Acceptable Risk Criteria for Infrastructure Protection

by

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Acceptable Risk Criteria for Infrastructure Protection

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ABSTRACT

This paper reviews risk-based approaches to assessing the risk acceptability and cost-effectiveness of protective measures for infrastructure. The paper describes three risk acceptance criteria based on fatality risks, failure probabilities and net benefit assessment. These criteria can be applied to any item of infrastructure such as buildings, bridges, dams, offshore platforms, etc. and also applies to any man-made or natural hazard such as earthquakes, cyclones, terrorism, floods and so on. The decision support framework accompanying these risk acceptance criteria considers hazard and threat probabilities, value of human life, physical and indirect damages, risk reduction and protective measure costs. This has specific utility for the safety and economical design and assessment of new and existing protective structures against shock and impact loading. Risk assessments are conducted for a bridge over an inland waterway where the hazard is ship impact and a building subject to terrorist attack. The illustrative examples showed under what combination of risk reduction, and fatality and damage costs the fatality and failure risks would be acceptable, and when protective measures would be cost-effective.

Key words: Risk, Structural Reliability, Ship Impact, Terrorism, Decision Making, Cost Benefit

1. INTRODUCTION

An issue often facing asset owners and regulatory agencies is how safe is safe enough, and to ensure that expenditure on proposed protective measures is invested in a manner that optimises public safety in a cost-effective manner. Such issues may be addressed by risk-based approaches to decision making where the definition of risk is the combination of hazard or threat probability, risk reduction and consequences (e.g. [1]). This definition is consistent with that used by many industries, and cost-benefit and other risk acceptance studies are routinely conducted by the Nuclear Regulatory Commission, the Environmental Protection Agency, the Federal Aviation Administration, and other agencies. These studies are particularly useful for low probability – high consequence events where public safety is a key criterion for decision-making. This includes the design and assessment of buildings, bridges, levees, and other infrastructure systems for protection against seismic, flood, hurricane and other natural and man-made hazards. The uncertainties associated with protection of infrastructure to shock and impact loading may be higher than for other hazards which makes probabilistic risk assessment particularly appropriate for these items of infrastructure. The present paper will thus describe risk-informed decision support for assessing the risks, costs and benefits of protective measures for infrastructure.

Various protective measures are used to protect infrastructure from a variety of hazards, these include, e.g.:

1. terrorist bombings: vehicle barriers, increased stand-off, enhanced perimeter security, resilient facility design.
2. bridge ship impact: impact fender systems, improved navigation markers.
3. cyclone damage: improved roof fixings, shutters, impact resistant windows.

What is unclear, however, is the effectiveness of these and other protective measures, and how to quantify their risks, costs and benefits in a manner to improve decision support. A cost-benefit analysis provides a means to measure the cost associated with reducing, avoiding or transferring the risk. This allows the decision maker to make a risk-informed decision about whether such a cost is excessive, therefore failing to be a productive utilization of society's resources. Activities related to nuclear energy, chemical processes, aviation, etc. with large potential for loss of life or severe economic or social consequences have since the 1960's been subject to methodical and quantitative risk assessment [2]. Many of these systems are characterised by their low probability of failure and high consequences, as well as the need to address such contentious issues of value of life, risk aversion, risk acceptability, and in many cases, modelling human actions and reactions using a human reliability analysis. Natural hazards and terrorist threats have similar characteristics and decision support challenges and issues.

For many engineering systems the hazard (or threat) rate is known or predicted 'a priori', but for terrorism and other malevolent acts the threat is from an intelligent adversary who will adapt to changing circumstances to maximise likelihood of success. Some statistical approaches exist for terrorist threat prediction (e.g., [3, 4, 5]), however, these rely heavily on expert judgments from security experts, game theory, etc. so the inherent uncertainties can still be high. For this reason, a U.S. Department of Homeland Security (DHS) report on bioterrorism risks [6] states that "the assessment of the probabilities that adversaries will choose courses of action should be the *outputs* of analysis, not required *input parameters*." Hence, it is recommended that the cost-benefit analysis be used to calculate the minimum (threshold) threat probability for a specific counter-terrorism (CT) protective measure to be cost-effective. In other words, the threat probability is the output of the cost-benefit analysis and it is the prerogative of the decision-maker, based on expert advice about the anticipated threat probability, to decide whether or not a CT protective measure is cost-effective. For example, expert advice about the anticipated threat probability is used by the Transportation Security Administration Office of Intelligence who have developed likelihood estimates for specific threat scenarios for highway infrastructure [7].

Stewart [8, 9] have developed risk assessment methods for designing and assessing the safety and cost-effectiveness of protective structures against terrorist threats, and Stewart and Mueller [10] have assessed the cost-effectiveness of aviation security including air marshals and hardening of cockpit doors. While this work has focused on terrorist threats, the principles are applicable to any hazard. Hence, the present paper extends this work by describing risk assessment and cost-benefit analysis for any item of infrastructure that needs protecting from one or more hazards. The paper reviews three risk acceptance criteria: (i) fatality risk, (ii) failure probability, and (iii) net benefit (cost-benefit) assessment. The decision support framework accompanying these criteria considers hazard and threat probabilities, value of human life, physical and indirect damages, risk reduction and protective measure costs. Previous work has used single-point (deterministic) estimates for parameter values, but the present paper now includes the effect of random variables which allows upper and lower bounds of risks and net benefit to be calculated. Probabilistic risk assessments are conducted for (i) a bridge over an inland waterway where the hazard is ship impact, and (ii) an institutional building subject to a terrorist Vehicle Borne Improvised Explosive Device (VBIED). The illustrative examples will show under what combination of risk reduction, and fatality and damage costs the fatality and failure risks would be acceptable, and when protective measures would be cost-effective. This has specific utility for the safe and economical design and assessment of new and existing protective structures against shock and impact loading. The risk-based decision support used herein is relatively simple, and so is most suitable for preliminary risk assessments or risk screening. In principle, however, the approach used herein can be extended for a more detailed analysis of costs and benefits of protective measures. In the absence of hazard occurrence or engineering performance data decision makers may need to rely on judgement and scenario analyses to develop and quantify threat scenarios, risk reductions and damage consequences. It should be noted that the probabilistic risk assessment developed herein will provide complementary information to decision-makers, but this or any other risk assessment should not be viewed as the sole criterion for decision-making.

2. RISK ACCEPTANCE CRITERIA

There are many risk acceptance criteria and these depend on the type of risk being quantified (life safety, economic, environmental, social), the preferences of the interested parties and the decision maker, and the quality of the information available. In the present paper three widely used risk acceptance criteria are presented and discussed.

2.1. FATALITY RISKS

Stewart and Melchers[2] reviewed the quantitative safety goals used by the U.S. Nuclear Regulatory Commission, Australian and Dutch hazardous industrial development regulators, U.S. environmental carcinogenic exposure regulators and others. These government regulators are concerned with low probability – high consequence system failure not unlike many threats to infrastructure. The consensus risk acceptance criteria obtained for involuntary fatality risk to an individual are thus:

- Annual fatality risks higher than 1×10^{-3} are deemed unacceptably high.
- Annual fatality risks in the range of 1×10^{-3} to 1×10^{-6} are generally acceptable if the benefits outweigh the risks to provide an economic or social justification of the risk.
- Annual fatality risks smaller than 1×10^{-6} are deemed as negligible and further regulation is not warranted.

The above criterion relates to individual fatality risks, though in some cases reference need also be made to societal risks where there is aversion to single events causing large loss of life (e.g., [11]).

The well known formulation for annual risk (loss) for a system exposed to a hazard is

$$\Pr(L) = \sum_{H}\sum_{DS}\sum_{L} \Pr(H)\Pr(DS|H)\Pr(L|DS) \qquad (1)$$

where Pr(H) is the annual probability of hazard (or threat) occurrence per item of infrastructure, Pr(DS|H) is the conditional probability of a damage state (e.g., collapse, fire, etc.) given occurrence of the hazard, and Pr(L|DS) is the conditional probability of a loss (e.g., damage costs, fatalities) given occurrence of the damage state. The summation signs in Eqn. (1) refer to the number of possible hazard intensity levels, damage states and losses. The product Pr(H)Pr(DS|H) is often referred to as the probability of failure (p_f) if the damage state defines 'failure'.

If the loss refers to the fatality of an individual, then Pr(L) represents an individual annual fatality risk. To assess the life safety of a protective measure, risks are compared to the baseline case of no extra protection. It is assumed that Pr(H) represents the annual probability of a hazard for the baseline case of no extra protection. This may represent losses resulting from total devastation where Pr(DS|H) = 1 and Pr(L|DS) = 1, i.e., everyone in the item of infrastructure is killed. However, this will be overly conservative. Protective measures should result in risk reduction (R) that may arise from a combination of reduced likelihood of hazard attack, damage states, safety hazards and and/or people exposed to the safety hazard. To allow for the reduction in fatality risks arising from protective measures it follows from Eqn. (1) that

$$\Pr(L) = \frac{(100-R)}{100}\Pr(H)\Pr(DS\,|\,H)\Pr(L|DS) \qquad (2)$$

where R is the percentage risk reduction. For any protective measure the percentage risk reduction R can vary from 0% to 100%. For example, if risk reduction is R = 20% then the existing risk is multiplied by (100-R)/100 = 0.8. If a combination of protective measures will foil every hazard or threat then the sum of risk reductions from these protective measures is 100%. This soon becomes a multidimensional decision problem with many possible interactions between protective measures, hazard scenarios, hazard and damage state probabilities, risk reduction and losses.

Estimates of probability of failure (Pr(DS|H) and/or Pr(L|DS)) may be obtained from a probabilistic risk assessment which considers temporal and spatial variabilities and uncertainties of variables influencing system performance (e.g., [2]). For structural systems this is often referred to as a structural reliability analysis where failure occurs when a load effect (S) exceeds a capacity (R) such that the probability of failure (p_f) is

$$p_f = \Phi(-\beta) = \Pr\left(R \le S\right) = \int_0^\infty F_R(r) f_S(r)\,dr \qquad (3)$$

where R and S are statistically independent random variables, $f_S(r)$ is the probability density function of the load, $F_R(r)$ is the cumulative probability density function of the resistance, $\Phi()$ is the standard Normal distribution function (zero mean, unit variance) and β is the 'reliability index' or 'safety index'. A limit state is a boundary between desired and undesired performance and is referred to as $G(\mathbf{X})$ where the vector $\mathbf{X}$ represents the basic variables involved in the problem, which in the present case is equal to R-S. For many realistic problems the simplified formulation given by Eqn. (3) is not sufficient as usually several random variables will influence structural capacity, such as material properties, dimensions, model error, etc. Moreover, there are likely to be several load processes acting on the system at the same time. Equation (3) can be generalised to

$$p_f = \Pr\left[G(\mathbf{X}) \le 0\right] = \int \dots \int_{G(\mathbf{X})\le 0} f_{\mathbf{X}}(\mathbf{x})d\mathbf{x} \tag{4}$$

where $f_{\mathbf{x}}(\mathbf{x})$ is the joint probability density function for the n-dimensional vector $\mathbf{X} = \{X_1,....,X_n\}$ of random variables each representing a resistance random variable or a loading random variable acting on the system. These computational and probabilistic methods described herein are also appropriate for other load-resistance or demand-capacity systems, such as geotechnical, mechanical, hydraulic, electrical and electronic systems where performance failure is defined as when a predicted load/demand exceeds a resistance/capacity. For more details on structural reliability theory see Stewart [12], Melchers [13], and Nowak and Collins [14].

While there is considerable work devoted to structural reliability analysis of structural and other load-capacity systems to natural hazards, there is relatively little devoted to impact and shock loading of protective structures. However, there is some recent work on the structural reliability analysis of protective structures (e.g., [15–19]), as well as recent life-cycle and cost-benefit analyses for infrastructure protective measures [8, 9,18 ,20]. If the hazard under consideration is terrorism, then much of this work can be categorised as 'probabilistic terrorism risk assessment' [21].

2.2. FAILURE PROBABILITY

For structural safety assessment, a safe service life is reached when the probability of failure exceeds a target reliability. The Australian and ISO Standards 'General Principles on Reliability of Structures' [1,22] suggest that the lifetime target reliability index (β_T) is 3.1 to 4.3 for ultimate (strength) limit states design. In structures where there is little redundancy a higher target reliability may be selected. Such target values are 'informative' only, as the selection of the target reliability level depends on the different parameters such as type and importance of the structure, possible failure consequences, socio-economic criteria, etc. (e.g., [23]). For example, the Danish Road Directorate [24] provides guidelines for reliability assessment of existing bridges for an ultimate limit state with a high safety class (see Table 1) that are influenced by the mode of failure and the level of warning. Equation (2) can be used to assess the probability of failure where Pr(L|DS) = 1 and the product Pr(DS|H)Pr(L|DS) is obtained from Eqns. (3) and (4). Other failure probability criteria exist for other infrastructure, such as the probability of a ship collision causing fewer than 19 fatalities should be less than 3×10^{-3} accidents/year or 5×10^{-6} accidents/year if 20–200

Table 1. Annual target probabilities of failure for strength (collapse) limit state (24)

Failure with Warning and Bearing Capacity reserve	Failure with Warning but Without Reserve Capacity	Failure Without Warning
10^{-5}	10^{-6}	10^{-7}

fatalities are expected [25]. The later risk acceptance criterion represents societal risk and the risk aversion to accidents causing large loss of life.

2.3. NET BENEFIT (COST-BENEFIT) ASSESSMENT

An approach suitable to optimise CT protective measures is a decision analysis that compares the extra (marginal) costs of protective/CT measures with the extra (marginal) benefits in terms of fatalities and damages averted. The decision problem is then to maximise the net benefit E_b such that:

$$E_b = E(C_B) + \sum_{i=1}^{M}\sum_{j=1}^{N} \Pr(H_i)\Pr(DS|H_i)\Pr(L_j|DS)L_j \frac{R_{i,j}}{100} - C_R \qquad (5)$$

where $E(C_B)$ is the expected benefit from the protective measure not directly related to mitigating the hazard (e.g., employment and economic benefits to local community during bridge strengthening or reduction in criminal behaviour due to enhanced building security), C_R is the extra cost of the protective measure, M is the number of threat scenarios where H_i is the threat or hazard scenario (e.g., i = 1: ship impact, i = 2: vehicle overload, i = 3: earthquake, etc.), L_j is the loss or consequence, N is the number of loss attributes (e.g., j = 1: lives lost, j = 2: physical damage, j = 3: reduction of GDP, etc.), $\Pr(L_j|DS)$ is the conditional probability of loss given occurrence of the damage state assuming no protective measures (e.g., probability of occupant fatality given ship impact or probability of occupant fatality given a terrorist attack), and $R_{i,j}$ is the percentage reduction in risk due to protective measures for the i^{th} threat or hazard and the j^{th} loss attribute. The product $\Pr(L_j|DS)L_j$ refers to the expected loss given the occurrence of a damage state. All consequences need to be given in the same units, which are usually monetary. It is most convenient to consider a time period of one year, such that Eqn. (5) refers to an annual net benefit where costs and benefits are expressed as annual values. A protective measure is viewed as cost-effective if the net benefit exceeds zero. If more than one protective measure is assessed, then the protective measure with the maximum net benefit is the most cost-effective. The cost of protective measures (C_R) might also include opportunity costs such as increased delays due to parking restrictions caused by vehicle barriers or increased stand-off, emergency vehicle access may be delayed, etc.

Equation (5) is a relatively simple expression of expected costs and benefits and can be generalised to also consider multiple protective measures, multi-objective decision criteria, risk aversion, utility theory, discounting of future costs, etc. While more complex models are available, these require more input parameters and assumptions, and given that it is very difficult to know the key parameters in even a simple model the net benefit calculation given by Eqn. (5) is very useful for preliminary risk assessments or risk screening.

If the loss attributes are in units other than cost (such as fatalities) then it may be appropriate to define cost-effectiveness by the marginal (or incremental) cost-effectiveness ratio (CER) defined as:

$$CER = \frac{\text{cost spent on protective measure}}{\text{losses averted by protective measure}} = \frac{C_R}{\sum_{i=1}^{M} \Pr(H_i)\Pr(DS|H_i)\Pr(L|DS)L\frac{R_i}{100}} \qquad (6)$$

For example, if L is expressed as number of fatalities then Eqn. (6) is the estimated cost per life saved.

A cost-benefit analysis is a robust indicator of societal risk acceptability as it considers costs and benefits in a logical and transparent manner. However, results should be interpreted with some flexibility as other non-quantifiable criteria may be important also in judging the overall acceptability of risks (e.g., [2, 26–28]). Past experience shows that it is likely that decisions may be made (or over-ruled) on political, psychological, social, cultural, economic, security or other non-quantifiable grounds. For example, some risks may be deemed unacceptable under any conditions based on morality [29] or based on their symbolic value to society.

2.4. DISCUSSION

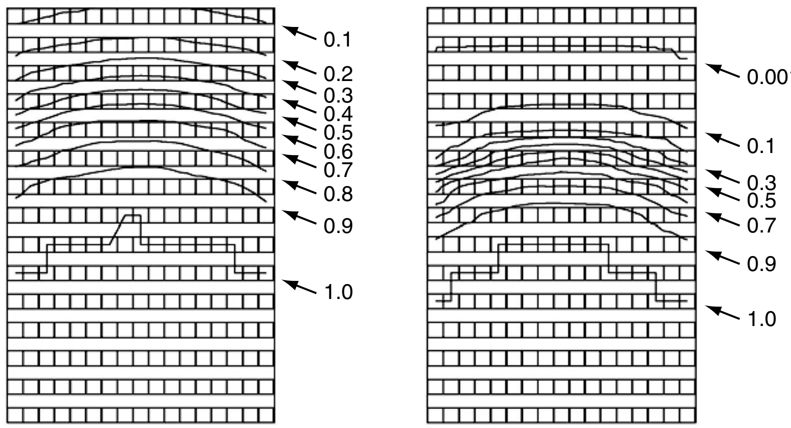
2.4.1. Risk Reduction

The concept of risk reduction needs clarification as there are, in general, numerous risk mitigating measures in the existing item of infrastructure, and normally several protective measures can be proposed for additional risk reduction. In this paper, the percentage risk reduction (R) is the additional risk reduction achieved by the presence of the protective measure when compared to the overall risk reductions achieved by the presence, absence and/or effectiveness of all protective measures. If predictive resistance, load and threat probabilistic models are available then probabilistic risk assessment is useful for assessing risk reductions. For example, consider the CT protective measure of installing fully tempered glazing for a typical 15 storey commercial building where the main safety hazard to building occupants is assumed to arise from glass fragments. The facade comprises 2 m × 2 m windows and according to Australian glazing design an acceptable design solution for wind loading is either 10 mm annealed glass or 8 mm fully tempered glass. A computational tool "Blast-RF" (Blast Risks for Facades) that undertakes a probabilistic risk assessment procedure is used to predict glazing safety hazard risks [30]. The reliability analysis considers the variability of explosive material energetic output, glazing stress limit, fragment drag coefficient, glazing dimensions, stand-off distance and explosive weight to calculate probabilities of glazing safety hazards. The threat scenario is a 100 kg VBIED at a stand-off of 10 m directly in front of the building. The results from Blast-RF are shown as High Safety Hazard risk contours, see Figure 1. Across the whole facade, the average High Safety Hazard risk is 0.79 for the 10 mm annealed glazing, as compared to 0.63 for the 8 mm fully tempered glazing; i.e., a 20% reduction in risk. As there is a close correlation between a High Safety Hazard rating and extremely serious, if not fatal, wounds then 8 mm fully tempered glazing would reduce fatality risks by 20%. If no other CT protective measures were adopted then risk reduction for this situation is R = 20%.

While there are many advantages to probabilistic and reliability analyses for calculating risk reductions, they are not always sufficient, particularly for the 'new hazard' of terrorism. Hence, as is the case with any risk analysis of a complex system, information about risk reductions may be inferred from expert opinions, scenario analysis, statistical analysis of prior performance data, system modelling as well as probabilistic and reliability analysis.

2.4.2. Value of Life, Risk Aversion and Other Issues

One of the more contentious issues associated with cost-benefit analyses is how to place a monetary value on human life, often referred to as the value of a statistical life (VSL). Paté-Cornell [26] suggests that a cost per life saved of $2 million or less is appropriate for current practice, and the United States Department of Transport adopts a figure of $3 million [31]. For most activities a VSL not exceeding $1–$10 million is typical for most U.S. federal agencies as this provides a reasonably accurate reflection of societal considerations of risk



(a) 10 *mm Annealed glazing* (b) 8 *mm Fully tempered glazing*

Figure 1. Risk contours for high safety hazards to 15 storey building facade (30)

acceptability and willingness to pay to save a life [31]. More recently, Robinson [32] in a report for the DHS concluded that $6.3 million is the best VSL estimate for homeland security regulatory analysis. This VSL is appropriate also for many other low probability - high consequence events associated with the design and assessment of protective structures. As most VSL studies generally focus on relatively common risks (e.g., workplace or motor vehicle accidents), then Robinson [32] comments that 'more involuntary, uncontrollable, and dread risks may be assigned a value that is perhaps twice that of more familiar risks' and so Robinson [32] recommends a doubling of VSL estimates in a sensitivity analyses, which is essentially a measure to include risk aversion in cost benefit analyses. In the present paper, a VSL of $6.3 million (in 2009 U.S. dollars) is adopted, and double that value ($12.6 million) will be used in a sensitivity analysis.

Society tends to spend more money per life saved for efforts to prevent death from 'dread' type risks such as exposure to asbestos and arsenic than for some efforts to prevent death from more mundane activities such as driving a motor vehicle. This is often a function of psychological and political aspects of risk perception [33]. While it is understandable that many individuals will be risk averse, governments need to be risk neutral (i.e., use expected values) and distribute risk reduction funds in a consistent and equitable manner in order to achieve the best outcomes (risk reduction) for society as a whole. The reason for being risk averse is that the events involving high consequences often are associated with 'follow-on' events which themselves may contribute significantly to the risk [11]. The follow-on consequences for many natural and man-made hazards may cause a significant loss of employment and business transactions, reduced government/tax revenue, etc. All such 'follow-on' consequences should be included in the estimation of losses (L) which will lead to a 'risk neutral' risk analysis. Nevertheless, utility theory can be used if the decision maker wishes to explicitly factor risk aversion into the decision process (e.g., [34]).

There are many more issues associated with cost-benefit and decision analyses, issues which cannot all be covered in this paper. The field of cost-benefit analysis is one that encompasses technical (economics, finance, probability, reliability), social (political, psychological, cultural) and other multidisciplinary fields. The influence of all these fields to decision support is well described in the literature (e.g., [34–36]).

3. ILLUSTRATIVE EXAMPLES

To illustrate the application of risk acceptance criteria to the risk and cost-benefit assessment for the protection of infrastructure systems, this section describes risk and cost-benefit assessment for the following infrastructure systems:

(i) bridge subject to ship impact, and

(ii) institutional building subject to terrorist VBIED.

To be sure, the illustrative examples, where possible, use actual or representative threat, consequence and cost data. However, some hypothetical data is used (particularly when dealing with terrorist threats) as the intention of the examples is to show the methodology of various risk acceptance criteria and not to make any definitive conclusions about a specific item of infrastructure.

3.1. BRIDGE PROTECTION FROM SHIP IMPACT

Bridges that cross rivers and harbours are vulnerable to ship impact (e.g., [25]). This is particularly the case for historic (older) bridges over inland waterways, that although many were originally designed for ship impact, the dramatic increase in ship dead weight loads and the increasing speed of inland ships may result in bridge failure in the event of ship impact [37]. In Germany the mean mass of inland ships has doubled over the past 30 years with a breadth of up to 12 m - this all suggests that the probability and consequences of ship impact are increasing. This illustrative example is based on the results of the structural reliability and probabilistic analysis of ship impact on a historic inland river bridge in Germany described by Proske and Curbach[37]. The intention of this example is to assess if current risks of ship impact are acceptable and if strengthening (protective) measures are cost-effective.

The probability of ship impact Pr(H) ranges from 0.0088 to 1.76 per bridge per year for German and European waterways. The number of fatalities as a result of bridge failures due to ship collisions varies from 1 to 176 [38]. The bridge considered herein is representative of historic German bridges with steel superstructure over inland waterways. The bridge has main beam spans of 39 m, has natural stone piers, and has been hit by ships in recent years - see Figure 2. Table 2 summarises results of the structural reliability analysis [37] that shows the probability of front impact Pr(H), probability of structural collapse given ship impact Pr(DS|H), risk reduction R, and probability of collapse Pr(collapse) for three proposed protective measures: (i) pier impact fender system, (ii) size of pier increased by factor of 2.3, and (iii) tensile strength of pier increased by a factor of 2 (based on a hypothetical material).

3.1.1. Fatality Risks

The average number of fatalities for road bridge failures caused by ship impact is approximately 10 people [37]. However, the probability of loss of life Pr(L|DS) will be less than one as not all vehicle occupants on a collapsed bridge will be killed. For example, the I35W bridge collapse in Minneapolis in 2007 killed 13 people, but it is estimated that 100 vehicles were on the bridge at the time of collapse. If it is estimated that the number of people exposed to the hazard is 50 then Pr(L|DS) is 10/50 = 0.2. The annual fatality risk for the existing bridge is calculated from Eqn. (2) as 1×10^{-3} fatalities/year. This is well above the risk acceptance criterion of 1×10^{-6} fatalities/year as described in Section 2.1, and so would suggest that life safety risks to bridge users is 'unacceptably high'. The adoption of protective measures reduces the annual fatality risks such that they range between 1.4×10^{-4} to 4.9×10^{-6} which are in the range of 10^{-3} – 10^{-6} fatalities/year and so according to Section 2.1 'are generally acceptable if the benefits outweigh the risks to provide an economic or social justification of the risk'. There is therefore a need to conduct a cost-benefit assessment to assess if the benefits outweigh the risks, and this is undertaken in Section 3.1.3.

Figure 2. Bridge over inland waterway (37)

Table 2. Probabilities of bridge performance and risk reduction for protective measures (adapted from proske and curbach[37])

	Pr(impact per year) Pr(H)	Pr(collapse| impact) Pr(DS|H)	Risk Reduction R	Pr (collapse) p_f
Existing Bridge	0.016	0.3137	–	5.02×10^{-3}
Protective Measure:				
Impact Fender System	0.016	0.0015	99.5%	2.46×10^{-5}
Increased Pier Size	0.016	0.0118	96.2%	1.90×10^{-4}
Increased Tension Strength	0.016	0.0432	86.2%	6.91×10^{-4}

Note that this type of risk acceptance metric makes no consideration of consequences other than fatalities. For instance, collapse of a bridge would cause significant user delays for vehicular traffic diversions and closure of the river to commercial and tourist shipping, that each would have flow-on effects to the economy and other economic and social impacts. This analysis also does not consider fatalities to those onboard a ship, which may be considerable.

3.1.2. Failure Probability

Table 1 shows that an acceptable probability of failure Pr(H) × Pr(DS|H) for bridge collapse without warning is 10^{-7} per year. If there is bridge failure with warning then the acceptable probability of failure reduces to 10^{-5} or 10^{-6} per year. Table 2 shows that the predicted probability of failure of the existing bridge is 5.02×10^{-3} per year. This well in excess of the DRD[24] guideline (see Table 1), as well as the Larsen[25] guideline of 3×10^{-3} accidents/year, and would suggest that bridge strengthening is required. However, although the proposed protective measures reduce the probability of failure considerably, even these reduced failure probabilities are still higher than the maximum allowable DRD failure probability of 10^{-5} per year. The risk acceptance criteria developed by the Danish Road Directorate suggests that the failure risks are high and need to be reduced, but these are only guidelines that recognise that there are socio-economic considerations that need to be considered before embarking on costly and disruptive protective measures. The following section will now consider the cost-effectiveness of bridge protective measures.

3.1.3. Net Benefit

Two types of loss attributes (N = 2: direct physical damage and fatalities) are considered. It is assumed that the benefit of bridge protective measures does not extend beyond their ability to reduce the probability of bridge collapse ($C_B = 0$). As there is only one hazard scenario then the net benefit given in Eqn. (5) is re-expressed for this example as

$$E_b = \Pr(H)\Pr(DS|H)\frac{R}{100}\left[\Pr(L_1|DS)L_1 + \Pr(L_2|DS)(L_2 \times C_{life})\right] - C_R \quad (7)$$

where L_1 is the direct and indirect costs of physical damage (bridge replacement, user delay), L_2 is the number of people exposed to the hazard (vehicle occupants), and C_{life} is the value of a single life (VSL) expressed in monetary units. As discussed in Section 3.1.1, the average number of fatalities $\Pr(L_2|DS)L_2$ is 10 people and we take C_{life} = \$6.3 million. Let us assume that a ship impact will collapse the bridge so $\Pr(L_1|DS) = 1$ and the replacement value for a multispan bridge crossing an inland river is \$60 million. User delay costs for a bridge under construction can total \$430,000 per day, which even for a rapid bridge replacement for a failed bridge in Oklahoma of only 46 days reconstruction will amount to nearly \$20 million [39]. If user delay costs are considered then L_1 = \$80 million. If net benefit is to exceed zero then Eqn. (7) can be used to determine the maximum annual protective costs (C_R) for bridge strengthening to be cost-effective. In this case the maximum amount that should be spent on protective measures to be cost-effective is shown in Table 3. If this annual expenditure is discounted at 4% pa then the net present value cost is also shown in Table 3 for a 25 year remaining service life.

The results show that the higher the risk reduction the greater the amount that can be spent on protective measures whilst still being cost-effective. The present value of such maximum expenditure is considerable and so it is expected, for example, that installing an impact fender system would cost considerably less than \$54.9 million. If it is assumed that the value of a human life should double to C_{life} = \$12.6 million then maximum expenditure for a protective measure to be cost-effective increases to \$79.1 million for installing an impact fender system. On the other hand, if the risk reduction for an impact fender system is only 50%, then the maximum expenditure for a protective measure to be cost-effective reduces to \$27.6 million.

If it is assumed that the cost of installing an impact fender system is \$250,000 per year then Eqn. (6) shows that the cost spent per life saved is \$5 million per life saved. This is slightly below the VSL of \$6.3 million used herein and so would be seen as an effective risk reduction expenditure. This criterion, however, may lead to conservative outcomes as it fails to account for factors other than lives saved. However, if net benefit is considered then

Table 3. Maximum expenditure for protective measure to be cost-effective

	Maximum Cost of Protective Measure (per year)	**Maximum Cost of Protective Measure over 25 years**
Protective Measure:		
Impact Fender System	\$714,086	\$54.9 million
Increased Pier Size	\$690,402	\$53.1 million
Increased Tension Strength	\$618,635	\$47.6 million

Eqn. (7) shows that $1 of cost yields $2.86 in benefits which is another way of showing that installing an impact fender system for $250,000 per year is cost-effective.

3.2. BUILDING PROTECTION FROM TERRORISM (VBIED)

A typical multi-storey building for which occupancy and loss data are available is an academic building located at the U.S. Naval Postgraduate School in Monterey, California [40]. In this case, measures to protect the building from VBIED and other explosive blast loads include strengthening perimeter columns and walls, blast-resistant glazing and other improvements to structurally harden the building.

Many uncertainties exist in quantifying risks, particularly for threats such as terrorism. While the bridge protection example used single-point estimates for parameter values, this section will represent threat, damage and loss parameters as random variables that explicitly consider aleatory and epistemic uncertainties. Moreover, in most cases the example will focus on the minimum (threshold) threat probability needed for risks to be acceptable or CT protective measures to be cost-effective.

Three threat scenarios are assumed to cover i = 1: low, i = 2: medium and i = 3: high terrorist threats, and two types of loss attributes j = 1: direct physical damage and j = 2: fatalities. A low threat may be a VBIED with low explosive weight or large stand-off, whereas medium or high threats would involve, for example, larger VBIED explosive weights and reduced stand-off. It is assumed that the threat probability $\Pr(H_i)$ is the product of probability of a terrorist attack (p_{attack}) and the relative threat probability given an attack $\Pr(H_i|\text{attack})$. It is assumed that $\Pr(H_i|\text{attack})$ reduces as the threat level increases due to reduced likelihood of conducting such an attack undetected as the size of vehicle increases or as the vehicle moves closer to the target building, see Table 4. Stewart[9] has shown that the probability of building occupant fatality given a terrorist attack $\Pr(L_2|H_i)$ varies from 0.0003 to 0.45 and so $\Pr(L_2|H_i)$ is assumed relatively low for low and medium threats, and is unlikely to reach above 0.5 even for a high threat. This example does not consider the risk and safety of people outside the building (such as pedestrians).

Although a small VBIED or IED can cause low casualties, the effect on physical damages can be much higher as although a VBIED may not totally destroy a building, it will often need to be demolished and replaced, hence the probability of physical damage is high even for a medium threat. As there is uncertainty about these threat and loss probabilities then they are treated as random variables and Table 4 shows their assumed statistical parameters and probability distributions. Note that a coefficient of variation (COV) of 0.25 represents a 95% confidence interval of approximately ± 50% about the mean value.

Table 4. Probabilistic models for hypothetical threats and losses

	Relative Threat Probability	Probability of Physical Damage $\Pr(L_1\|H_i)$			Probability of Fatalities $\Pr(L_2\|H_i)$		
Threat	**$\Pr(H_i\|\text{attack})$**	**mean**	**COV**	**Distribution**	**mean**	**COV**	**Distribution**
i = 1 Low	0.6	0.25	0.1	Lognormal	0.1	0.25	Lognormal
i = 2 Medium	0.3	0.80	0.1	Lognormal	0.25	0.25	Lognormal
i = 3 High	0.1	1.0	-	-	0.5	0.25	Lognormal

Note: probability distributions censored at 0.0 and 1.0

Table 5. Probabilistic models for hypothetical risk reduction

	Risk Reduction R_i		
Threat	**mean**	**COV**	**Distribution**
i = 1 Low	90%	0.064	Uniform [80–100]
i = 2 Medium	65%	0.089	Uniform [55–75]
i = 3 High	50%	0.115	Uniform [40–60]

Significant strengthening of a building is likely to reduce damage and fatality levels to near zero for low threat events, however, even a significantly strengthened structure can experience damage and casualties if the threat is high, such as a 1,000 kg TNT VBIED at a stand-off of 2 m from a critical supporting column. It follows that risk reduction will reduce, perhaps marginally, as the size of the threat increases. Risk reductions are also modelled as random variables, see Table 5, where it is assumed that the risk reduction is accurate to ± 10%.

3.2.1. Fatality Risks

The annual fatality risk given by Eqn. (2) can be re-written as:

$$\Pr(L) = p_{attack} \sum_{i=1}^{3} \frac{(100 - R_i)}{100} \Pr(H_i | attack) \Pr(L_2 | H_i) \quad \text{where} \quad \sum_{i=1}^{3} \Pr(H_i | attack) = 1.0 \quad (8)$$

where p_{attack} is the annual probability of a successful terrorist attack assuming no protective measures, the probability of loss given the hazard $\Pr(L_i|H)$ is the product of $\Pr(DS|H)$ and $\Pr(L|DS)$, and $\Pr(L_2|H_i)$ is the probability of building occupant fatality given a terrorist attack. A Monte-Carlo simulation analysis is used to solve Eqn. (8) where random variables R_i and $\Pr(L_2|H_i)$ and deterministic variable $\Pr(H_i|attack)$ are given in Tables 4 and 5. The outcomes of the simulation analysis are the mean and lower (5th percentile) and upper (95th percentile) annual fatality risks as a function of attack probability, see Figure 3. Figure 3 shows that the annual attack probability needs to be less than 1.6×10^{-5}/building/year for there to be 95% confidence that the annual fatality risks are below the target value of 10^{-6} fatalities/year (i.e. upper bound fatality risk less than 10^{-6}) and so deemed negligible. Ellingwood[41] suggests that the minimum attack probability be at least 10^{-4}/building/year for high density occupancies, key governmental and international institutions, monumental or iconic buildings or other critical facilities with a specific threat. It should be noted that although the probability of a terrorist attack may be high, the probability that any particular item of infrastructure will be attacked is very low. If the annual attack probability is 10^{-4}/building/year then the mean annual fatality risk is 3×10^{-6} fatalities/year, but the upper bound is higher at 6.5×10^{-6} fatalities/year and so these risks would only be acceptable only if the benefits were shown to outweigh the costs (E_b>0). Section 3.2.3 will assess net benefit to help address this issue.

3.2.2. Failure Probability

If the probability of damage is taken as 'failure' then Monte-Carlo simulation analysis of Eqn. (2) where $\Pr(DS|H) \times \Pr(L|DS) = \Pr(L_1|H)$ shows that the mean probability of failure Pr(L) is approximately $0.15p_{attack}$. Clearly the attack probability needs to be less

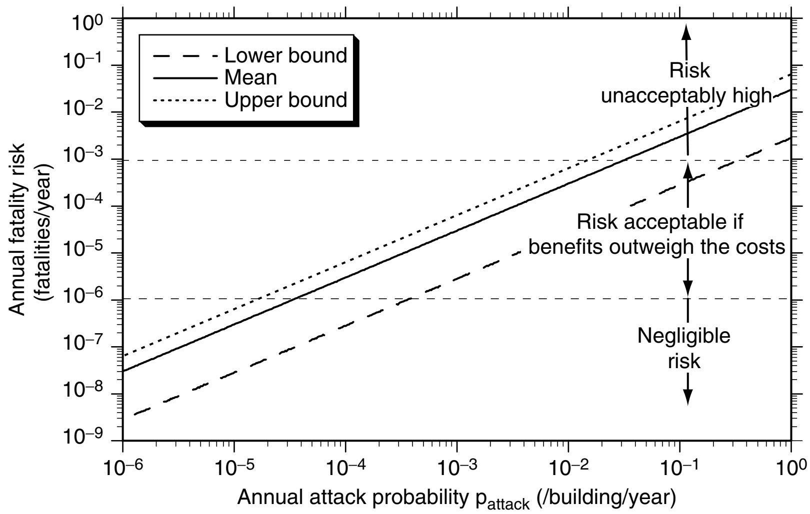


Figure 3. Annual fatality risk as function of attack probability, institutional building

than 6.7×10^{-5}/building/year for the probability of failure to be below the maximum target reliability recommended by DRD[24] - see Table 1.

3.2.3. Net Benefit

The net benefit given in Eqn. (5) is re-expressed for this example as

$$E_b = p_{attack} \sum_{i=1}^{3} \Pr\left(H_i \middle| attack\right) \frac{R_i}{100} \left[\Pr\left(L_1 \middle| H_i\right) L_1 + \Pr\left(L_2 \middle| H_i\right)\left(L_2 \times C_{life}\right) \right] - C_R$$
$$\text{where } \sum_{i=1}^{3} \Pr(H_i | attack) = 1.0 \tag{9}$$

where L_1 is the cost of direct physical damage (building replacement, damage to contents), L_2 is the number of people exposed to the hazard (building occupants), C_{life} is the value of a single life (VSL) expressed in monetary units, and R_i is the percentage reduction in risk due to CT protective measures for the i^{th} threat. As with the first example, we assume that $C_B = 0$. However, public awareness of enhanced security measures may mean a greater willingness to use the infrastructure leading to tangible direct and indirect benefits to the asset owner and society, and in principle such benefits could be included in a net benefit assessment.

The replacement value of the building is \$20.7 million (in 2009 dollars) and value of contents is \$8.3 million [40]. Demolition costs can be substantial, as can design and utilities re-installation costs – these costs are assumed as 25% of the replacement value of the building. Hence, the cost of physical damages is approximately L_1 = \$35 million. These costs could be inflated significantly if relocation costs, staff and student interruption costs, etc. are considered. There is more certainty about damage losses so L_1 is modelled as a normal distribution with mean = \$35 million and COV = 0.05.

The academic building is sizeable, with offices and teaching space, and peak usage comprising 319 building occupants [40]. To maximise the impact of a terrorist attack, an attack would most likely occur at a time of high building occupancy, so it is assumed herein that the number of occupants (L_2) is modelled as a normal distribution with mean = 250 people and COV = 0.17 so that there is a 10% probability than occupancy will be higher than 319 occupants in the event of a terrorist attack.

A literature review by Stewart [9] found that the minimum cost of protective measures (C_R) needed for substantial risk reduction for an existing building is at least 10% of building costs. If we assume that the budget time period for providing protective measures to the building is five years, then if the 10% increase in costs is annualised over five years with a discount rate of 3% then this equates to a present value cost of 2.18% per year. If initial building cost is \$20.7 million then the minimum annual cost of CT protective measures needed for substantial risk reduction is $C_R = 2.18\% \approx \$450{,}000$ pa.

Net benefit is calculated from Eqn. (9) using Monte-Carlo simulation analysis for a range of attack probabilities. Figure 4 shows the simulation histogram of net benefit for three attack probabilities: $p_{attack} = 10^{-2}$, 10^{-3} and 10^{-4} /building/year. As there is random variability with many of the input parameters then net benefit is variable as shown in Figure 4. With reference to Figure 4 it is clear that if $p_{attack} = 10^{-2}$/building/year then there is near 100% confidence that the net benefit is positive so near 100% sure that the protective measures are cost-effective. On the other hand, if $p_{attack} = 10^{-4}$/building/year then there is near 100% certainty that protective measures are not cost-effective. If $p_{attack} = 10^{-3}$/building/year then Figure 4 shows that there is only a 35% probability that protective measures are cost-effective (i.e., $\Pr(E_b)>0$). Figure 5 shows another way to present results and this shows the mean and lower and upper bounds (5th and 95th percentiles) of net benefit for various attack probabilities. It is clear that when the attack probability is very high the net benefit can be tens of millions of dollars. The threshold threat probability is 5.6×10^{-4}/building/year (mean $E_b = 0$) so if an attack probability exceeds this threshold value then the protective measure is

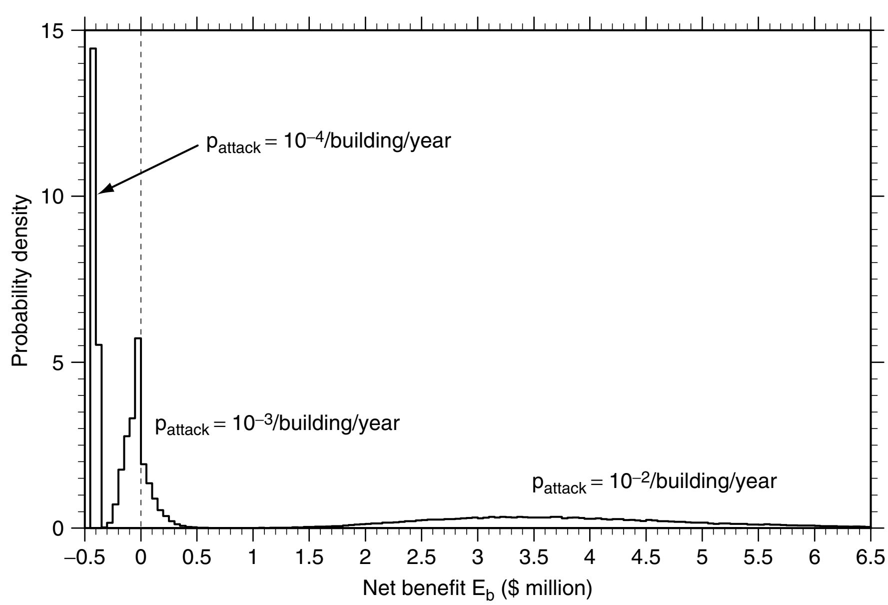


Figure 4. Histograms of annual net benefit (Eb) for institutional building, for attack probabilities of 10^{-2}, 10^{-3} and 10^{-4} per year

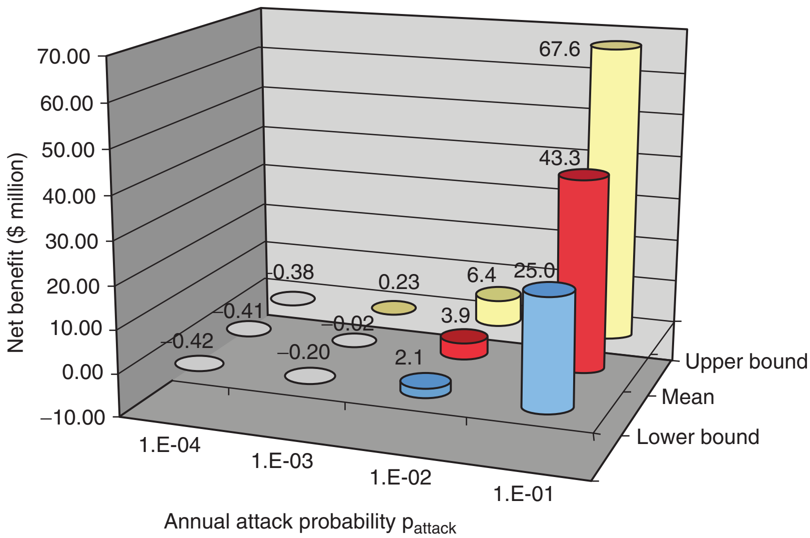


Figure 5. Annual net benefit (E_b) for institutional building

likely to be cost-effective. Clearly, due to the uncertainties inherent in such an analysis, a sensitivity analysis is recommended.

If risk reduction for protective measures increases then net benefit increases resulting in a slight decrease in threshold threat probability. Doubling the cost of physical damages (or increasing $Pr(L_1|H_i)$ has a negligible effect on net benefit, which illustrates that in this situation the expected losses are dominated by loss of life and not physical damage. Hence, if occupant numbers (or $Pr(L_2|H_i)$ or value of life) reduces then the benefits in terms of lives saved are reduced and a decrease in net benefit results in an increase in threshold threat probability. However, if value of life doubles (or number of occupants doubles), then there is an increase in net benefit and so the threshold threat probability reduces. A higher cost of protective measures means that net benefits decrease causing the threshold threat probability to increase. If the expected benefit from CT protective measures not directly related to mitigating terrorist threats $E(C_B)$ is included then the threshold probability will reduce.

3.3. DISCUSSION

In addition to the benefits of quantifying costs and benefits for decision support, the process of undertaking a safety and cost-benefit assessment, in a structured and methodical manner, will lead to a better understanding of the design and assessment of protective structures. Thus a risk assessment gives a better appreciation of how one or more protective measures fit within the overall ‘system’. This can often lead to new insights into the performance of protective measures, as well as inefficiencies.

To be sure, a number of other metrics can be used to assess safety and compare costs and benefits and the methods described herein provide relatively straightforward approaches, that over time, can be refined and improved to allow for more meaningful decision support about the acceptability of existing risks and the cost-effectiveness of risk mitigation strategies for the design and assessment of new and existing protective structures. While quantitative decision support tools hold some appeal to decision-makers, they cannot capture the full and diverse range of societal considerations of risk acceptability. This is why probabilistic risk assessment methods should be viewed only as an aid to decision support, where decisions about public safety will often require social, economic, cultural, environmental, political and other considerations, many of which are not quantifiable.

4. CONCLUSIONS

This paper presented risk-based approaches to assessing the safety and cost-effectiveness of protective measures for infrastructure. The paper reviewed three risk acceptance criteria based on fatality risks, failure probabilities and net benefit assessment which can be applied to any item of infrastructure subject to man-made or natural hazards. Illustrative examples of a bridge subject to the hazard of ship impact and building subject to terrorist attack showed under what combination of risk reduction, and fatality and damage costs the fatality and failure risks would be acceptable, and when protective measures would be cost-effective. The benefits of quantifying costs and benefits of protective measures for decision support also include the ability to reveal inefficiencies and suggest where resources may be better allocated to maximise public safety.

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