# Bridge Risk Assessment and Protective Design for Ship Collision

Evaluation des risques de collision et plan de protection.

Risikoschätzung und Schutzentwurf gegen Schiffskollisionen.

**Robert G. SEXSMITH**
Principal
Buckland and Taylor Ltd.
Vancouver, BC. Canada

Robert Sexsmith, born 1938, received his Doctorate in Structural Engineering at Stanford University in 1967. He has been engaged in teaching, research, and consulting in the fields of structural design, behaviour, safety and risk assessment. He is a principal of the consulting firm Buckland and Taylor Ltd.s Vancouver, Canada.

**SUMMARY**

Risk assessment procedures and assumptions for the 464 m cable stayed Annacis Island Bridge span at Vancouver, Canada, are described, preceded by a prescriptive account of a method for adopting a design return period that provides the appropriate balance between risk and initial cost.

**RÉSUMÉ**

Les procédés et hypothèses pour l'évaluation des risques dans le cas du pont haubanné Annacis Island de 464 m d'envergure à Vancouver, Canada, sont décrits. L'équilibre entre le risque et les coûts initiaux permet d'évaluer la durée de vie de l'ouvrage.

**ZUSAMMENFASSUNG**

Die Verfahren und Annahmen fur die Schätzung der Risiken der 464 m langen Schragseilbrücke Annacis Island in Vancouver, Kanada, werden beschrieben. Der Vergleich von Risiken und Initialkosten läßt die Lebensdauer des Werkes schätzen.

## 0. INTRODUCTION

Safety levels in structural engineering are generally established by precedent. However, in the case of ship collision on bridges there are few precedents, and economic sense requires that the choice of acceptable risk be site-specific because the cost of protection varies widely with circumstances. Acceptable risk should be that which minimizes the sum of present expected value of future collision consequences plus present protective expenditures. A methodology for adopting the appropriate risk level is presented in Section 1 using hypothetical numerical values for example purposes.

The choice of acceptable risk depends on the relations between risk (or return period for catastrophic collapse) and cost of protective works. In order to illustrate how this relationship can be developed and to demonstrate a practical risk analysis for an actual project, some aspects of the risk assessment study for the Annacis Island Bridge, Vancouver, are briefly presented. This 465 m span cable stayed bridge is being designed in both concrete and steel alternatives for the British Columbia Ministry of Transportation and Communications. CBA-Buckland and Taylor are responsible for the steel alternative and for the ship collision risk assessment. A model of the bridge appears in Figure 1, and an elevation and layout are shown in Figure 2.

## 1. CHOICE OF ACCEPTABLE RISK

The provision of protection to a bridge gives insurance against serious damage or catastrophic collapse of the bridge due to ship collision. Thus the amount spent initially should be related to the degree of protection, and to the consequences of collision. For the case of a heavily travelled bridge, the acceptable return period for catastrophic collapse is so great that the risk to human lives from ship collision will be relatively small compared with that accepted by the motorists in their normal travel over the bridge. Thus a focus on only economic consequences is realistic. Available traffic statistics can be used to verify this assumption, and traffic warning devices can be developed to improve the safety of motorists (1).

The objective is to choose the level of risk (in terms of return period for catastrophic collapse) that provides a minimum of the sum of protection costs and expected present value of future consequences. The bridge owner, or his consultant, is assumed to be the decision maker and will pay the costs of protective works and absorb losses due to catastrophic collapse.

Excluded are losses associated with the vessel, such as cargo spills. These losses cannot necessarily be mitigated by the bridge protective works, in fact the chance of collision may be increased by construction of protective works. Risk management decisions that include vessel or cargo losses must be made at the bridge conceptual stage because they may strongly affect the site selection and pier locations.

The methodology suggested here is based on well established principles of minimum expected cost optimization (2). Some useful commentary on issues raised by the approach is found in (3) and (4).

### 1.1 Present Value of a Future Loss

Assume that a loss $C_f$ will occur at a definite time in the future. Then the present value of this loss is

$$C_o = C_f e^{-it} \qquad (1)$$

where

- $C_o$ is the present value of the future loss
- $C_f$ is the future loss in present monetary units (not inflated)
- $i$ is the real interest rate (excluding inflation)
- $t$ is the time to the future loss.

Note a number of assumptions, i.e. constant real rate of interest and known real cost of consequences. Inflation need not be considered because it is assumed that the rate of return on an investment will be the sum of the inflation rate and the real interest rate.

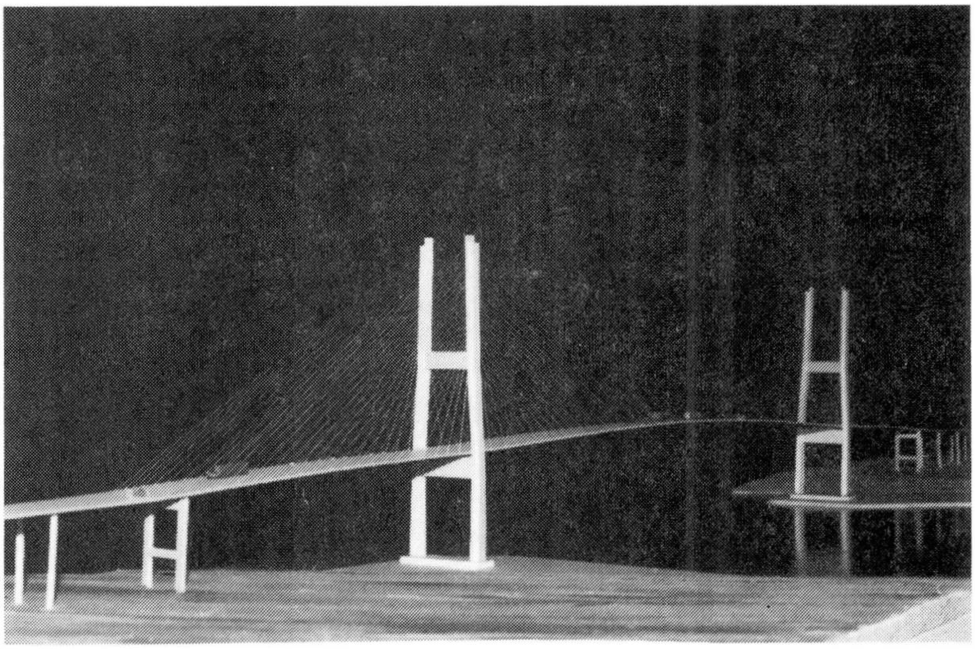

Figure 1 Model of the 465m Annacis Island Bridge

### 1.2 Present Value of a Series of Future Losses

Ship collision consequences are expected to have return periods of the order of hundreds or thousands of years. The present value of the consequences of a second loss in a series will be negligible compared with those of the first loss in the series. It is therefore reasonable to limit the problem to consideration of the first occurrence of catastrophic collision only.

### 1.3 Present Value of a Future Loss Occurring at Random Time

When the time to occurrence of the loss is a random variable, the present expected value, based on Equation 1, becomes

$$C_o = E[C_f e^{-it}] \tag{2}$$

$$= C_f \int e^{-it}\, f(t)\, dt \tag{3}$$

where

- $C_o$ is the present expected value of the future loss
- E(.)is the expectation operator
- f(t)is the probability density function on t, the time to occurrence of the catastrophy.

Ship collision events are rare and are independent random events in time. They can therefore be considered as Poisson events. The time to first occurrence is therefore exponentially distributed.

$$f(t) = ue^{-ut} \tag{4}$$

where u is the rate parameter (reciprocal of return period).

It follows that

$$C_o = \int C_f e^{-it} u e^{-ut}\, dt \tag{5}$$

$$= C_f u/(i+u) \tag{6}$$

As an illustrative example, assume a loss of $\$2\text{x}10^8$ in the event of catastrophic collapse due to ship collision and assume that such an event has annual probability $u = 0.001$ or return period $T = 1000$ years.
Assume a real interest rate of 3% or $i = 0.03$. Then

$$C_o = \$2\text{x}10^8(0.001)/0.031 = \$6.5\text{x}10^6$$

It should be emphasized that the losses include direct economic losses associated with the bridge structure, as well as indirect losses that occur as a result of loss of use of the bridge. The latter may be considerable (1).

## 1.4 Acceptable Risk or Return Period

In the hypothetical example of the foregoing section, a return period of 1000 years is assumed. In fact it is more straightforward to develop some reasonable design for protection of the bridge, then estimate its cost and the resulting return period. Assume that the return period 1000 years in the example was for failure of a protective system with the ability to absorb 1000 MN-m of energy before collapse of the bridge. Assume that the cost of this protective system is $C_c = \$6\text{x}10^6$. Then the present value of total expected cost chargeable to ship collision is $C_o+C_c = \$6.5\text{x}10^6+\$6.0\text{x}10^6 = \$12.5\text{x}10^6$.
The objective is to find the level of risk that minimizes this sum. Table 1 shows assumed values for two other trial designs, one for protection for 800 MN-m and another for 1400 MN-m. Each of these has a corresponding annual rate of exceedence (or probability that greater energy will be found). The calculations show that the design for the 1000 year return period is optimal in this example, because the total cost Co + Cc is a minimum. Only a few discrete trial designs need be prepared in order to find a near-minimum in the cost function, as it will normally not be sensitive to minor changes in the trial energy levels.

Table 1

| Energy Capacity (MN-m) | Annual rate of Exceedence | Return period for Exceedence T | $C_o$ | $C_c$ | $C_o+C_c$ |
|---|---|---|---|---|---|
| 800 | .002 | 500 yrs | $12.5\text{x}10^6$ | $3.0\text{x}10^6$ | $15.5\text{x}10^6$ |
| 1000 | .001 | 1000 yrs | $6.4\text{x}10^6$ | $6.0\text{x}10^6$ | $12.5\text{x}10^6$ |
| 1400 | .0002 | 5000 yrs | $1.3\text{x}10^6$ | $12.0\text{x}10^6$ | $13.3\text{x}10^6$ |

It is evident that when the consequences are very high, or when the cost of protection is relatively low, a high level of protection is optimal. Conversely, when the cost of protection is high or the consequences are low, little protection is justified. The analysis can properly weigh these variables to approach an optimal solution, but it is important to recognize the approximate nature of all the input variables. The calculation of risk, and the actual capacity of a proposed protective work, are very crude.

## 2. RISK ASSESSMENT FOR THE ANNACIS ISLAND BRIDGE - A CASE STUDY

### 2.1 The Site

The bridge site is at the east end of Mungo bend in the main channel of the Fraser River at the approach to the Port of New Westminster near Vancouver, Canada. The main piers proposed are outside the navigation channel but water depth is sufficient to expose the piers to possible ship collision. The superstructure is set to clear all shipping and is not considered to be at risk. Figure 2 indicates the shipping channel and clearances.

River current can be slightly upstream at flood tide and low flow periods, and reaches about 2 m/s downstream at ebb tide and high flow periods. Water elevation varies from -1.2 m to + 3.5 m.

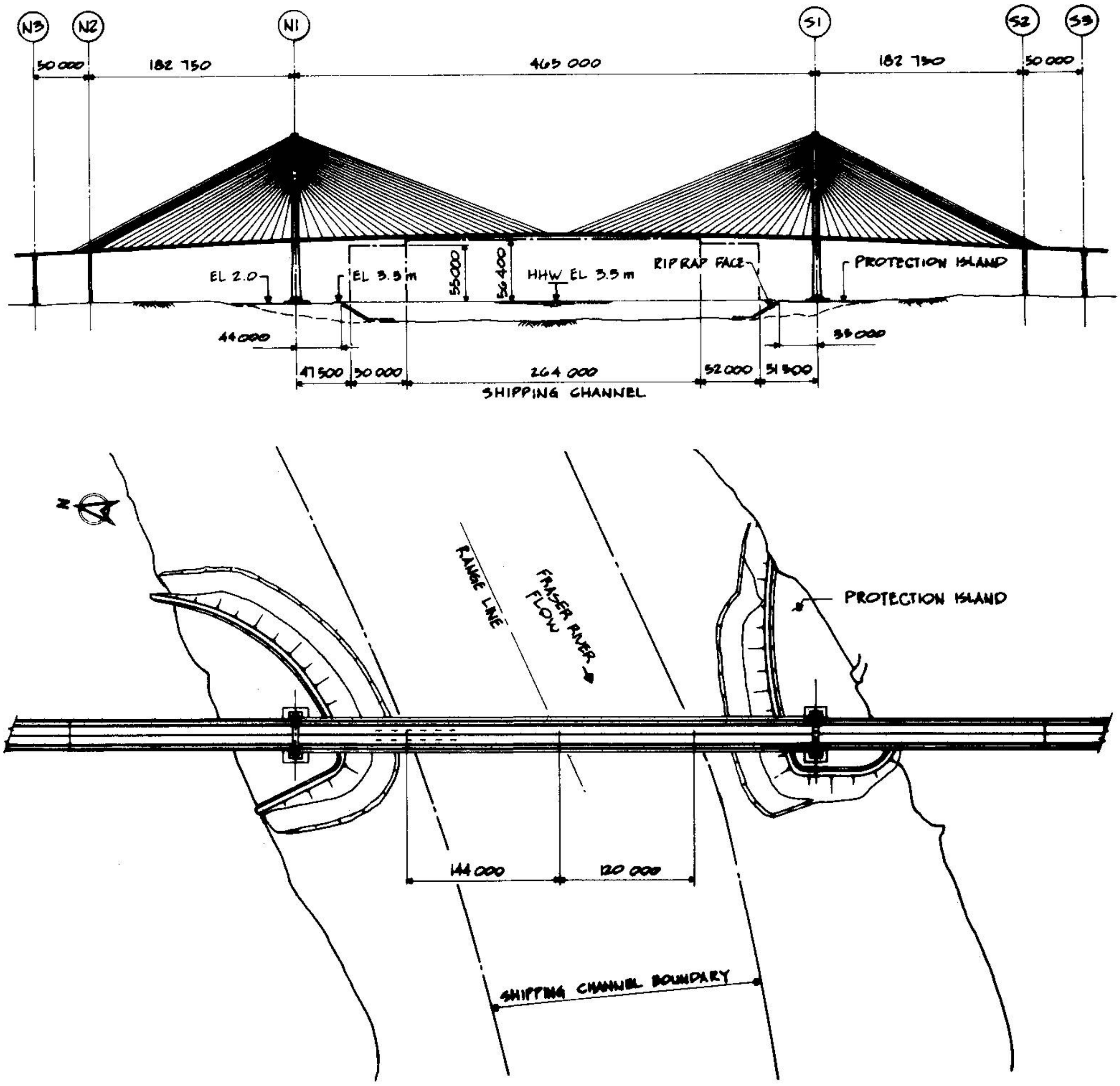


Fig. 2 Annacis Island Bridge, Arrangement of Protection Islands

### 2.2 Vessel Traffic Characteristics

Traffic types and volumes were obtained from logs of the Pacific Pilotage Authority, which supplies pilot services for vessels larger than 300 deadweight tons. One year of records were used to develop a discrete relative frequency model for vessel mass (Table 2). Accuracy of this model at the lower mass values is poor, but the larger vessels are well documented. The model has several limitations; prediction of the future from the chosen record is a major one. The rather coarse discrete increments chosen facilitate numerical work and are justified by the very approximate nature of the entire analysis.

It was assumed that vessel speed at collision is independent of mass. This is not likely to be true, but is a convenient simplification. Based on observation, discussion with the Pilotage Authority, and records of river current, a discrete probability mass function was constructed of vessel speed at collision with the bridge pier (Table 3).

Table 2

| Vessel Mass (Tonne) | Relative Frequency |
|---|---|
| 20000 | 0.25 |
| 30000 | 0.30 |
| 40000 | 0.30 |
| 50000 | 0.10 |
| 60000 | 0.05 |

Table 3

| Vessel Speed (m/s) | Probability |
|---|---|
| 1.8 | 0.7 |
| 2.5 | 0.1 |
| 3.2 | 0.1 |
| 6.0 | 0.1 |

The probabilities are subjective of necessity because a survey of speeds of normal traffic cannot represent the collision scenario. Data from actual collisions would aid in construction of this type of information, but reliable data is still sparse.

### 2.3 Rate of Collisions with the Piers

Ten years of records of River traffic indicated 20 incidents, or 2 per year, involving loss of control in the approach channel to the site. The fraction of these that might occur near the bridge is taken as 0.2 because the length over which reporting is done is about 40 km while the region near the bridge is taken as 8 km. Thus incidents of interest are 0.2(2) or 0.4 per year.

This is probably quite conservative, since the reported incidents are mostly docking incidents, which have little bearing on the chance of striking a pier. For comparative purposes, it is worth noting that the "causation probability" (probability that a given ship will be uncontrollable while passing the vicinity of the bridge pier) used in the risk analysis for the Great Belt Bridge, Denmark, was taken as $2 \times 10^{-4}$ (1). The comparable value used herein for Annacis Island is 0.4 incidents per year for 1098 transits past the bridge, or $0.4/1098 = 3.6 \times 10^{-4}$.

The channel is about ten times the width of a large vessel. It is assumed that the pier or its protective system would be struck with probability 0.1 given that a loss of control incident has occurred. This is the geometrical probability. Thus the net rate of arrival of collisions on piers is 0.4(0.1) = 0.04 per year. This is the accident arrival rate as far as the bridge is concerned. It is reasonable to assume that accidents are independent events with a small chance of occurrence in any given short time period. It then follows that the value 0.04 may be assumed to be the rate parameter $\lambda$ of the Poisson stochastic process. The arrival rate gives the accident frequency for all ships in the size category sampled, i.e. greater than 300 deadweight tons. Obviously most of these accidents will involve the smaller ships and low energy. This arrival rate corresponds to about 4 accidents per 100 years, or a return period of 25 years.

## 2.4 Energy Content of Accidents

Assume that a vessel chosen at random from the relative frequency distribution of vessel masses (Table 2) has a velocity (as it strikes the pier protective system) from the probability mass function of velocities (Table 3). Mass and velocity are assumed independent. Then the energy $E_k$ is computed for each combination of mass and velocity, and a probability distribution of energy is constructed. Table 4 gives the resulting conditional probability mass function on kinetic energy of vessels given that impact has occurred. Note that the energy is low with very high probability. It takes the rare joint event of a large vessel moving at a high speed to produce large energy.

Table 4

| Vessel Energy (MN-m) | Probability |
|---|---|
| 100 | 0.855 |
| 300 | 0.070 |
| 500 | 0.030 |
| 700 | 0.030 |
| 900 | 0.010 |
| 1100 | 0.005 |

Denote the event $Q_0$ no energy of impact in a given year, $Q_1$ the lowest energy level and so on for each of the discrete energy levels. Let $H_0$ be the event of "no collision" and $H_1$ be the event of a collision, in a given year. $H_0 = 0.96, H_1 = 0.04$. Then, by the theorem of total probability,

$$P(Q_i) = P(Q_i/H_1)P(H_1)+P(Q_i/H_0)P(H_0) \qquad (7)$$

for all $Q_i$. Thus

$$P(Q_0) = 0.96 \text{ (no energy demand in a year)}$$

$$P(Q_1) = 0.855(0.04) = 0.0342 \text{ (energy 100 MN-m)}$$

$$P(Q_2) = 0.070(0.04) = 0.0028 \text{ (energy 300 MN-m)}$$

and so on.

The probability mass function on the energy demand in one year, and the probability of equalling or exceeding a given level of energy in one year, are given in Table 5.

Table 5

| Energy (MN-m) | Probability of Equalling | Probability of Equalling or Exceeding |
|---|---|---|
| 0 | 0.96 | 1.0000 |
| 100 | 0.0342 | 0.0400 |
| 300 | 0.0028 | 0.0058 |
| 500 | 0.0012 | 0.0030 |
| 700 | 0.0012 | 0.0018 |
| 900 | 0.0004 | 0.0006 |
| 1100 | 0.0002 | 0.0002 |

The Table reflects the very high probability that nothing will happen in a given year, thus zero energy will be found. The non-zero values represent the other possible occurrences in a given year.

For the Annacis Bridge several levels of energy capacity were considered, corresponding to several levels of pier protection. Table 6 is a representation of the risk predicted for the bridge assuming a design protection level and then finding the probability that it will be exceeded from Table 5. The variation of risk with protection level is thus portrayed. Table 6 is similar to Table 1 in the preceding discussion of acceptable risk levels.

Table 6

| Energy Capacity (MN-m) | Annual Rate of Exceedence u | Return Period T |
|---|---|---|
| 800 | .0006 | 1667 |
| 1000 | .0002 | 5000 |
| 1200 | .0001 | 10000 |
| 1400 | 0 | inf |

The choice of acceptable risk could be made at this point by establishing cost of consequences and cost of protective works for each of the four energy levels in Table 6. This was not done for the Annacis Bridge. Based on estimates of feasible protective works and comparisons of risk with other risks, such as earthquake, a design energy capacity for pier protection of 1200 MN-m was adopted. The corresponding return period is 10000 years.

## 2.5 Design of the Protection System

A study of available literature on protective systems shows great variety, depending on the magnitude of the energy demand and the circumstances at the site (6). The Annacis design energy demand is relatively large, but the superstructure is not exposed, and the piers are located well out of the navigation channel. After examination of several alternatives including collision dolphins (which cause extreme scour problems), a protective frangible concrete shell at the piers, and protection islands, it was decided to construct protection islands. The proposed design indicated in Figure 2, provides sand-filled protection islands faced with rip-rap. The elevation of the islands is 2.0 m, thus water level is above the islands only for a small percentage of the time. The islands provide a sliding or ploughing distance for a moving ship of about 25m through which energy of at least 1200 MN-m can be absorbed. Calculations were similar to those suggested in (5) for a ship grounding and sliding over the island.

Because the risk was assessed with approximate conservative assumptions, no experimental work on energy absorption in the islands was considered justified. Extensive hydraulic studies were performed at Western Canada Hydraulic Laboratories to assess scour and flow characteristics around the protection islands.

The protection islands provide technical advantages for the bridge foundations regarding settlement and access, thus their cost is partially justified on these grounds. The cost of the islands is of the order $\$5x10^6$, an expenditure that appears to be in the correct order of magnitude for protection of an investment with failure consequences in excess of $\$2x10^8$.

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