Risk probability × consequences (million €)
1	156×10^{-9}	2	312×10^{-9}	320×10^{-6}	5	1.6×10^{-3}
2	440×10^{-9}	2.1	924×10^{-9}	640×10^{-6}	5.2	3.33×10^{-3}
3	1.21×10^{-6}	2.2	2.66×10^{-6}	959×10^{-6}	5.4	5.18×10^{-3}
4	3.28×10^{-6}	2.3	7.54×10^{-6}	1.28×10^{-3}	5.6	7.17×10^{-3}
5	8.63×10^{-6}	2.4	20.7×10^{-6}	1.60×10^{-3}	5.8	9.28×10^{-3}
6	22.1×10^{-6}	2.5	55.3×10^{-6}	1.92×10^{-3}	6	11.5×10^{-3}
7	55.2×10^{-6}	2.6	144×10^{-6}	2.23×10^{-3}	6.2	13.8×10^{-3}
8	133×10^{-6}	2.7	359×10^{-6}	2.55×10^{-3}	6.4	16.3×10^{-3}
9	311×10^{-6}	2.8	871×10^{-6}	2.87×10^{-3}	6.6	18.9×10^{-3}
10	698×10^{-6}	2.9	2.02×10^{-3}	3.19×10^{-3}	6.8	21.7×10^{-3}
11	1.51×10^{-3}	3	4.53×10^{-3}	3.50×10^{-3}	7	24.5×10^{-3}
12	3.11×10^{-3}	3.1	9.64×10^{-3}	3.82×10^{-3}	7.2	27.5×10^{-3}
13	6.11×10^{-3}	3.2	19.6×10^{-3}	4.13×10^{-3}	7.4	30.6×10^{-3}
14	11.4×10^{-3}	3.3	37.6×10^{-3}	4.45×10^{-3}	7.6	33.8×10^{-3}
15	19.9×10^{-3}	3.4	67.7×10^{-3}	4.77×10^{-3}	7.8	37.2×10^{-3}
Total risk			142×10^{-3}			262×10^{-3}

Table 4
The effect of intervention 1

Year	Traffic			Flood		
	Probability	Consequences (million €)	Risk probability × consequences (million €)	Probability	Consequences (million €)	Risk probability × consequences (million €)
1	100×10^{-9}	2	200×10^{-9}	320×10^{-6}	5	1.60×10^{-3}
2	100×10^{-9}	2.1	210×10^{-9}	640×10^{-6}	5.2	3.33×10^{-3}
3	100×10^{-9}	2.2	220×10^{-9}	959×10^{-6}	5.4	5.18×10^{-3}
4	100×10^{-9}	2.3	230×10^{-9}	1.28×10^{-3}	5.6	7.17×10^{-3}
5	100×10^{-9}	2.4	240×10^{-9}	1.60×10^{-3}	5.8	9.28×10^{-3}
6	100×10^{-9}	2.5	250×10^{-9}	1.92×10^{-3}	6	11.5×10^{-3}
7	100×10^{-9}	2.6	260×10^{-9}	2.23×10^{-3}	6.2	13.8×10^{-3}
8	100×10^{-9}	2.7	270×10^{-9}	2.55×10^{-3}	6.4	16.3×10^{-3}
9	100×10^{-9}	2.8	280×10^{-9}	2.87×10^{-3}	6.6	18.9×10^{-3}
10	100×10^{-9}	2.9	290×10^{-9}	3.19×10^{-3}	6.8	21.7×10^{-3}
11	100×10^{-9}	3	300×10^{-9}	3.50×10^{-3}	7	24.5×10^{-3}
12	100×10^{-9}	3.1	310×10^{-9}	3.82×10^{-3}	7.2	27.5×10^{-3}
13	100×10^{-9}	3.2	320×10^{-9}	4.13×10^{-3}	7.4	30.6×10^{-3}
14	100×10^{-9}	3.3	330×10^{-9}	4.45×10^{-3}	7.6	33.8×10^{-3}
15	100×10^{-9}	3.4	340×10^{-9}	4.77×10^{-3}	7.8	37.2×10^{-3}
Total risk			4.05×10^{-6}			262×10^{-3}

9.6. *Optimal intervention*

The two interventions for the example bridge are: (1) a strengthening of the concrete beam in flexure and (2) the replacement of the existing abutment with a new deeper abutment. Each of the interventions is expected to reduce the probability of the respective level of inadequate service to 1×10^{-7} in each of the years in the investigated time period. This reduces the risk of inadequate service to the traffic hazard from 142×10^3 to 4.05 € (Table 4), and the risk of inadequate service to the flood hazard from 262×10^3 to 9.6 € (Table 5).

The risk of inadequate service after intervention 1 would then be 262×10^3 €. The risk of inadequate service after intervention 2 would be 142×10^3 €. If it is assumed that the interventions require the same resources, the optimal intervention with a reduction of risk of 262×10^3 €, is intervention 2 (Table 6).

10. Conclusions

A risk-based approach can be used to determine the optimal intervention for a bridge subjected to multiple

Table 5
The effect of intervention 2

Year	Traffic			Flood		
	Probability	Consequences (million €)	Risk probability × Consequences (million €)	Probability	Consequences (million €)	Risk probability × Consequences (million €)
1	156×10^{-9}	2	312×10^{-9}	100×10^{-9}	5	500×10^{-9}
2	440×10^{-9}	2.1	924×10^{-9}	100×10^{-9}	5.2	520×10^{-9}
3	1.21×10^{-6}	2.2	2.66×10^{-6}	100×10^{-9}	5.4	540×10^{-9}
4	3.28×10^{-6}	2.3	7.54×10^{-6}	100×10^{-9}	5.6	560×10^{-9}
5	8.63×10^{-6}	2.4	20.7×10^{-6}	100×10^{-9}	5.8	580×10^{-9}
6	22.1×10^{-6}	2.5	55.3×10^{-6}	100×10^{-9}	6	600×10^{-9}
7	55.2×10^{-6}	2.6	144×10^{-6}	100×10^{-9}	6.2	620×10^{-9}
8	133×10^{-6}	2.7	359×10^{-6}	100×10^{-9}	6.4	640×10^{-9}
9	311×10^{-6}	2.8	871×10^{-6}	100×10^{-9}	6.6	660×10^{-9}
10	698×10^{-6}	2.9	2.02×10^{-3}	100×10^{-9}	6.8	680×10^{-9}
11	1.51×10^{-3}	3	4.53×10^{-3}	100×10^{-9}	7	700×10^{-9}
12	3.11×10^{-3}	3.1	9.64×10^{-3}	100×10^{-9}	7.2	720×10^{-9}
13	6.11×10^{-3}	3.2	19.6×10^{-3}	100×10^{-9}	7.4	740×10^{-9}
14	11.4×10^{-3}	3.3	37.6×10^{-3}	100×10^{-9}	7.6	760×10^{-9}
15	19.9×10^{-3}	3.4	67.7×10^{-3}	100×10^{-9}	7.8	780×10^{-9}
Total risk			142×10^{-3}			9.60×10^{-6}

Table 6
Savings for each intervention

	Risk (million €)	Savings (million €)
Do nothing	405×10^{-3}	0
Intervention 1	262×10^{-3}	142×10^{-3}
Intervention 2	142×10^{-3}	262×10^{-3}

hazards. A risk-based approach requires the determination of the likely ‘levels of service’ to be provided by the bridge (e.g. both lanes of traffic open, only one lane of traffic open or both lanes closed), the evaluation of the probability of having these levels of service due to the multiple hazards as well as the consequences of each of these levels of service, and selecting the interventions to minimise risk.

An incorporation of a risk-based approach into bridge management systems will provide decision makers with a more complete tool to help them development optimal management strategies for their bridges that are subject to multiple hazards.

Acknowledgements

The authors would like to acknowledge the financial contribution of the Alliance for Global Sustainability (AGS) a university partnership involving the Swiss Federal Institutes of Technology (ETH), the Massachusetts Institute of Technology (MIT), the University of Tokyo (UT) and the Chalmers University.

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