Extreme Event Scenarios for Planning of Infrastructure Projects

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Abstract: In project planning, several design concepts are considered to examine the potential to lower the lifecycle costs of the structure without sacrificing significant performance. Various natures of unusual and extreme events should be considered, and the nature and frequencies of such events may not yet be known. In addition, the details of design alternatives in early feasibility stages may not yet be specified. The identification of multiple stakeholders (e.g., local, regional, and national interests) may not be complete. A cost-benefit analysis would require complete knowledge of design alternatives, event frequencies and impacts, and stakeholders. A process is developed in this work to explore the costs and performance of preliminary design concepts for infrastructure projects that are vulnerable to several extreme events that would have an impact to multiple stakeholders. An example with inland navigation lock walls subjected to barge impacts and earthquake loads is provided. Complementary performance metrics that are applied include repair cost, time to recover, and cost to industry. Several magnitudes and frequencies of event scenarios are characterized, and some relevant features of a software tool developed for preliminary design evaluation of navigation lock walls are described.

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Introduction

Many rivers have been made navigable by requiring infrastructure improvements that include the building of locks and dams in conjunction with the dredging of a channel to a required depth for navigation. In particular, a typical navigation lock and dam, as shown in Fig. 1, supports the transit of material and goods between the navigable pools of the river system. At each dam, a lock chamber enables commercial and recreational river traffic to economically and safely transit from one navigation pool to the next. Guide or guard walls extend beyond the lock chamber wall to assist and guide barges as they enter and exit the chamber. In the United States, the U.S. Army Corps of Engineers (USACE) has been charged to construct, maintain, and operate navigation locks and dams that are subject to diverse design circumstances including both natural and man-made hazards. Extreme events, i.e., events that could cause a catastrophic failure but typically have a small likelihood of occurring, are taken into account in the design of these structures. Two important extreme events faced by lock walls are barge impact and earthquake loads. Heavy, cargo-loaded barges can impact and damage guide and guard walls as they approach the lock chamber. The likelihood of an extreme barge impact event increases with poor weather conditions and higher flow rates in the river. Planners also consider the susceptibility of the design of lock wall to earthquake ground motions that can potentially damage the entire structure during an extreme event. Other extreme events to which navigation structures may be vulnerable include severe floods, operation and maintenance errors, and possible terrorist bombing.

Preliminary design of a major infrastructure project involves (1) a goal and objectives for the infrastructure component, leading to system requirements, and (2) general ideas or concepts for design implementation. In exploring system requirements and implementation, there needs to be some understanding of extreme events with the potential impacts to the infrastructure. The relevant questions for preliminary design of infrastructure systems include (1) What type of extreme events (barge collision, earthquake, bombing) could occur? (2) What are the frequencies of occurrence (e.g., return periods) of the extreme events? (3) What should be the performance of the project subject to various magnitudes (collision forces, earthquake loads, and explosive loads) of extreme events? (4) What preliminary design concepts are deserving of further study, including the development of design alternatives? (5) Who are the stakeholders, what is the scope (local, regional, national) of a risk-cost-benefit analysis, and what are the associated measures of performance? (6) What will be the critical or driving parameters of the risk-cost-benefit analysis, including uncertainties and sensitivities? Fig. 2 illustrates that extreme-events scenarios and stakeholder perspectives can influence and be influenced by the definition of requirements and the preliminary evaluation of infrastructure design concepts. The aim of this work is a methodology to compare preliminary design concepts for civil infrastructure projects that are vulnerable to extreme events and subject to multiple stakeholder perspectives.

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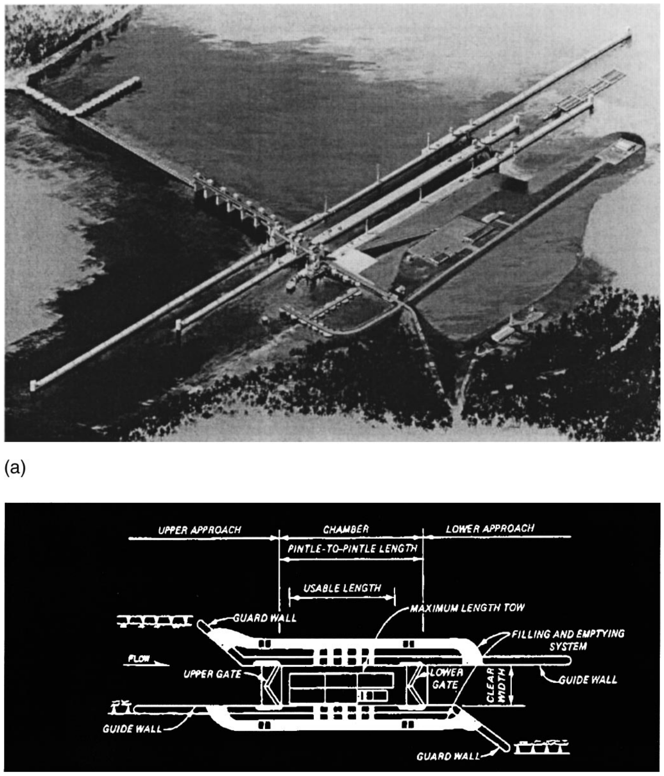

Fig. 1. (a) Aerial view of navigation dam, lock, and lock walls and dam (U.S. Army Corps of Engineers); (b) Plan view of a lock, which is vulnerable to barge collisions and earthquake loads and is important from a variety of stakeholder perspectives (McCartney et al. 1998).

Background

Benefit-cost analysis for infrastructure systems is discussed by Loucks et al. (1981) and Taylor et al. (1992). Loucks et al. (1981) describe the challenges of benefit-cost analysis including how to tie noncommensurate benefits and costs together as well as how to characterize needed benefits. Loucks et al. (1981) show that it is important that monetary value (i.e., price) reflects social values of the item under consideration.

Pomerol and Barba-Romero (2000) describe multicriteria decision making. Sage and Rouse (1999) and Patterson (1999) describe systems engineering, management, and life cycle costs for infrastructure components. Gibson (1991) gives a systems methodology for problem solving in which decision criteria are set before considering design alternatives. The design for multiple failure modes has been addressed by many, including Ellingwood (1995) and Ang and Tang (1984). Identifying multiple failure modes and estimating failure probabilities are detailed by Ang and Tang (1984). Heaney et al. (2000) and Chang and Shinozuka (1996) describe that natural hazards need be to better addressed in life-cycle cost evaluation of infrastructure systems.

Lowrance (1976) defines *risk* as a measure of the probability and severity of adverse effects. Kaplan and Garrick (1981) add to the basic definition by asking three questions: (1) What can happen? (*i.e.*, What can go wrong?) (2) How likely is it to happen? (3) If it does happen, what are the consequences? Haimes (1991) explains risk management by asking a complementary set of questions: (1) What can be done (*i.e.*, What options are available?) (2) What are the associated tradeoffs between the options in terms of cost, benefit, and risks? (3) What are the future impacts of current management decisions on future options? There are various complementary definitions of risk, risk assessment, and risk management for engineering systems (e.g., Diewald 1987).

Economic analyses for the USACE concerning inland navigation infrastructure waterways have employed risk analysis (Moser 1996). These efforts started with simple calculations of the expected annual flood damage as the area under a flood damage frequency curve. The USACE had been designing its navigation infrastructure to meet strict engineering standards and safety guidelines. These standards have helped to prevent damage by extreme events such as floods and earthquakes. Diewald (1987) describes some merits and disadvantages of standards-based design. Moser (1996) shows that the USACE has begun to explicitly integrate risk analysis methods into their decision making for infrastructure projects since about 1986. Recent works by the USACE show their adoption of risk analysis methodologies into their design process (Institute 1992; Institute 1990; USACE 1996). Walker (1998) discusses the advantage of using probabilistic-based methods over deterministic standards-based methods for evaluating potential USACE projects, such as the ability to predict likelihood of component failure. Yoe (1989) describes inherent uncertainties in economic and engineering analyses, motivating the consideration of tradeoffs between project cost and risk cost. Moser and Stakhiv (1989) emphasize accounting for costs over the lifespan of a project when performing a benefit-cost analysis and suggest how to treat nonmonetized considerations such as environmental concerns and human health and safety. Taylor et al. (1992) survey methodologies for benefit-cost analysis, including methods to obtain probabilities when historical data are unavailable.

Walker (1998) underscores benefit-cost analysis to determine the value of maintaining a reliable inland navigation system. Ellingwood (1995) has analyzed the probabilities of coincident failure modes occurring at a navigation lock, considering pairs of coincident failure modes including operating loads and wind, operating loads and earthquakes, operating loads and barge impact, earthquake and barge impact, and earthquake and flood. Beim and Hobbs (1997) used event trees to estimate the frequency of a lock failure caused by a vessel or railroad collision, eliciting subjective probabilities for the events. Beim and Hobbs (1997) demonstrate the usefulness of an event tree to model the possible paths to failure. They also demonstrate the use of subjective probabilities from expert elicitation to complement historical data.

The USACE has commissioned studies of barge impact loads on the walls at the Marmet Lock (Patev 2000) and at the Winfield Lock (Glosten 1995). Patev (2000) has performed probabilistic barge impact analysis (PBIA) to calculate the maximum barge

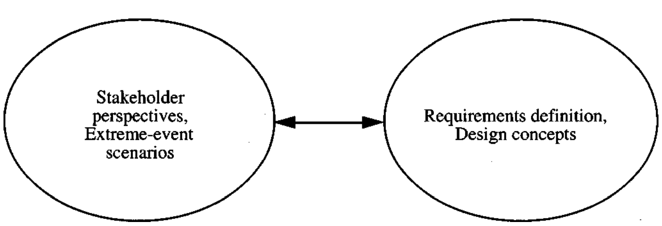

Fig. 2. Extreme events and stakeholder perspectives influence and are influenced by requirements definition and design concepts in early stages of design life cycle

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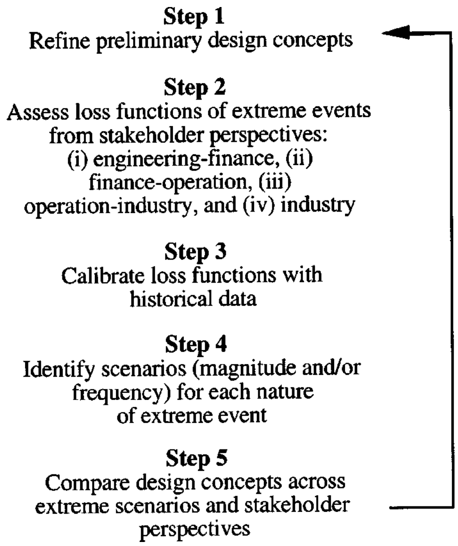

Fig. 3. Methodology for using extreme-event scenarios and stakeholder perspectives in the comparison of design concepts

impact loads associated with specific return periods for lock wall structures using probabilistic values for impact velocity, angles, and tow mass. Patev (2000) examines the impact loads for three levels of events: usual, unusual, and extreme events. Each scenario level had return periods for impact loads in the range of 5, 50, and 1,000 years, respectively. The USACE design guidance engineering manual, (USACE 1999) defines probabilistic seismic hazard analysis and return periods for navigation infrastructure. Green and Hall (1997) and Lindbergh et al. (1997) describe some applications of probabilistic seismic hazard analysis.

In the above context, there is the opportunity for the current work to provide for the screening of preliminary design concepts, specifically when there is evolving knowledge of system requirements, design alternatives, failure modes, stakeholder perspectives, and extreme-event scenarios. Tsang et al. (2002) and Tsang (2001) address the design and demonstration of a related case study and software tool supporting the direction of the current effort. Lambert (2001) gives some additional background relevant to the current work.

Methodology

Steps to explore design concepts in terms of extreme-event scenarios and stakeholder perspectives are shown in Fig. 3. In a first step, preliminary design concepts are generated. The second step develops performance functions for the infrastructure components that are subjected to extreme events and are identified from several stakeholder perspectives. The third step ensures that the assessed functions are consistent with the historical data. The fourth step develops scenarios for each nature of the extreme event being considered. Finally, the planners compare the design concepts from the combined perspectives of several levels and magnitudes of extreme events and stakeholder perspectives. If design concepts are not yet differentiated, the analyst repeats the steps with a new set of concepts and/or scenarios and/or stakeholder perspectives. The steps are described in detail below using an example to compare preliminary concepts for lock walls that may be vulnerable to barge impacts and earthquakes and that are associated with several stakeholder perspectives.

Step 1: Identify Preliminary Design Concepts

Estimated construction costs and nominal design loads are used to characterize each design concept. A design concept may have a design load (the smallest load beyond which the structure will fail) for each of several natures of extreme event: a barge impact of 4,000 kN and an earthquake load of 1.0 g. Table 1 shows three preliminary design concepts being considered (concept 1, a pontoon with a 9.14-m diameter; concept 2, a drilled-shaft design; concept 3, a pontoon with a 15.24-m diameter) and their associated barge impact and earthquake design loads and construction costs.

Step 2: Assess Loss Functions of Extreme Events from Stakeholder Perspectives

Loss functions (*e.g.*, repair cost, ratio of repair cost to reconstruction cost, time to recover, and cost to industry) are assessed through a series of questions to infrastructure experts and through derivation using data on cost of reconstruction and on the cost to industry for delays. The questions to determine repair cost as a loss function is as follows:

- For each design concept, what is the greatest magnitude of the extreme event that results in no repair costs?
- For each design concept, what is the repair cost for a magnitude of the extreme event equal to the design load?
- For each design concept, what is the least magnitude of the extreme event that results in a repair cost equal to the total reconstruction cost?

The three assessment points corresponding to these three questions are physically meaningful to the expert and straightforward from the point of view of an engineer designing the lock wall concept. The definition of design load is not coupled to the assessment of repair costs. The writers consider that typically the response to the first question will be less than or equal to the design load, which in turn will be less than or equal to the response to the third question. The expert will give a minimum, most likely, and maximum value for each question indicating the level of uncertainty in each response. The minimum and maximum values are used later to explore the sensitivity of the comparisons of the design concept to the uncertainty of the expert. The piecewise-linear form of the assessed function is suggested to be sufficiently accurate for the preliminary screening that is the topic of this paper; refinement of the function can be considered

Table 1. Entering Design Concepts as Defined by Cost and Barge Impact and Earthquake Design Loads

Concept 1			Concept 2			Concept 3		
Design Loads		Cost	Design Loads		Cost	Design Loads		Cost
(g)	(kN)	($k)	(g)	(kN)	($k)	(g)	(kN)	($k)
1.0	3,114	23,000	0.8	2,669	30,000	1.2	4,448	43,000

Note: g = ground motion acceleration.

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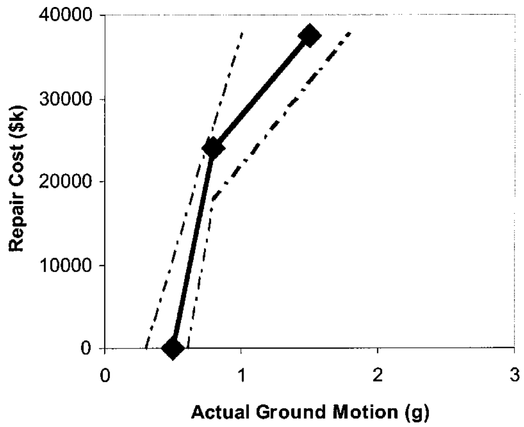

Fig. 4. Step 2: repair cost for lock wall as function of magnitude of earthquake ground motion

for subsequent stages of design evaluation. The assessed function enables obtaining another loss function: ratio of repair cost to reconstruction cost. An example of the repair cost as an assessed function of earthquake ground motion is shown in Fig. 4. The dashed lines show the minimum and maximum values.

A second loss function that is assessed is ''time to recover,'' in terms of the magnitude of the extreme event that occurred. Time to recover is the time for the lock to become operational after being made inoperable by an extreme event or load. The following are questions asked of the expert to assess the relationship:

- For each concept, what is the greatest magnitude of the extreme event that results in no closure of the lock?
- For each concept, what is the duration of closure (weeks) for a magnitude of the extreme event equal to the design load?
- For each concept, what is the least magnitude of the extreme event that results in a lock closure for 1 year or more?

The definition of design load is not coupled to the assessment of closure durations. The writers consider that typically the response to the first question will be less than or equal to the design load of the structure, which in turn will be less than or equal to the response to the third question. Fig. 5 shows the time to recover after barge impacts as a function of the impact magnitude.

Each performance metric, *e.g.*, repair cost, ratio of repair cost to reconstruction cost, time to recover, and cost to industry gives

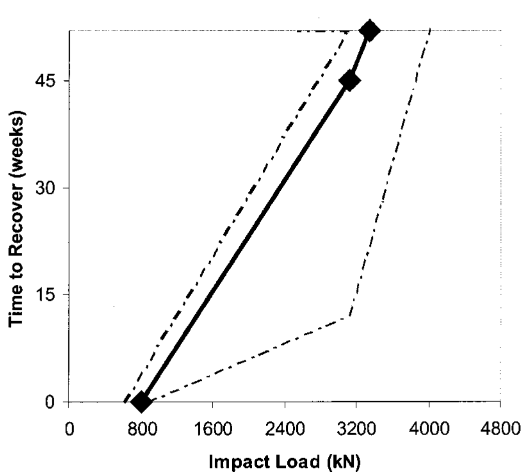

Fig. 5. Step 2: time to recover as an assessed function of magnitude of barge impact

Table 2. Four Stakeholder Perspectives on Impact of Extreme Events

Stakeholder perspective	Performance metric
Engineering and finance	(Repair cost)/(Reconstruction cost)
Finance and engineering	Repair cost ($)
Operation and Industry	Time to recover (weeks)
Industry	Cost to industry ($)

a perspective to support the comparison of the concepts across extreme events. Table 2 shows the performance metrics and the corresponding stakeholder perspective. The stakeholders involved in infrastructure systems include: (1) *engineering-finance*; (2) *finance-engineering*; (3) *operation-industry*; and (4) *industry*. For example, the metric for time to recover has an operations and industry perspective because the amount of time that a lock is closed due to an extreme event would greatly effect both operation of the river system and the cost to industry because navigation traffic is either stopped or delayed. Industry relies on the operation of the lock and is foremost concerned with the time to recover. Clearly, the cost to industry provides an industry perspective.

Step 3: Calibrate Loss Functions with Historical Data

Data on barge impact incidents and earthquakes can be useful in the assessment of loss functions. For example, data on earthquakes that have damaged similar structures can give an idea of the reasonableness of the assessed function of repair cost in terms of magnitude of earthquake. Data on the extreme events are typically sparse. In this example application of the methodology, hypothetical but reasonable historical events are used for the purpose of demonstration. The writers used the best judgments of professionals familiar with the infrastructure to make the most of the little available data. Fig. 6 gives a plot of the assessed functions and sample historical data on a normalized scale. Table 3 shows the supporting historical data. The midpoint on the damage curve for concept 1 is associated with the second question, which asks for the repair cost caused by ground motion equal to the design load. The value on the horizontal axis is equal to ground motion divided by design load. Because ground motion at this point is equal to design load, the value is one. The value on the vertical axis is equal to repair cost divided by reconstruction cost. The repair cost elicited is $24,000. Therefore, the value is $24,000/$39,000 or 0.62. In the example, the reconstruction cost is considered 1.3 times the construction cost. This cost factor can

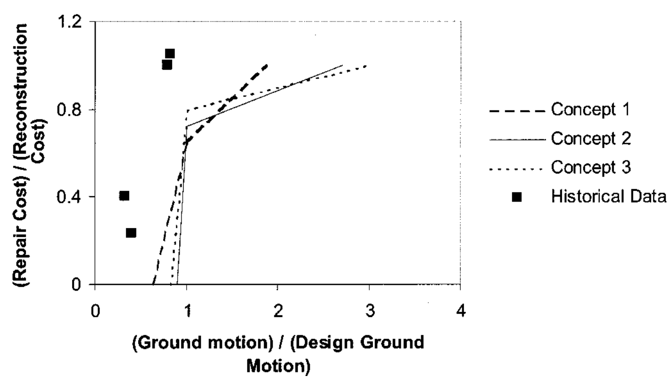

Fig. 6. Step 3: comparing historical data with repair cost as assessed function of ground motion

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Table 3. Historical Data to Calibrate Assessed Relationship between Repair Cost and Ground Motion

Description of earthquake	Design load (g)	Cost of wall ($k)	Actual load (g)	Cost of repair ($k)
E01	1.5	20,000	0.5	8,000
E02	1.0	18,000	0.8	18,000
E03	2.0	43,000	0.8	10,000
E04	1.8	40,000	1.5	42,000

Table 4. Historical Data of Barge Impacts on Lock Walls for Calibration of Assessed Loss Functions

Description of barge impact	Design load (kN)	Barge impact load (kN)	Time to recover (weeks)
C01	2,669	2,224	48
C02	2,669	2,891	52
C03	4,003	445	5
C04	4,003	1,779	20

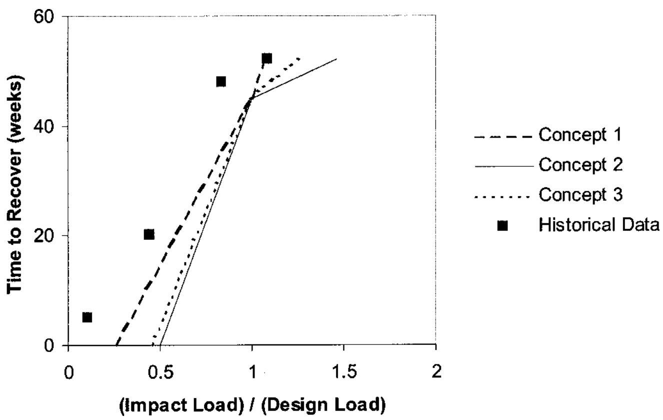

Fig. 7. Step 3: comparing historical data with time to recover as an assessed function of impact load

Table 5. Database Relating Cost to Industry and Length of Lock Closure due to Damage and Repair of Lock Wall

Description of event	Length of closure (weeks)	Cost to industry ($k)
Full operation	0.0	0
15 Day main closure	2.1	123
45 Day main closure	6.4	442
90 Day main closure	12.9	869
180 Day main closure	25.7	2,017
365 Day main closure	52.1	4,192

Table 6. Defining Three Barge Impact Scenarios for Comparison of Preliminary Design Alternatives

Scenario 1		Scenario 2		Scenario 3	
Magnitude (kN)	Return Period (years)	Magnitude (kN)	Return Period (years)	Magnitude (kN)	Return Period (years)
2,669	5	3,336	50	4,003	1,000

easily be adjusted by the expert. Historical data lie to the left of the assessed functions, suggesting that the expert might have underestimated the repair cost of earthquake damage. The expert can consider whether to modify answers to the questions in light of the historical data and/or revisit the relevance of the historical data to the current situation. Table 4 is an example set of historical data for calibration of the loss function for time to recover in terms of the magnitude of barge impact. Fig. 7 shows a plot of loss function and historical data. Unlike other loss functions, the function for cost to industry in terms of length of lock closure is defined sufficiently by historical data, which is given in Table 5.

Step 4: Identify Extreme Event Scenarios in Terms of Magnitude and/or Frequency for Each Nature of Extreme Event

This step identifies the extreme event scenarios across which the concepts are tested. In this example of lock wall design, two natures of extreme events are considered: barge impact and earthquake. The scenarios can be characterized in terms of magnitude and/or frequency, as appropriate to the state of knowledge of the expert. Table 6 gives an example set of barge impact scenarios. The scenarios are displayed in a reverse logarithmic plot of return period versus magnitude; a straight line would suggest the return period is an exponential function of magnitude. Fig. 8 shows a plot of the barge impact historical data of Table 6. Reverse logarithmic plots are used in some seismic analysis performed by the U.S. Army Corps of Engineers (USACE 1999).

Step 5: Compare Design Concepts across Extreme Scenarios and Stakeholder Perspectives

Tradeoff graphs illustrate the cost of construction of a concept versus each of the performance metrics and give designers an at-a-glance comparison of the concepts. Fig. 9 shows a comparison of concepts across the three barge impact scenarios discussed previously where tradeoffs among the concepts are in terms of construction cost and ratio of repair cost to reconstruction cost (the *engineering and finance* perspective). Fig. 9 alone suggests it is not worthwhile to choose the medium-cost concept over the low-cost concept because the performance metric is not improved with the more costly concept in any of the scenarios. Under the "*usual*" barge impact scenario, the value for "*repair cost/reconstruction cost*" is actually worse (greater) for the medium-cost concept than for the low-cost concept. Under the "*unusual*" and "*extreme*" scenarios, the values of the performance metric are the same for the medium-cost and low-cost concepts.

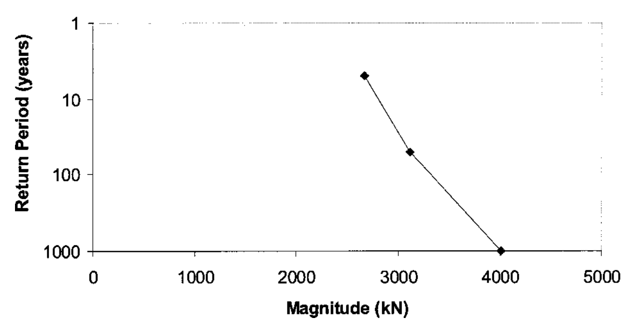

Fig. 8. Step 4: reverse log plot of extreme event scenarios involving barge impact

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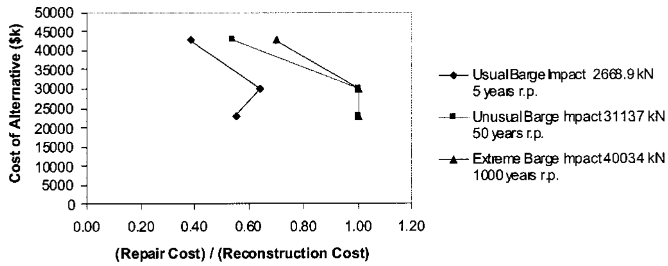

Fig. 9. Step 5: comparing three design concepts across three barge-impact scenarios from an *engineering and finance* perspective

Fig. 10 is an *engineering-finance* stakeholder perspective on the tradeoffs among the concepts across three earthquake scenarios. Fig. 10 suggests it is not worthwhile to choose the medium-cost concept over the low-cost concept. If these were the only two relevant tradeoff graphs, the planner would eliminate the medium-cost concept and compare the other two concepts. More typically, the planner would continue with the comparison of the concepts from the other stakeholder perspectives across the variety (natures and magnitudes) of extreme event scenarios. Before deciding on a concept, the concepts need to be compared using different shapes of the loss functions as provided by the range of uncertainty from step 2. The methodology enables the planner to consider a great number of design concepts in little time and narrrow down to a smaller set to be developed in detail and evaluated further in the next design phase. It is reccommended that planners realize that the accuracy of the results of the comparisons are dependent on the quality of the assessed functions.

Conclusions

This work has contributed a methodology based on risk-cost tradeoff analysis for the preliminary design evaluation of infrastructure designs vulnerable to extreme events and subject to multiple stakeholder perspectives. The methodology assists engineers in defining the nature, magnitude, and frequency of extreme event scenarios to consider in preliminary design and identifies performance metrics that address various perspectives, including *engineering and finance*, *finance and engineering*, *operations and industry*, and *industry*. By enabling the application of critical knowledge and experience early in the design lifecycle, the methodology helps assure that innovative and potentially lower-cost and higher-performing concepts are not rejected out of hand. The methodology has been demonstrated in an example of navigation lock wall design subjected to two extreme loading events: barge impact and earthquake loads. The work contributes techniques for elicitation of experts to define the underlying relationships between *repair cost* and *impact load*, between *repair cost* and *actual ground motion*, between *time to recover* and *impact load*, and between *time to recover* and *actual ground motion*. Some features of a software tool developed by the authors for the U.S. Army Corps of Engineers for multicriteria design evaluation of lock walls have been presented.

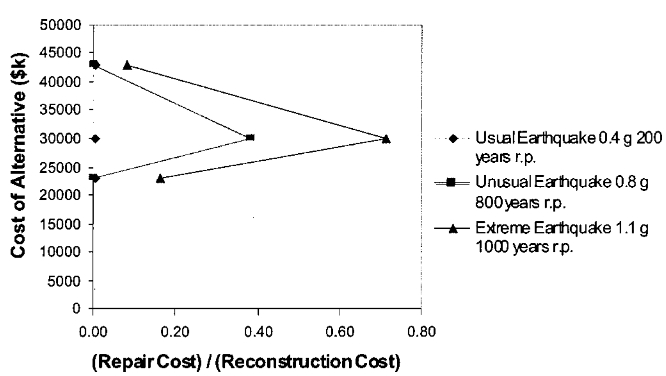

Fig. 10. Step 5: comparing three design concepts across three earthquake scenarios from an *engineering and finance* perspective

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