ECONOMIC CONSIDERATIONS IN DESIGNING BRIDGE SCOUR COUNTERMEASURES

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ABSTRACT

The authors originally developed a model, HYRISK, to prioritize efforts on scour evaluations for bridges with unknown foundations. The model is based on data stored in the National Bridge inventory and accounts for ADT, detour lengths, value of lost time, bridge condition, bridge geometry, bridge age, and many other factors. An update to the model is presented which uses the HYRISK determined scour failure probability (or user defined failure probability) to evaluate the economic benefits of various countermeasure options. The model will provide information on the expected life of the bridge and costs and benefits of various levels of protection. The model determines the optimum level of protection for the bridge and the maximum expenditure that should be accepted to increase the level of protection. A computer tool has been developed which implements the methodology.

INTRODUCTION

A need exists for a systematic, risk-based method to determine the level of resources appropriate for protection of a bridge that is scour critical but has a limited life before scheduled replacement (NTSB, 1988; Thompson, 1989; Richardson, 1991; MD State Highway Administration, 1990; NC Department of Transportation, 1990). The purpose of this paper is to posit one method by which bridge owners may make these determinations.

In October, 1998, a U.S. panel sponsored by and comprising personnel from the Transportation Research Board (TRB), American Association of State Highway and Transportation Officials (AASHTO) and the Federal Highway Administration (FHWA) visited several European countries in the interest of information exchange on bridge scour countermeasures (Bryson, 2000). The panel discovered that at least some form of risk analysis was used for countermeasure design in the countries visited.

The keen interest in this topic by several members of the U.S. panel prompted the authors of this paper to look at the potential for developing a new application for the FHWA's HYRISK Software (Elias, 1994), an existing program for prioritizing bridges based on presumed risks, and using the same basic logic to evaluate the risks associated with a specific bridge to determine resource levels appropriate to reduce those risks.

EXISTING HYRISK METHODOLOGY

A primary objective of the effort which led to HYRISK was to provide a method for assessing the risk of scour failure at bridge installations over water without the need for extensive and expensive field work to gather data. The method developed uses data from the National Bridge Inventory (NBI) (FHWA, 1988) as augmented by cost-related factors provided by the user. Table 1 lists the NBI items used by the HYRISK method. Much of the NBI data are subjective, but are provided by state agencies in compliance with a standardized data coding method to provide as much uniformity in data collection as practicable.

Table 1. NBI items used in HYRISK calculations.

NBI Item	*Description*
19	Bypass, Detour Length
26	Functional Classification of Inventory Route
27	Year Built
29	Average Daily Traffic
42	Type of Service
43	Structure Type, Main
49	Structure Length
52	Deck Width, Out-to-Out
60	Substructure Condition
61	Channel and Channel Protection
71	Waterway Adequacy
109	Average Daily Truck Traffic
113	Scour Critical Bridges

The risk (expected loss) calculated by the existing HYRISK method is the product of the probability of scour failure (or heavy damage) and the economic losses associated with such an event. It determines the year-to-year risk (expected loss) of scour failure associated with a bridge installation over water. Codified, the equation is

$$\text{Risk} = KP([\text{Rebuild Cost}] + [\text{Running Cost}] + [\text{Time Cost}]) \quad \textbf{(1)}$$

where

Risk = risk of scour failure, \$ (for one year given current physical condition),
K = risk adjustment factor based on foundation type and type of span (NBI 43), and
P = probability of failure each year (NBI Items 26, 60, 61, 71).

Probability of Failure

Probability of scour failure is estimated based on NBI recorded values for waterway adequacy, functional classification of inventory route, substructure condition, and channel protection. The procedure for deriving the probability is straightforward and can be found in (Elias, 1994).

Costs

The cost used in the model is the sum of the cost of replacing the bridge (rebuild cost), the cost of maintaining traffic flow without the bridge (running cost), and the value of time lost utilizing alternate routes (additional time cost). Each of these are calculated using equations 2, 3 and 4, respectively.

$$\text{Rebuilding Cost} = C_1WL \quad \textbf{(2)}$$

where

C_1 = rebuilding cost, (\$646/m^2 by default or user-supplied value),
W = bridge width, m. (from NBI Item 52), and
L = bridge length, m. (from NBI Item 49).

$$\text{Running Cost} = C_2 DAd \tag{3}$$

where

C_2 = cost of running vehicle, (\$0.16/km by default or other user-supplied value),
D = detour length, km. (from NBI Item 19),
A = ADT (from NBI Item 29), and
d = duration of detour, days (estimated from NBI Item 29).

$$\text{Time Loss} = \left[C_3 O \left(1 - \frac{T}{100} \right) + C_4 \frac{T}{100} \right] \frac{DAd}{S} \tag{4}$$

where

C_3 = value of time per adult, \$7.05/h (by default or user-supplied value),
O = occupancy rate, 1.56 adults (by default or user-supplied value),
T = average daily truck traffic, percent (from NBI Item 109),
C_4 = value of time for truck, \$20.56/h (by default or user-supplied value), and
D = detour length, km. (from NBI Item 19),
A = ADT (from NBI Item 29), and
d = duration of detour, days (estimated from NBI Item 29).
S = average detour speed, 64/km/h (by default or user-supplied value).

EXTENDING THE HYRISK MODEL

The HYRISK model proves useful in answering the question it was originally conceived to contend with: Without extensive additional and bridge-specific data gathering, which bridges represent the greatest annual expected loss due to failure or heavy damage due to scour? Risk rankings produced by the model, however, are not intended to be used to place hard actual monetary values on losses nor were they intended to be used as direct guidance to bridge owners to answer the current question: How much is reasonable to spend on scour countermeasures to protect a bridge with a known, finite life before scheduled replacement?

Probability of Failure and Expected Bridge Life

To begin answering this question, the probability of failure during the life expectancy of the bridge must be calculable. This can be done using

$$P_L = 1 - (1 - P_A)^L \tag{5}$$

or

$$L = \frac{\log(1-P_L)}{\log(1-P_A)} \tag{6}$$

where

P_L = probability of failure over the expected life of the bridge,
P_A = annual probability of failure calculated by HYRISK or supplied by the modeler, and
L = the expected life of the bridge in years.

depending on whether the modeler wishes to determine the probability failure at a specific point in time (such as with a scheduled bridge replacement) or wishes to determine a bridge's expected life given an acceptable probability of failure while the bridge remains in service. Modelers are encouraged to adjust P_A based on what may be known about the specific bridge being investigated.

As an example, if scour analysis indicates that a bridge will fail given the 20-year return period flood, P_A should be set to 0.05. For such a bridge, the graph shown in Figure 1 gives the probability of failure in any year between the present and 100 years hence.

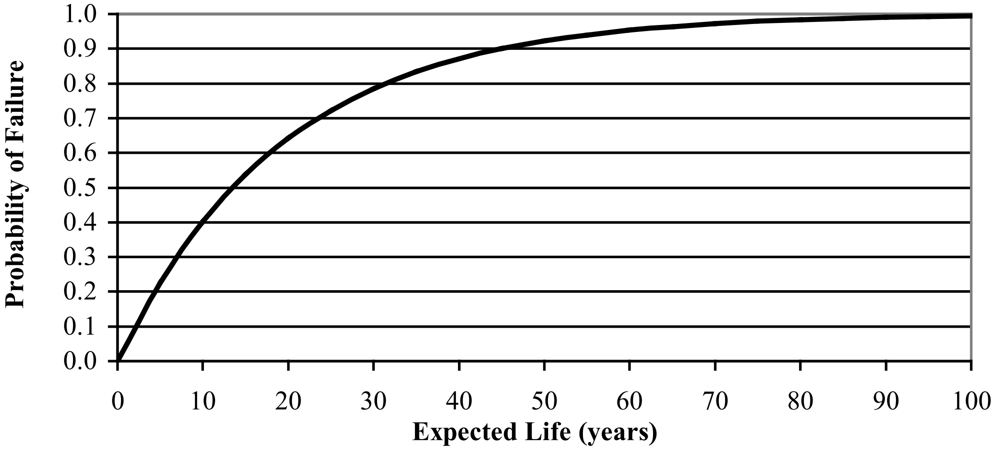

Figure 1. Probability of failure versus expected life.

Adjusting HYRISK-Calculated Risk

Lacking specific data about the costs associated with bridge failure, the modeler may use the values calculated by HYRISK. However, if better numbers are available, they should be used to obtain a tailored risk value. The extension of HYRISK allows for an additional cost lacking in the original HYRISK calculations – that associated with injury or loss of life. Using these, the cost of bridge failure may be calculated using

$$R = C_F P_L \tag{7}$$

where

R = risk (value of expected loss) due to failure,
C_F = cost of failure, including injury and loss of life, and
P_L = probability of failure over the expected life of the bridge.

Cost Benefit Analysis

A reasonable measure of resources appropriate for protection of a particular bridge is the present value benefit of any countermeasure contemplated. This value may be calculate using

$$B = C_F \left(P_L - P_L' \right) \tag{8}$$

where

B = present value benefit,
C_F = cost of failure, including injury and loss of life,
P_L = probability of failure over the expected life of the unprotected bridge, and
P_L' = probability of failure over the extended life of the protected bridge.

This relationship may be used to explore the range of economic benefits offered by providing various levels of protection at the bridge site. Consider a bridge with a cost of failure of \$1,000,000 and, without countermeasures, the bridge has an annual probability of failure of 0.05 and a lifetime probability of failure of 0.51 over an expected life of 14 years. For this bridge, the benefit of countermeasures calculated using Equation 8 for protection up to 100 years is shown in Figure 2.

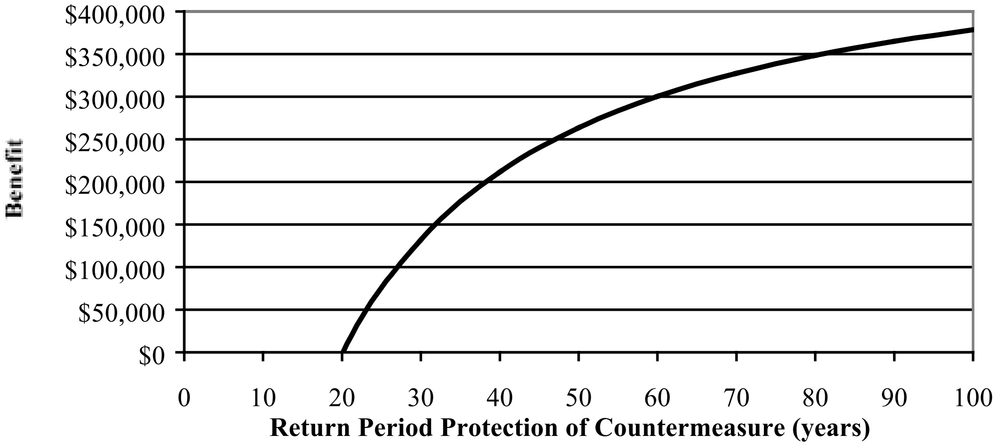

Figure 2. Economic benefit of protection versus countermeasure protection levels.

Benefit/Cost Ratio and Net Benefit

The benefits calculated above, however, ignore the costs of implementing the countermeasures. To decide on a particular countermeasure appropriate for the bridge, these costs must be accounted for. This can be done using a simple benefit-to-cost ratio or net benefit analysis for candidate countermeasures. Consider three countermeasures which might be feasible to employ at the bridge site as shown in Table 2.

Table 2. Example Benefit/Cost Analysis of Scour Countermeasures.

Countermeasure	*Cost*	*Return Period Protection*	P_L'	*Net Benefit*	*Benefit/Cost Ratio*
Small Riprap	$125,000	25	0.435	-$50,327	0.60
Large Riprap	$175,000	50	0.246	$88,642	1.51
Grout Mats	$275,000	100	0.131	$103,746	1.38

Bridge owners may use this information on which to make a better-informed decision about which form of protection provides the economic value while accounting for the expected (or desired) service life of the structure.

CONCLUSIONS AND PRACTICAL CONSIDERATIONS

The basic question can now be addressed: how much money should be spent on a bridge with a limited remaining service life to reduce the risks associated with major damage or failure. Three determinations may be made:

1. The minimum design return interval to balance costs of countermeasures with risks
2. The countermeasure design return interval that will yield the greatest net cost benefit, and
3. The return interval that will yield the maximum benefit/cost ratio.

It is envisioned that scour countermeasures would not be a consideration unless at least some elements of the bridge are scour critical. It is further envisioned that one would have access to a scour evaluation in order to determine the return interval that would cause failure or major expected damage if no countermeasures are provided. Further it is required that countermeasure costs can be assigned for protection to various levels of flooding above that return interval. A single bridge risk analysis is dependent on cost data associated with various probabilities of failure or major damage levels and it is reasonable that these costs should be provided by the designer as input to the model. Countermeasure costs are unique for each bridge.

A designer may have several alternative countermeasures available. It is still reasonable, however, to assume that one alternative will be either preferable for some non-economic cause or be the most cost effective for a given flood level. This alternative may then be selected and its cost used. For example, the designer may choose small riprap for lower level flooding with lower velocities, choose a larger class riprap for intermediate flood levels, and choose cable-tied block or another alternative for high flood levels because the next size riprap may be unavailable or prohibitively expensive. A sample input table for countermeasure costs as illustrated in Table 3.

Table 3. Sample input table for countermeasures costs.

Return Interval (yrs)	*Design Velocity (m/s)*	*Countermeasure*	*Cost ($)*	*Comment*
20	2.5	none	0	Failure R.I. with no protection
25	2.75	Class I Riprap	50,000	
50	3.0	Class II Riprap	75,000	
75	3.2	Class II Riprap	75,000	
100	3.4	Class III Riprap	100,000	
200	3.7	Cable tied blocks	175,000	

The lower level of protection that should be considered can be visualized by plotting the annual risk costs and the annual cost of providing protection against return interval as illustrated in Figure 3. The lines may be quite irregular but they cross where the risks balance the costs of providing protection. If budget conditions allow for a higher level of protection the designer could either maximize the net benefit or the cost benefit ratio as illustrated in Figures 4 and 5. The net benefit is the decrease in risk costs (over providing no protection) less the cost of the countermeasure. The benefit/cost ratio is the net benefit divided by the cost of the countermeasure.

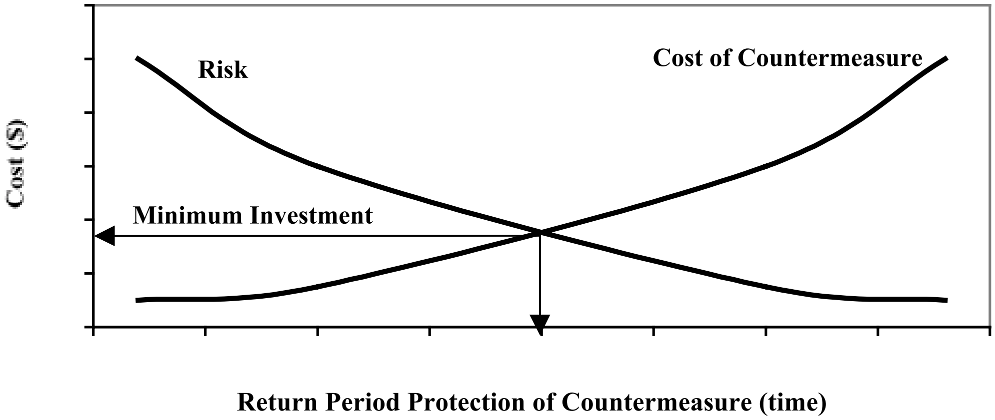

Figure 3. Minimum reasonable expenditure for countermeasure.

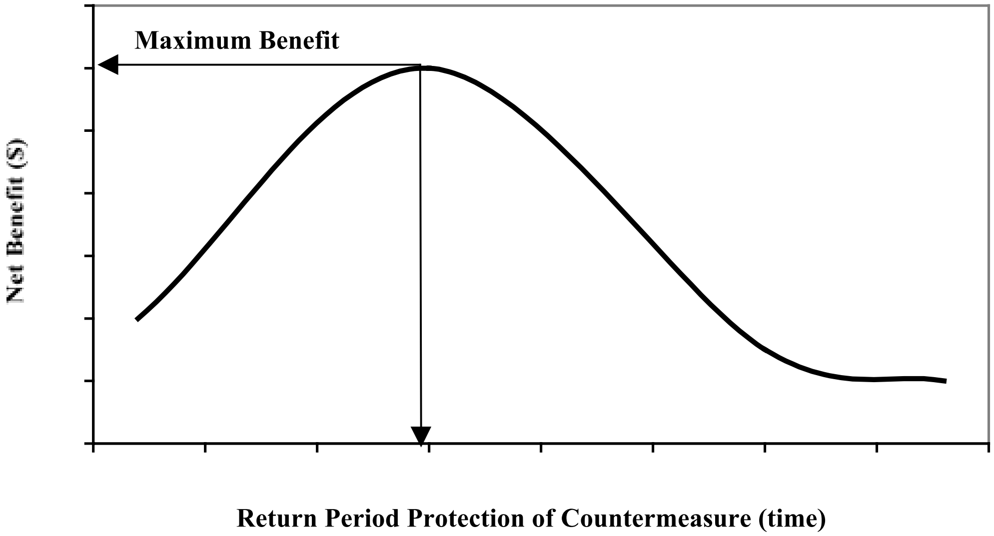

Figure 4. Maximum benefit from expenditure on countermeasure.

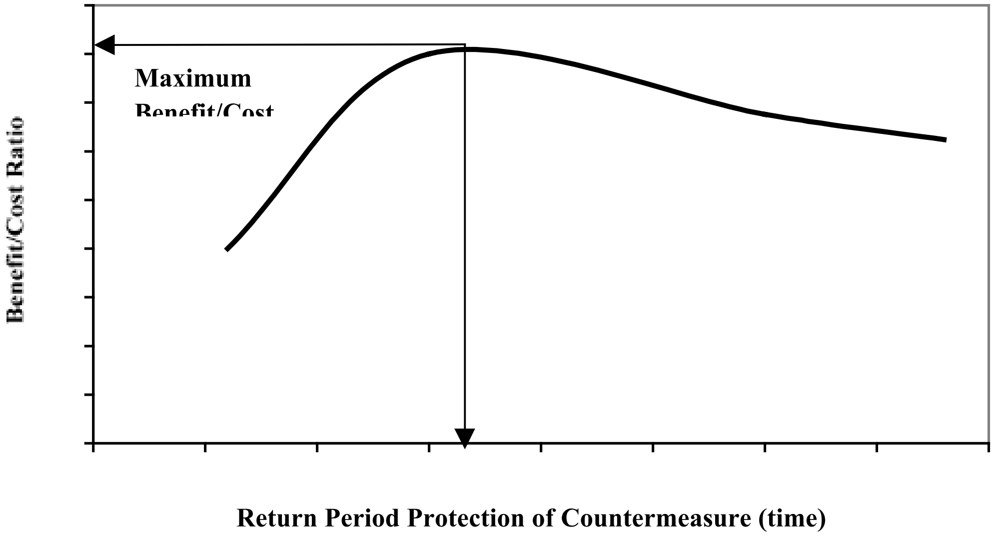

Figure 5. Maximum benefit/cost from expenditure on countermeasure.

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