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Ship and Bridge Collisions - The Economics of Risk

Collisions: risque du point de vue de la science économique

Kollisionen: Risikofaktoren aus wirtschaftlicher Sicht

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SUMMARY

Bowen Bridge, Hobart, Australia is being constructed as a back-up to Tasman Bridge, which was disrupted for three years following a ship collision in 1975. The economic evaluation of Bowen Bridge illustrates the objective analysis of the risk of bridge collapse, the disruption costs which can be avoided, and the initial costs of measures which reduce disruption costs. The cost/economic/risk equation is illustrated by a powerful graphical method developed for this case. The method is suitable for general use in evaluating a new bridge across shipping lanes.

RÉSUMÉ

Le pont Bowen de Hobart, Australie, a été construit comme complément au Pont Tasman, dont l'usage a été interrompu par suite de la collision d'un navire en 1975. L'évaluation économique du pont Bowen explique l'analyse objective du risque d'écroulement des ponts, le coût d'interruption qui pourrait être évité et le coût initial de mesures réduisant le coût d'interruption. L'équation coût/économie/risque est illustrée par une méthode graphique et dynamique qui a été développée pour ce cas. La méthode est destinée à un usage général pour évaluer un nouveau pont au travers de voies de navigation.

ZUSAMMENFASSUNG

Die Bowen-Brücke in Hobart, Australien, ist als Zusatzbrücke zur Tasman-Brücke gedacht, die nach einer Schiffskollision im Jahre 1975 drei Jahre lang verkehrsuntauglich war. Die vorliegende ökonomische Bewertung der Bowen-Brücke enthält eine objektive Analyse des Risikos von Brückeneinsturz, der Folgekosten, welche vermieden werden können, und der Kapitalkosten von Maßnahmen, welche die Folgekosten einer Verkehrsunterbrechung verringern. Das Verhältnis zwischen Kosten, Wirtschaftlichkeit und Risiko ist anhand einer überzeugenden graphischen Methode dargestellt, welche für die vorliegende Analyse entwickelt wurde. Diese Methode ist für die Bewertung einer neuen Brücke über Schiffahrtswege allgemein gültig.

1. INTRODUCTION

The possibility of ship bridge collisions is a matter that must be taken into consideration in the design of bridges over navigable waters. It is preferable that this possibility be incorporated in an explicit manner, and within a rigorous framework.

In an economic evaluation study [1] for a new river crossing following the collapse, due to ship collision, of the Tasman Bridge in Hobart, Australia, a methodology for incorporating the possibility of ship bridge collisions into the decision frame was established. The method considered simultaneously the probability of ship bridge collision and the uncertainty associated with the measurement of disruption costs.

The basic approach of that study is described in this paper. The way in which the methodology can be used in the general case as an aid to selecting the appropriate risk level and thence in setting design criteria is also explained. The importance of this research is that it shows how, even when the disruption cost associated with bridge collapse is uncertain, it is still possible to utilize cost-benefit analysis to derive the most appropriate design criteria.

2. BACKGROUND TO THE EVALUATION STUDY

Three spans of the Tasman Bridge in Hobart, Australia were demolished by ship collision in January 1975. There were substantial economic and social disruption costs as a result of this unexpected closure. Tasman Bridge, was re-opened in October 1977.

Bowen Bridge is now being constructed 7 kilometres upstream from the Tasman Bridge, at a cost of approximately $A35 million (1983 dollars). It will be opened to traffic in 1983. Economic analysis demonstrated that its primary purpose was to provide an alternate river crossing in the event of a future closure of Tasman Bridge. The principal economic benefit therefore, is the avoidance of disruption cost in the event of a future ship collision with the Tasman Bridge, an insurance benefit.

The population of Hobart (at June 1974) was approximately 150,000, persons of which some 45,000 persons lived on the eastern shore of the Derwent River and 105,000 on the western shore. Economic and social activities for the 150,000 Hobart residents were heavily dependent on the single transport link, the Tasman Bridge. The only alternative road link between the two shores was the Bridgewater Bridge involving a one-way trip of 43 kilometres (86 km round trip). Disruption costs associated with collapse of the Tasman Bridge therefore included the massive disruption of economic and social linkages within the city as well as the costs of temporary bridging and of rebuilding the Tasman Bridge.

The situation thus provided a unique opportunity to develop a methodology that would enable the risk of ship bridge collision to be included in the decision frame. The objective of the study was to evaluate the proposed second crossing (Bowen Bridge), of the Derwent River. To assess the proposed Bowen Bridge a means had to be developed to incorporate, in a rigorous way, the possibility of future closure of the Tasman Bridge and the wide variation in the estimates of avoidable disruption costs.

This work was undertaken prior to a decision to fund the construction of the second bridge and the results of the evaluation were a significant input into this decision.

3. COST AND BENEFITS

The economic evaluation was done at a time when the design of Bowen Bridge was substantially completed. The design involved full protection of all river piers [2]. As foreseeable river traffic involved only small vessels (up to 5000 tonnes displacement) the safety of the new bridge against serious damage arising from a ship collision could be guaranteed.

Thus the cost of Bowen Bridge including costs of supervision and approach roads could be accurately estimated and at mid 1978 prices was $28.5 million.

As construction expenditure would take place over 3 years the present value of these expenditures ranged from $28.5 million at zero rate of discount; $26.1 million at 5% rate of discount; $24.8 million at 7% rate of discount and $23.4 million at 10% rate of discount.

There are three major identifiable economic and social benefits accruing from the construction of Bowen Bridge. They are:

- o Reduction of disruption costs from a further collapse of Tasman Bridge - the insurance benefit
- o Traffic facilitation due to the additional traffic lanes across the Derwent River provided by Bowen Bridge
- o Cost reductions for new urban development

The largest of these is the insurance benefit which is discussed separately below. The other benefits are discussed briefly now.

The urban development benefit is the reduction in the cost of servicing new urban settlements. It is calculated by comparing the pattern of development and associated infrastructure budget if Bowen Bridge is constructed, with alternative budgets that are associated with other selected development patterns. The net present value of this benefit is within the range of $0 to $5 million.

Two types of traffic benefits were calculated:

- o Some existing trips will be reduced in length or cost by the availability of the bridge. The benefit is the saving in vehicle operating costs and travel time.
- o Some trips not now made will be made because the bridge is there. In this case the surplus value of the trip is equal to the difference between the cost of making the trip and the intrinsic value of the trip.

The net present value of traffic benefits for the three rates of discount were $6.6-10.8 million for a 5% discount rate, $4.7-7.7 million for a 7% discount rate and $3.3-5.4 million for a 10% discount rate. That is the present worth of the traffic benefit lies approximately in the range of $3m to $11m.

4. DISRUPTION COST ANALYSIS

It will be seen that even at high values of traffic and urban development benefit, these benefits cannot in themselves justify the cost of constructing the second crossing. It was therefore necessary to obtain an estimate for the third type of benefit, avoidance of disruption cost.

Disruption cost analysis [1] provides a methodology for assessing the benefits of projects designed to avoid or minimise future disruption costs caused by expected events. The methodology can be applied to both common and infrequent events. It is necessary to postulate two time series of disruption costs; one if the project is not undertaken and a second if the project that will reduce disruption costs is undertaken. These time series of expected disruption costs can be translated into present worth values once the probability of experiencing disruption in each year of the future is known and a discounting factor selected. The expected present value of the benefit is the difference between the two present worth estimates.

The analysis is developed as follows:

D_n = Disruption cost in year n given the disruption event occurs

Dk_n = Disruption cost in year n given the disruption event occurs and the project being evaluated has been implemented

DA = Avoidable disruption cost = D-Dk

p_n = Probability of disruption event occurring in time period n

i = Rate of discount

g = Real annual rate of growth of disruption costs

PW = Present worth

The present worth equations are:

$$PW\ (D) = \frac{D_1 p_1}{(1 + i)} + \frac{D_2 p_2}{(1 + i)^2} + ---- + \frac{D_n p_n}{(1 + i)^n} + ----$$

A similar equation may be written for PW (Dk)

If the following simplifications are made:

- o The probability of the disruption event is equal in each year i.e. $p_1 = p_2 = p_n$
- o Given that the project is not undertaken the disruption cost is the same in each future time period i.e. $D_1 = D_2 = D_n = D$
- o Given that the project is undertaken the disruption cost is the same in each future time period i.e. $Dk_1 = Dk_2 = Dk_n = Dk$

Then PW (DA) = PW (D) - PW (Dk) which by algebra reduces to:

$$PW\ (DA) = p\ [\frac{DA}{(1 + i)} + \frac{DA}{(1 + i)^2} + ---- + \frac{DA}{(1 + i)^n} + ----]$$

If the growth factor g is now introduced

$$PW\ (DA) = p\ [DA\ \frac{(1 + g)}{(1 + i)} + DA\ \frac{(1 + g)^2}{(1 + i)^2} + ---- + DA\ \frac{(1 + g)^n}{(1 + i)^n} + ----]$$

For small values of g the infinite series reduces to

$$PW\ (DA) = \frac{p\ DA}{i-g} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 1.$$

That is the present worth of future disruption cost avoidable by the specified project is equal to the probability of collapse in any year, multiplied by the disruption cost avoided when the disruption event occurs, divided by the discount rate less the rate of growth in disruption cost.

If the factor P/i-g is calculated for various values of p, i and g it is easily demonstrated that even for a relatively low probability event the present worth of the disruption cost is a significant percentage of the disruption cost when it occurs. Suppose the probability of the event occuring is once in every 100 years and that the net discount rate (i-g) is 3 percent then the present worth of future disruption cost is equal to 33 percent of the contingent disruption cost (in the year the disruption occurs). This indicates that for this probability, if the contingent disruption cost is high, it is appropriate to spend a considerable sum to avoid that disruption. One approach would be to consider the costs of decreasing to say 1 in 1000 or 1 in 10000 years, the probability of the disruption event occurring. This would, in many cases require the selection of new design criteria for the bridge. Another approach would be to consider projects that would reduce the magnitude of disruption costs in the event that a disruption occurs. (The

Bowen Bridge solution to the possibility of collapse of the Tasman Bridge is an example of the latter approach).

5. INSURANCE BENEFIT

The insurance benefit for Bowen Bridge was determined using disruption cost analysis as follows:

Avoidable government disruption costs (based on the Tasman Bridge experience) were calculated to cover items such as temporary bridging, additional government services, roads, ferries, ferry terminals, ferry subsidy, additional bus services. In 1978 dollars these were assessed at a lower bound estimate of $10 million and an upper bound estimate of $22 million.

Avoidable private disruption costs were calculated to cover three items; value of additional travel time, additional money costs of travel and value of trips foregone. In 1978 dollars these were assessed to have a lower bound estimate of $18 million and an upper bound estimate of $37 million.

Thus the total avoidable disruption costs were calculated to be in the range $28 million to $59 million.

The present worth of avoidable disruption costs was calculated using formula 1., given above.

The probability of a future collapse of Tasman Bridge was determined to have a recurrence interval of between 10 years and 40 years [3] [4]. The value of p which is the reciprocal of the recurrence interval was therefore assessed to be between 0.1 and 0.025.

The net rate of discount (i-g) was taken as a variable of 4%, 6% and 9% consistent with a rate of discount of 5%, 7% and 10% with a 1% rate of growth in disruption.

The present worth of avoidable disruption cost (the insurance benefit) was calculated using the above estimated ranges for avoidable disruption cost, net discount rate and probability of collapse of the Tasman Bridge, and was calculated to lie within the range of $8 million and $148 million; as shown in the table below:

1/p Recurrence Interval years	i					
	5%	7%	10%	5%	7%	10%
10	70	47	31	148	98	66
40	18	12	8	37	25	16
	DA = $28m lower bound			DA = $59m upper bound		

6. DECISION FRAMEWORK INCORPORATING PROBABILITY OF COLLAPSE

The aggregate total of present worth of benefits is therefore as follows.

Urban Development	-	$ 0 to $ 5 million
Traffic	-	$ 3 to $ 11 million
Insurance	-	$ 8 to $148 million
Total	-	$11 to $164 million

The range for present value of project benefit is extremely wide and this information as such is of limited value. Consequently techniques were developed for calculating the probability that project benefit is greater than project cost.

Each estimate of aggregate project benefit depends on the values assigned to nine parameters and a large number of estimates of project benefit is possible. A computer model was developed to calculate the probability that the aggregate benefit of the project exceeded any particular amount. This probability was calculated for various rates of discount and a range of assigned recurrence intervals (probability of collapse of Tasman Bridge); these two parameters having most influence on the calculated project benefit.

For each of the other seven parameters namely:

Unit cost of vehicle operation
Value of travel time in normal circumstances
Value of travel time in abnormal circumstances
Weeks to construct temporary crossing
Weeks to reconstruct Tasman Bridge
Government expenditure in year of collapse
Urban development benefit

the probability that the true but unknown value of the parameter lay at various points of the range was assessed and a probability distribution established for each of these parameters. The technique used is illustrated below for the value of travel time in abnormal circumstances.

Value of travel time (dollars per hour)	Probability that true value exceeds selected value
2	80%
3	40%
4	0%

(In this case the value of travel time was resticted to the integer values of 2, 3 and 4).

With the probability assessments for each parameter it was possible to calculate the probability that the aggregate benefit would exceed any value of aggregate benefit for each set of collapse probability and discount rate values. This provides a cumulative probability distribution. The results are presented graphically as shown in Figs. 1-4.

Conclusions from the graphs are easily drawn. For instance for a median project benefit (50% probability that project benefit is greater) and for discount rates of 5%, 7% and 10% project benefit exceeds project cost when probability of collapse is less than once in 80, once in 50 and once in 30 years respectively. The result of the evaluation therefore indicates that the aggregate benefits of the Bowen Bridge most likely exceeds its cost.

In this context it is noted that a separate study [3] showed that the cost of protecting the piers of Tasman Bridge against ship collision was far greater than the cost of constructing a back up bridge.

As the Tasman Bridge, which is undoubtedly vulnerable to further ship collisions, is not being protected the remaining matter to be resolved was that of protecting the public using the bridge. The restored bridge which carries 50,000 vehicles per day has computer controlled traffic lights, on gantries, for tidal flow of traffic in peak hours. This system was modified simply and cheaply to enable the bridge to be used in a manner similar to a railway level crossing. In peak road traffic periods ships are not permitted to navigate the bridge. At all other times the bridge deck is completely cleared of all traffic while a ship passes beneath the bridge. The traffic delay is about 3 minutes and the public have not objected.

7. RISK LEVELS USING DISRUPTION COST ANALYSIS

Risk models can be and usually are established by engineers, particularly for consideration of problems such as ships hitting bridges. Engineering parameters such as statistics of shipping, distribution of ship sizes, the fraction of passing ships which are uncontrollable (causation probability),

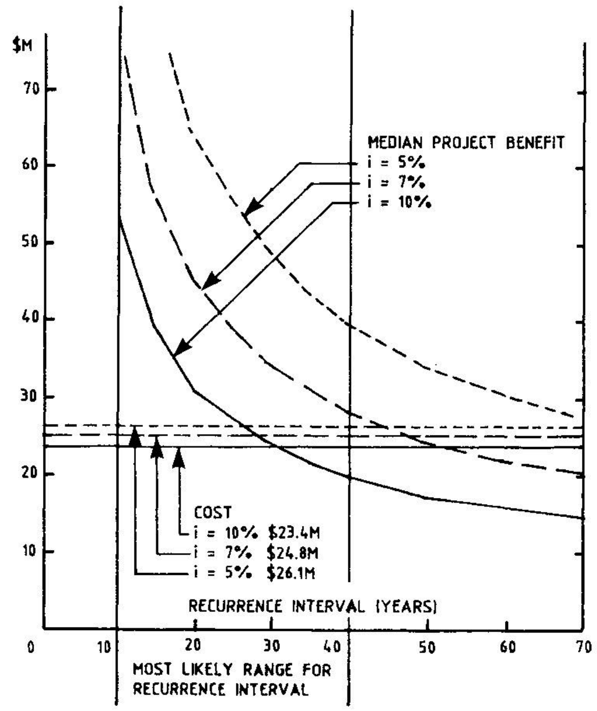

Fig. 1 Median Project Benefit by Recurrence Interval and Discount Rate (Million dollars, 1978 prices)

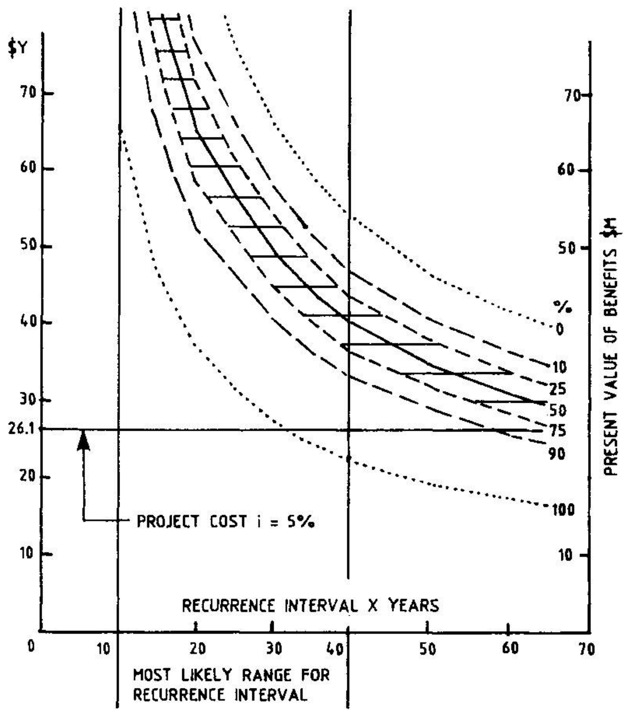

Fig. 2 Probability that Project Benefit is Greater than $Y for Recurrence Interval of X Years for Discount Rate 5%

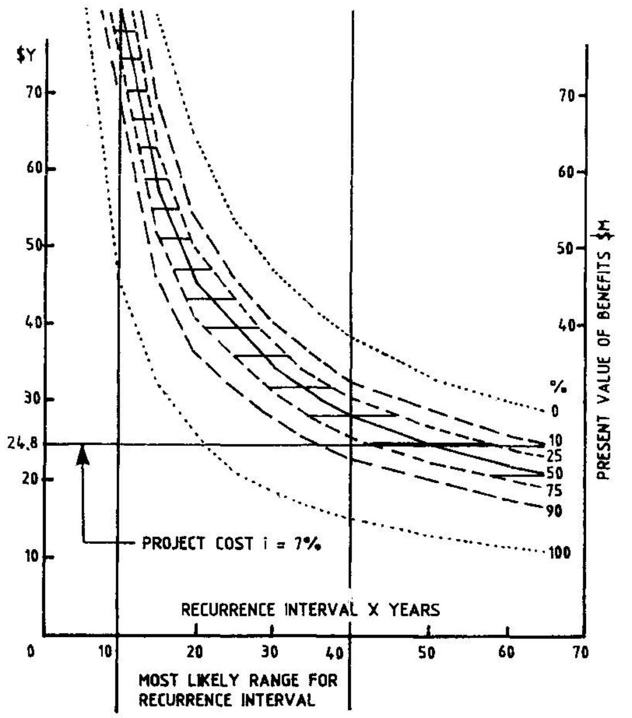

Fig. 3 Probability that Project Benefit is Greater than $Y for Recurrence Interval of X Years for Discount Rate 7%

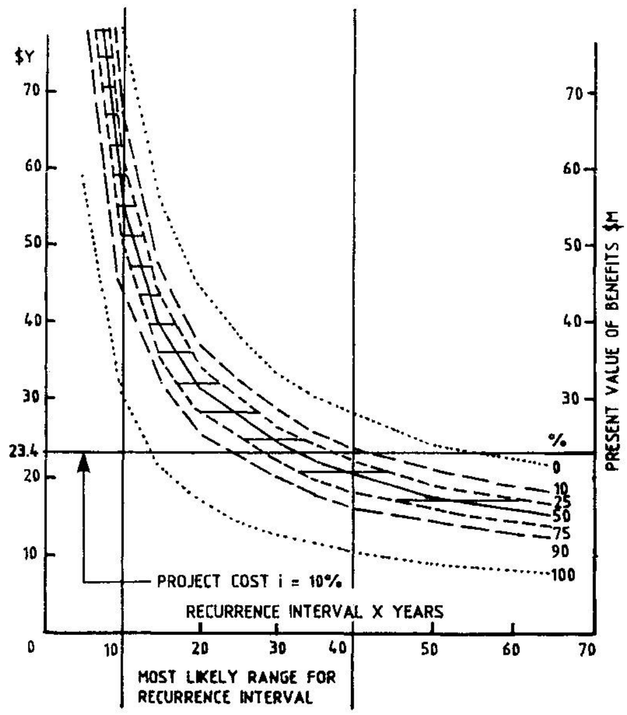

Fig. 4 Probability that Project Benefit is Greater than $Y for Recurrence Interval of X Years for Discount Rate 10%

the probability of a ship out of control hitting a pier (geometric probability) are available to estimate the biggest ship which can hit a pier in a given period. The difficult question is the choice of the acceptable recurrence interval or risk level of the structure.

Disruption cost analysis as described in this paper provides a framework based on cost benefit analysis which will aid the choice of risk level on a rational basis. In the past cost benefit analysis has not generally been used due to the variability of the parameters and the difficulties in evaluating the economic consequences. The method described in the paper which deals with the variability of parameters on a probability basis provides a satisfactory way of presenting the cost benefit data in graphical form so that the information is both comprehensive and easy to assess, thus leading to an informed decision on the risk level to be adopted.

The method can be applied to a "greenfields" site where a new major bridge is to be built across existing shipping lanes. Presumably the decision to construct such a bridge in the first place would be justified on economic grounds; that is the economic benefit derived from its construction exceeds its cost. In considering the design of the bridge the risk level to be adopted, the number of piers in navigable water versus the cost of longer spans etc. can be determined on the basis of disruption cost theory starting from the economic costs associated with the disruption of this benefit. In this context and in hindsight it is interesting to consider the design of Tasman Bridge (carried out in 1956). This bridge has 20 piers [5] in navigable water with spacings of generally 43m. The overriding consideration of the design at the time was capital cost. The authors suggest that if the bridge were designed today, using the disruption cost analysis described in this paper, the resulting design would have been totally different with longer spans and considerably higher initial capital cost, which would have been seen to be fully justified.

The disruption cost method might even be extended to the general level of safety for which major structures should be designed. With the advent of limit state design theory the concepts of the resistance R and load Q effect and are well established. Typically 5 and 95 percentile values are chosen for the characteristic values R_k and Q_k in specifying design values for checking ultimate (or collapse) limit states, while mean values are used in considering serviceability limit states. With most codes such an approach leads to a Safety Index (β) for individual elements of approximately 4. This is roughly equivalent to a probability of failure of 10^{-4}. Disruption cost analysis could help to provide an answer to the question (assuming that it is posed) of whether such typical levels of structural safety are satisfactory or desirable for a particular structure of major significance (and presumably substantial economic benefit) which is being designed.

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