ERDC/ITL TR-02-5

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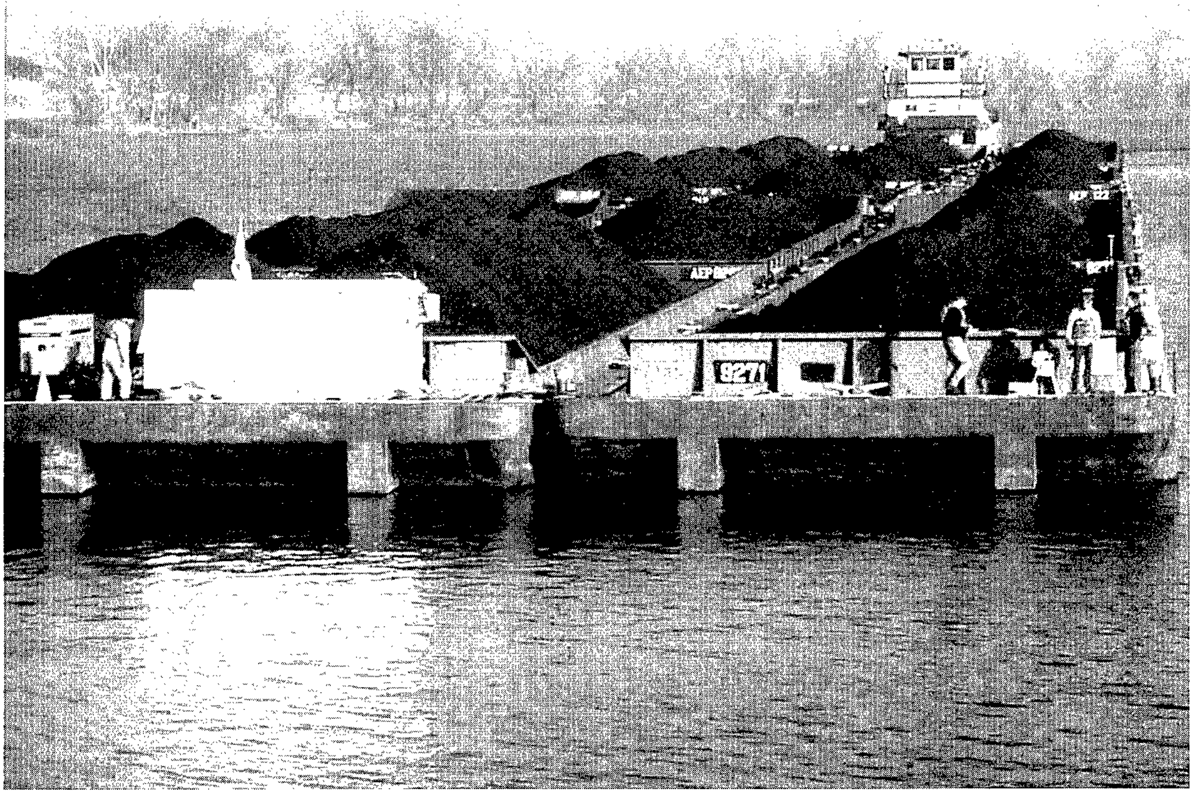
Multiple-Criteria Decision-Making in the Design of Innovative Lock Walls for Barge Impact; Phase 2, Implementation of Methodologies

Joshua L. Tsang, James H. Lambert,
and Robert C. Patev

December 2002



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Projects Research Program

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Multiple-Criteria Decision-Making in the Design of Innovative Lock Walls for Barge Impact; Phase 2, Implementation of Methodologies

by Joshua L. Tsang, James H. Lambert

Center for Risk Management of Engineering Systems
University of Virginia
PO Box 400736
Charlottesville, VA 22904-4736

Robert C. Patev

U.S. Army Engineer District, New England
696 Virginia Road
Concord, MA 01742-2751

Final report

Prepared for U.S. Army Corps of Engineers
Washington, DC 20314-1000

Under INP Work Unit 33143

Monitored by Information Technology Laboratory
U.S. Army Engineer Research and Development Center
3909 Halls Ferry Road, Vicksburg, MS 39180-6199

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Preface

The study described in this report was authorized by Headquarters, U.S. Army Corps of Engineers (HQUSACE), as part of the Innovations for Navigation Projects (INP) Research Program. The study was conducted under Work Unit (WU) 33143, Design of Innovative Lock Walls for Barge Impact Loads." This research was initiated by Mr. Robert C. Patev, former Principal Investigator of WU 33143. Current Principal Investigator is Dr. Robert M. Ebeling of the U.S. Army Engineer Research and Development Center (ERDC) Information Technology Laboratory (ITL).

Dr. Tony C. Liu was the INP Coordinator at the Directorate of Research and Development, HQUSACE; Research Area Manager was Mr. Barry Holliday, HQUSACE; and Program Monitors were Mr. Mike Kidby and Ms. Anjana Chudgar, HQUSACE. Mr. William H. McAnally of the ERDC Coastal and Hydraulics Laboratory was the Lead Technical Director for Navigation Systems; Dr. Stanley C. Woodson, ERDC Geotechnical and Structures Laboratory (GSL), was the INP Program Manager.

This research was performed and the report was written by Mr. Joshua L. Tsang and Dr. James H. Lambert of the Center for Risk Management for Engineering Systems, University of Virginia, and Mr. Patev, U.S. Army Engineer District, New England, Concord, MA. The research was monitored by Dr. Ebeling, under the supervision of Mr. H. Wayne Jones, Chief, Computer-Aided Engineering Division, ITL; Dr. Jeffery P. Holland, Director, ITL; and Dr. David R. Pittman, Acting Director, GSL.

At the time of publication of this report, Dr. James R. Houston was Director of ERDC, and COL John W. Morris III, EN, was Commander and Executive Director.

Summary

The objective of this research is to develop and implement a methodology for multiple-criteria tradeoff analysis supportive of lock wall design subject to extreme events. The work is the first effort of the U.S. Army Corps of Engineers (USACE) to perform tradeoff analysis for lock wall design and to consider very rare and severe damages such as barge impacts and earthquakes.

In designing lock walls, engineers consider different levels of the extreme events for which to design (e.g., a 50-, 100-, or 500-year return period event). In the past, lock walls may have been designed for the conservative and extreme scenario. Looking at tradeoffs among design alternatives may reasonably lower costs without sacrificing significant performance.

Several criteria or metrics are identified for considering tradeoffs among different designs, including construction cost, the ratio of repair cost to reconstruction cost, repair cost, time to recover, and cost to industry. These metrics reflect the degree of severity of a barge impact or earthquake. In the methodology, three scenarios each of possible barge impacts or earthquakes are selected by a lock wall designer for evaluating the alternatives. By studying the metrics, a decision-maker can see the tradeoffs among different designs.

Graphs with the cost of alternative on the vertical axis and the value of a risk metric (e.g., repair cost) on the horizontal axis show the tradeoffs among the alternatives under the extreme event scenarios. A software workbook is developed for the methodology. The implemented methodology is tested using a realistic design situation, making use of data from actual lock projects. Sensitivity analysis is performed to assess the robustness of the model results.

1 Introduction

1.1 Problem Statement

Currently, the design of U.S. Army Corps of Engineers (USACE) navigation structures involves considering the combination of possible extreme events such as barge impact forces and earthquake loading. Designing to such arbitrary extreme events can result in substantial increases in the final design and construction costs. However, with the trend toward thinner, more economical structures using innovative design and construction techniques, the existing design criteria and decision process should be examined in detail to ensure the viability, including safety and cost-effectiveness, of such designs.

The USACE has tried to establish criteria for lock wall design that consider barge-impact forces and earthquake loads for various return period scenarios, for example, usual (1-year return), unusual (500-year return), and extreme (1,000-year return). Typically, depending upon the worst-case scenario that impacts the safety and economic development of the structure's future, the design favors the larger return periods, leading to higher construction costs.

The previous project and theoretical methods described in Lambert et al. (2001) involved the development of a process to aid the USACE in seeking an appropriate balance among the risks of multiple-impact hazards and present and future costs for the design of innovative lock walls. The process is grounded in existing models for the failure modes of the lock walls, multiple-criteria decision-making theory and methodology, and the assessment and management of risk of extreme events.

1.2 Background

1.2.1 Navigation system

Natural riverbeds are generally quite uneven and usually have steep downhill slopes. Without improvements, the depth of water in a river would vary greatly with the seasonal rainfall. Shallow parts of the river would obstruct navigation during a rather dry season. Navigation dams are constructed to create artificial steps (called lifts) and pools in the river, preventing draining during dry periods and enabling navigation for the entire year (USACE 2001). Unlike some dams, navigation dams do not directly block the flow in a river. These structures are typically composed of a line of concrete piers across the river with movable gates between the piers (U.S. Army Engineer District, St. Paul 2000). Other older structures have dam structures that have fixed crests, which permit the flow of water above certain pool elevations.

A channel in the river is maintained to a minimum prescribed depth depending upon its authorization for the river project. For example, the guaranteed minimum depth of the Mississippi River navigation channel is 9 ft. Most frequently, the average depth of the Mississippi River (above Lock and Dam 27 in Missouri) exceeds 13 ft of draft. On a navigable riverway, there is at least one lock chamber at each dam that allows river traffic to safely travel from one pool level to the next. A lock chamber is basically a concrete box in the riverbed with gates at the upstream and downstream ends. One gate opens to allow a watercraft into the chamber. Then the gate closes to let the water level rise or lower to that of the next pool. Then, the other gate opens, releasing the watercraft. Raising and lowering of the water level in a lock is called a "lift" (USACE 2001).

1.2.2 Physical structure of locks

Most locks are located near the bank of a river instead of in the middle. Usually, this is the result of the lock design, which permits the addition of a specific length of dam to assist with the control the navigation pools. There are a number of different lock designs, but some basic components are common to all designs. These components include guide and guard walls, pylons, nose piers, and lock chambers. Figure 1.1 shows a plan view of a typical lock chamber and approach walls. There are walls that extend from the walls of the lock chambers that guide barges as they enter and exit the chamber. These walls are called guide walls. Sometimes these walls also serve to protect the barges from damaging the lock or going toward the dam. In this case, the walls are called guard walls.

Figures 1.2 and 1.3 show a concept drawing for the innovative lock design for Olmsted Lock and Dam on the Ohio River. The approach structures use floating walls as part of the innovative initiative to reduce overall cost. Large

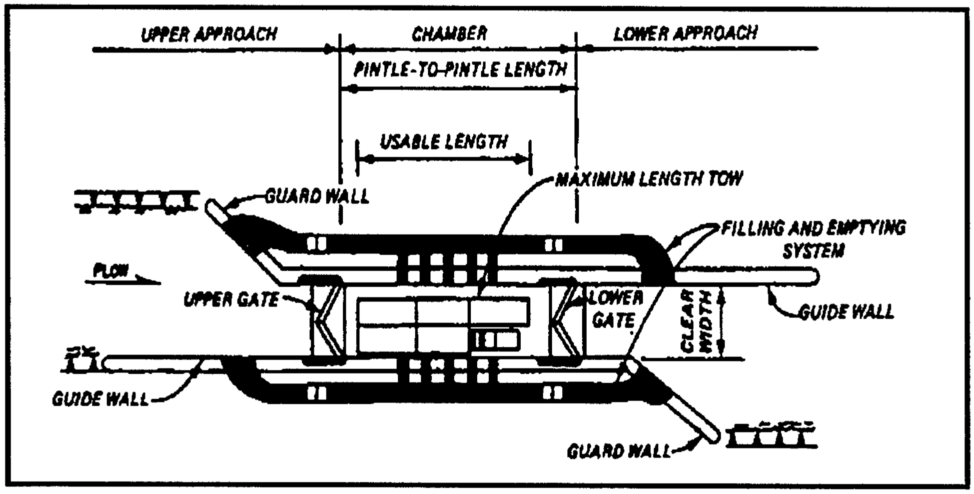


Figure 1.1. Plan view of a typical lock (ASCE 1998)

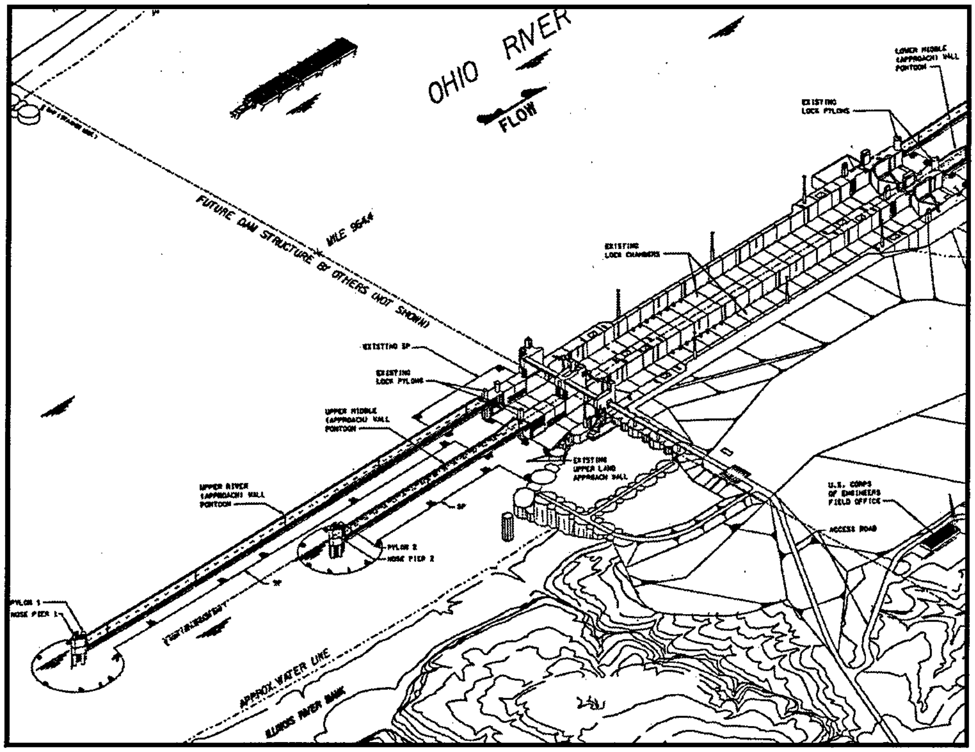


Figure 1.2. Sketch of Olmsted Lock–upstream part (INCA Engineers, Inc. 1999)

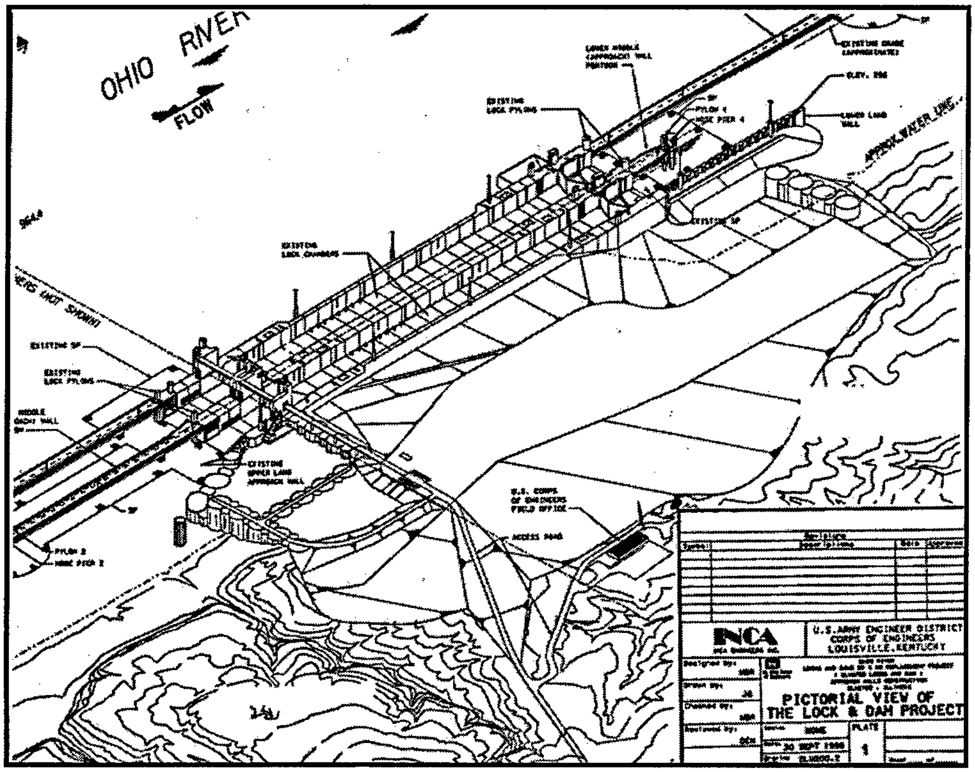


Figure 1.3. Sketch of Olmsted Lock–downstream part (INCA Engineers, Inc. 1999)

concrete drilled shafts called pylons are attached to the approach wall pontoons in various locations to anchor the pontoons. The pylons prevent the pontoons from shifting horizontally while allowing them to rise and fall with the river stage. A triangular-shaped tip or round cellular structure (called a nose pier), which is placed at the end of each wall for protection, is susceptible to possible barge impact by a transiting barge.

1.3 Lock Wall Design

1.3.1 Guide wall

The main purpose of guide walls is to guide barges and their towboat safely into and out of the lock chamber. Another purpose of guide walls is to provide a place to dock groups of barges that are too long to go through the lock in one process (Engineer Manual 1110-2-2602, USACE 1995a). This is called cutting of a tow. There are many types of guide walls, including fixed, floating, or a combination of both fixed and floating. The type is dependent upon the hydraulic conditions at the site and the position within the lock structure.

1.3.2 Consideration of extreme events in design process

The USACE is charged to keep locks operable under a diversity of circumstances. Therefore, extreme events—events that could cause a catastrophic failure but have a small likelihood of occurring—are taken into account in the design phase. Two important extreme events faced by lock walls are barge impacts and earthquakes. When designing locks, USACE design engineers study the risks to the structures for barge impact because the heavy, cargo-loaded barges can hit and damage the guide walls as they enter and exit the lock chamber. The chance of an extreme barge impact event increases with bad weather and faster hydraulic flow conditions. Also, the engineers consider the susceptibility of the design to earthquake ground motions that can damage the entire structure. Other risks to the design that the USACE may consider are floods and terrorist bombing.

1.3.3 Additional relevant studies and methodologies

A study has been conducted on calculating the probability of different events or failure modes such as barge impact, earthquake, operator error, and floods occurring at the same time. For a particular facility, it has been shown that one needs only to be concerned about one failure mode occurring at a time because the annual probability of the joint occurrence of failure modes or events is tremendously small—on the order of 10^{-5} to 10^{-11} (Ellingwood 1995). The analysis described in Ellingwood should be performed for the site of concern to determine whether the probability of joint occurrence of failure modes is significant.

USACE has methodologies for determining the probability of occurrence of any barge impact given its magnitude, angle, and velocity or for earthquake based on spatial distributions of sources, rupture lengths, and magnitudes. This methodology is useful in showing what levels of impact are important to consider based on their probabilities of occurrence (Patev 2000).

2 Review of Literature

The sections of this chapter summarize previous work in the areas of benefit-cost analysis, risk analysis, risk of extreme events, and multiple-criteria decision-making that is relevant to this study.

2.1 Benefit-Cost Analysis

Loucks, Stedinger, and Haith (1981) explain economic benefit-cost analysis and the difficulties in doing such an analysis, including tying noncommensurate benefits and costs together and characterizing benefits. These authors explain that it is important that monetary value (price) reflects social values of the item under consideration. Benefit-cost analysis (or "BC ratio") is the current basis for funding of the design and rehabilitation of USACE navigation and flood control structures.

2.2 Risk Analysis

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

2.3 Multiple Failure Modes

Methods have been developed to analyze the probabilities of coincident failure modes occurring at a navigation lock (Ellingwood 1995). A particular site is studied by Ellingwood, and the pairs of coincident failure modes considered include operating loads and wind, operating loads and earthquakes, operating loads and barge impact, earthquake and barge impact, and earthquake and flood.

Methods for identifying multiple failure modes and estimating failure probabilities are shown by Ang and Tang (1984).

2.4 Extreme Distribution

Extreme distributions are used to define the events that exist in the tail of the underlying distribution. These distributions are valuable in selecting return periods for extreme events when data points for these events are not existent. Ang and Tang describe asymptotic forms (Type I, II, and III) of Gumbel distributions that characterize low- probability, high-consequence events (1984).

2.5 Earthquake Analysis

Green and Hall (1996) explain how probabilistic seismic hazard analysis (PSHA) has been widely adopted in favor of deterministic seismic hazard analysis. PHSA is also discussed in the Corps guidance document EM 1110-2-6050 (USACE 1999), which addresses earthquake analysis for hydraulic concrete structures. Nonetheless, there have been several strong critics of the probabilistic approach, especially when it is applied to critical structures and when limited probabilistic data are available. Lindbergh, Harlan, and Lafrenz (1996) noted the differences in available data for seismic hazard between the region west of the Rocky Mountains and the region east of them. The differences in data and events necessitate different design criteria and analysis using PHSA.

2.6 Barge Impact Analysis

The U.S. Army Engineer District, Huntington, has recently commissioned two studies of barge impact loads—on the walls at the Marmet Lock and Dam (Patev 2000) and at the Winfield Lock and Dam (Glosten Associates, Inc. 1995). In both studies, probabilistic modeling was used to calculate the maximum impact loads associated with specific return periods. The method used in both studies for calculating impact loads is based on the methodology contained in the USACE Engineer Technical Letter (ETL) 1110-2-338, Barge Impact Analysis (rescinded 1999).

2.7 USACE Applications

Moser (1996) relates that the USACE has used risk analysis techniques and ideas for many years. Within the USACE, this use started with simple calculations of the expected annual flood damage as the area under a flood damage frequency curve. However, only in the last 15 years has risk analysis been incorporated explicitly into the decision-making process of the USACE (Moser 1996). The USACE had been designing its structures to meet set standards. Diewald (1987) explains the advantages and disadvantages of standards-based design. Moser (1996) states that the USACE has began to explicitly integrate risk analysis methods into their decision-making since only about 1986, and that by explicitly examining risk-cost tradeoffs, the USACE is reconsidering some standards that are required for all projects.

Various works by the USACE show their adoption of risk analysis methodologies (Institute for Water Resources 1992a,b; Engineer Regulation (ER) 1105-2-101, USACE 1996). Walker (1997) gives an advantage of probabilistic-based methods over deterministic standards-based methods for evaluating potential USACE projects: ability to predict likelihood of component failure. Moser (1996) mentions an application of risk analysis to evaluate an existing requirement to provide an emergency closure system for hydroelectric unit intake gates that can stop the flow of water within 10 min. Expert judgments and historical frequencies were combined using Bayes theorem.

It is shown that there is inherent uncertainty in the economic and engineering analyses, thus giving leeway to the determination of design and project costs by explicitly considering tradeoffs between project cost and risk cost (Yoe 1987). Moser and Stakhiv (1987) emphasize the importance of accounting for all costs during 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. (1991) survey the current methodologies for benefit-cost analysis, including alternative methods to obtain probabilities when historical data are unavailable. Finally, benefit-cost analysis has been used to justify maintaining the inland navigation system. Walker (1997) underscores the need for using benefit-cost analysis to accurately determine the value of a reliable navigation system.

Beim and Hobbs (1997) used event trees to estimate the frequency of a lock failure due to a vessel or railroad collision, eliciting subjective probabilities for the events. Beim and Hobbs demonstrated the usefulness of an event tree modeling the possible paths leading to a failure. Beim and Hobbs conduct a workshop to elicit probabilities from experts and have shown that, when limited historical data are available, it is necessary to obtain subjective probabilities and use the available historical data.

2.8 Multiple-Criteria Decision-Making

Pomerol and Barba-Romero (2000) describe that the field of multiple-criteria analysis was established in 1972, although the field's roots lie in earlier works in economics and political science. Pomerol and Barba-Romero categorize the field into three main schools of thought: the French school, which thoroughly studied discrete multiple-criteria outranking relations; the American school, which consists of Keeney-Raiffa's additive utility and other pragmatists using other methods; and the Pacific school.

Many multiple-criteria methods have been implemented into software programs. Perhaps the most well known method that has been implemented is the Analytic Hierarchy Process (AHP). The AHP process uses weights in a weighting method, and they are not assigned levels of importance. Much work in economics has been done on concepts of Pareto optimality and dominance. Further background on multiple criteria can be found in Lambert et al. (2001).

3 Underlying Methodologies for Analysis

3.1 Determination of Design Load

Part of the design process for lock walls involves determining design loads, which are criteria for determining the strength required for the lock walls. For each navigation project, the USACE selects three design loads with associated return periods for consideration in the design. The three design loads represent a usual, unusual, and extreme case. Example return periods for design loads in these cases may be 50, 100, and 500 years, or maybe 2, 50, and 500 years, respectively. The design loads are forces that the walls may expect over its service life. The typical service life for a USACE navigation structure is 50 years. The USACE decides which design load case should be applied for wall design, such that the walls may sustain some significant damage but will not experience catastrophic failure or collapse.

For this analysis, the annual exceedance probabilities for the design loads are calculated. Thus, the methodology becomes probabilistic in nature. These probabilities are used in the current project of seeing the tradeoffs between different design alternatives. A decision-maker can choose loadings that have a small, medium, or large probability of occurrence such that alternatives can be analyzed. By knowing the reasonable probabilities of occurrence of loads, the decision-maker can ensure that the final design can be expected to perform successfully under events that may occur during its service life.

3.2 Determination of Design Ground Motions

The choice of design ground motions should be based on seismic analyses according to ER 1110-2-1806 (USACE 1995c). The Corps has two methods for determining peak ground acceleration: Response Spectrum Analysis (RSA), which is discussed in EM 1110-2-6050 (USACE 1999); and Time History Analysis (THA), which is discussed in Engineer Circular 1110-2-6051 (USACE 2000). Generally, for USACE structures, RSA is performed first to examine the behavior of the structure being designed. If the behavior of the structure is questioned (e.g., large displacements), then the next step is to use THA with the properly developed ground motions for the design site to more carefully model the structure. Appendix A describes a probability model used by the USACE to determine the frequency of ground motions.

3.3 Methodologies for Determining Exceedance Probabilities

The USACE employs methodologies to calculate probabilities of occurrence. The methodology for barge impacts is called Probabilistic Barge Impact Analysis (PBIA) (Patev 2000) and, for earthquakes, the Probabilistic Seismic Hazard Analysis (PSHA) (USACE 1999). PBIA is based on data collected either from physical scale-model experiments or from time-lapse field collection devices. PSHA uses information from past earthquake events that are near the structure as well as mathematical models to represent certain relationships for the earthquake parameters.

3.4 Separate Analyses for Each Type of Event

In the software developed for this report and discussed in future chapters, there are separate risk analyses that need to be performed for either barge impact forces or earthquake accelerations. One major reason for the separate risk analyses is the different potential contexts of their failure modes. An extreme barge impact incident tends to affect only the regional inland navigation system. If the inland navigation system is down in a particular region of the river, the commodity may be transported by road and rail, depending upon the duration of the closure at a particular lock. On the other hand, an extreme earthquake event would potentially affect the inland navigation system, the road system, as well as rail systems. Thus, the contexts and costs to industry from barge incident are relatively different compared with those due to earthquakes.

3.5 Risk Metrics Identified for Multiple-Criteria Tradeoff Analysis

Various metrics have been identified to aid in the building of the tradeoff analysis methodology. These metrics are the multiple criteria with which design alternatives may be evaluated in the tradeoff analysis. Table 3.1 shows these metrics with accompanying explanations.

Table 3.1
Risk Metrics as Multiple Criteria

Metric	Definition
Ratio of repair cost to reconstruction cost	Repair cost divided by the initial construction cost
Repair cost ($)	Damage caused by a failure mode
Time to recover (week)	Time it takes to return to normal operation
Cost to industry ($)	Loss to industries due to locks being out of commission

3.6 Estimating Structural Damage Due to Barge Impacts

It is important to obtain available data on damage caused by actual barge impact incidents. While these data may not be readily available to most, potential sources include the collison/allision database assembled by the Coast Guard as well the operational and insurance records at USACE projects. In addition to or in lieu of obtaining data on actual incidents, the levels of damage could be inferred from description of the consequences caused by the usual, unusual, and extreme impact loads (Patev 2000).

Usual load cases are those that occur most commonly during the life of a project, including normal operation and flood conditions (USACE 1995b). Under these cases, the structure stays in the elastic range and only cosmetic damage occurs to the structure (Patev 2000). Unusual loading conditions include maintenance, infrequent floods, barge impact, construction, hurricanes, or earthquakes with nonspecific ground motions for Operating Basis Earthquake (USACE 1995c). This load condition results in nonlinear behavior and some minor damage that can be repaired in the future (Patev 2000). Extreme loads are accidental or natural disasters that have a remote probability of occurrence and require emergency maintenance. Special provisions such as frequent and continuous field monitoring of performance are required during and after this type of load. An example of this kind of load is an earthquake with nonsite-specific ground motion for maximum credible earthquake (USACE 1995c). The extreme load case will result in heavy damages and emergency repairs (Patev 2000).

From these descriptions, repair costs as a percentage of the construction cost can be estimated. From the descriptions of the damage under the usual, unusual, and extreme load cases, it is interpreted that the repair costs as a percentage of the initial construction cost are 5, 10, and 80 percent, respectively. Figure 3.1 shows the relationship between damage and load case for the upper river wall of Olmsted Lock. Figure 3.1 can be used for comparing with the relationships assessed in the spreadsheet software.

3.7 Model for Cost to Industry

The cost to industry due to closure of a lock is typically measured in dollars per hour of closure. Normally, the cost to industry is between \$400 and \$600 per hour of closure. The USACE has a system-wide modeling program called the Waterways Analysis Model (WAM). The WAM model relates closure duration of a lock chamber to the cost to industry. The output from WAM produces the costs to industry for different requested closure lengths (15, 45, 90, 180, and 365 days). Table 3.2 shows an example of output from the WAM.

The formula for calculating the cost to industry is as follows:

$$\text{Cost to industry} = (T - T_f)\ (\text{No. of tows})\ C$$

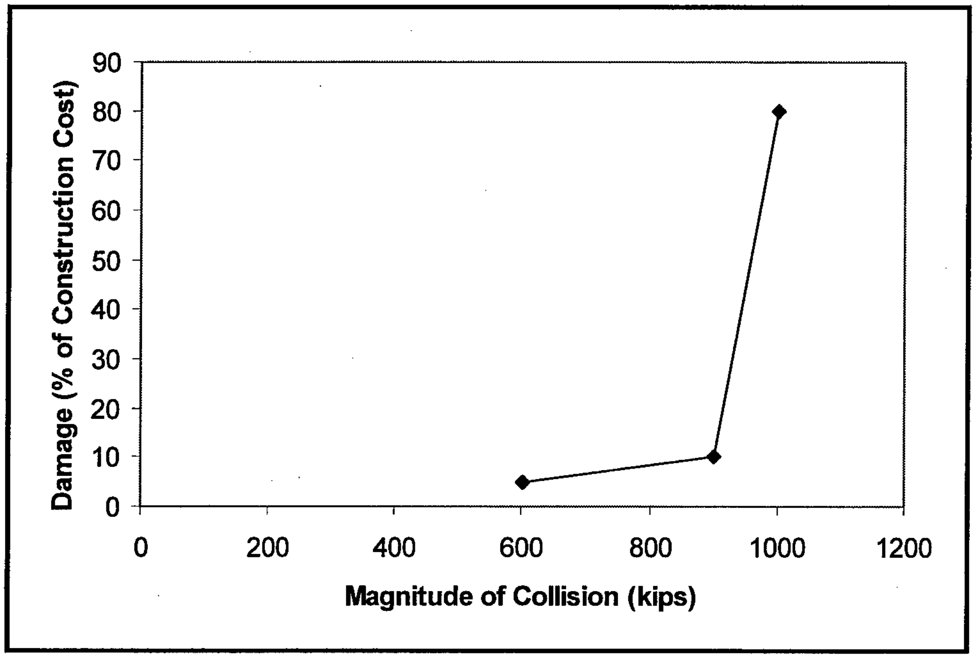


Figure 3.1. Relationship between damage and magnitude of collision for upper river wall of Olmsted Lock

Table 3.2
Example Waterways Analysis Model Output

Run ID	Transit Time (hr)	Cost to Industry ($)
Full operation	1.14	NA
15-day main closure	1.25	$122,740
45-day main closure	1.54	$441,727
90-day main closure	1.93	$869,488
180-day main closure	2.97	$2,017,242
365-day main closure	4.95	$4,192,091

where

T = transit time in hours with an x-day main closure

T_f = transit time in hours with full operation

C = constant that depends on location of the lock

The value for the constant C in the formula has been calibrated to previous traffic patterns at a system of locks and involves using simulations of the entire river system traffic in the models. WAM modeling was performed by the USACE Navigation Data Center for two actual lock systems. A piecewise linear regression is performed for each lock system between cost to industry and closure length. Therefore, a formula can be obtained that determines the cost to industry due to any closure length. The formula is used to calculate the cost to industry for any alternative under a particular extreme event scenario given the closure length of the lock. The *Time to recover* is assumed to be the same as closure length.

Therefore, the *Time to recover* calculated for a particular alternative and scenario is used in the linear programming formula to obtain the *Cost to industry.* For example, if a 100-kip (445-kN) barge impact causes a *Time to recover* of 10 weeks, then the linear relationship is used to find the cost to industry corresponding to a *Time to recover* of 10 weeks.

Assuming a linear relationship between length of closure and cost to industry seems reasonable after viewing a plot of the data points given by the USACE (Patev 2001). Appendix B presents other information on length of closure obtained from the U.S. Army Engineer Navigation Data Center.

3.8 Tradeoff Analysis

The following section describes the possible outcomes that may occur when using tradeoff analysis and graphing the results. By comparing alternatives in terms of construction cost and one risk metric (e.g., repair cost) under only one scenario, there are a number of possible cases that may exist. This section will assist the reader in the interpretation of the graphs that may result from using the developed software for the project.

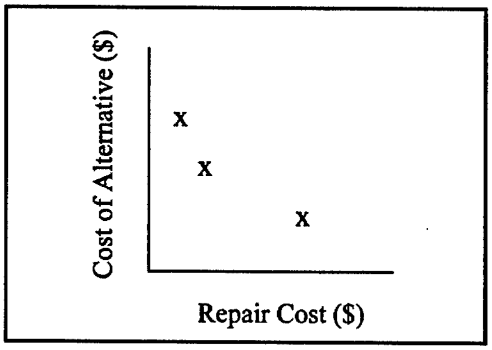


Figure 3.2. Pareto optimal alternatives for *Cost of alternative* in the short term and *Repair cost* in the long term

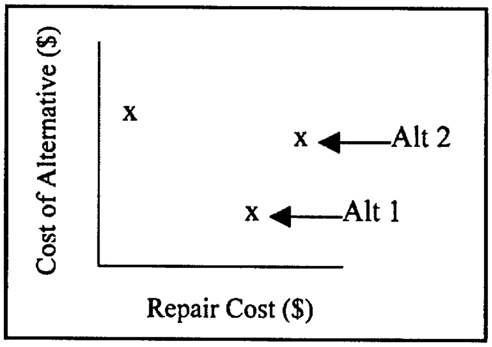


Figure 3.3. *Cost of alternative* in the short term versus repair cost in the long term

3.8.1 Pareto optimal alternatives

Of the alternatives that are shown in Figure 3.2, no single alternative is objectively better than another one. Between any two of the alternatives, there is tradeoff in the two factors being considered. If one alternative is more costly, then it will also have a smaller potential repair cost. The choice of an alternative depends on expert judgment or institutional preference.

3.8.2 Dominated alternative

In Figure 3.3, Alternative 2, which is to the upper right of Alternative 1, is considered a dominated alternative. This is because Alternative 2 is worse than Alternative 1 in both construction cost and repair cost. Therefore, Alternative 2 can be removed from consideration as a potential design choice.

3.8.3 Horizontal alignment: Alternative with same cost but different levels of performance

The outcome in Figure 3.4 is a special case of dominance in which both alternatives have the same cost, but Alternative 2 has a greater repair cost than Alternative 1. Therefore, in this case, Alternative 2 is dominated.

3.8.4 Vertical alignment: Alternative with same performance (i.e., repair cost) but different costs

If the tradeoff graph appears as in Figure 3.5, there is no need to invest more funds for the cost of an alternative than the minimum amount if there is nothing greater in return (i.e., lower repair costs). Figure 3.5 shows there are no reasons to choose Alternative 2 and invest the higher amount for the cost of the alternative. Vertical alignment is also considered a special case of dominance. An alternative that is directly above another alternative has no advantage in terms of repair cost.

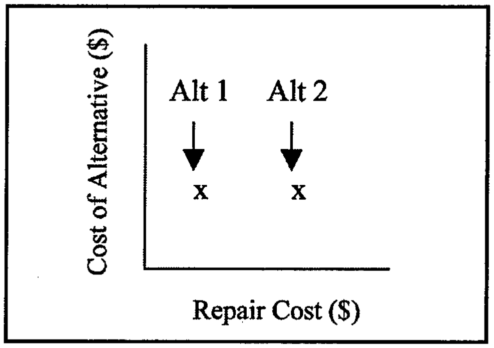


Figure 3.4. Horizontal alignment

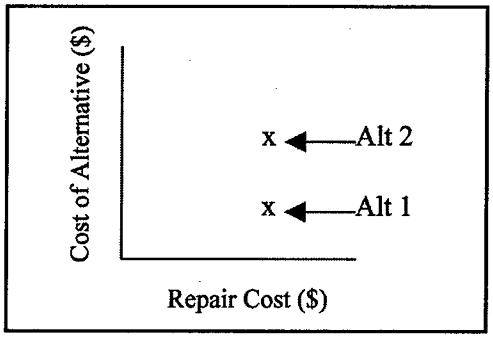


Figure 3.5. Vertical alignment

3.8.5 Pareto optimal alternatives with more than two criteria

Now assume that there is more than one risk metric used in evaluating the construction alternatives. As an example we consider two metrics, namely *Repair cost* and *Time to recover*. The following outcome is determined from the tradeoff analysis and is shown in Figure 3.6.

In terms of repair cost, Alternative 2 is dominated by Alternative 1. However, in terms of *Time to recover* no dominance is indicated. In this case, Alternative 2 cannot be removed from consideration as a viable solution because now there are two risk metrics with which to evaluate the tradeoff. At this point, one cannot say that one alternative is better than another one objectively. The choice between the alternatives may depend on factors that are not quantified for this example. For example, if the decision-maker considers *Time to recover* as greatly more important than repair cost, then the shorter *Time to recover* for Alternative 2 may make it the desired option. This shows that decisions can be made based on all the metrics established for the problem at hand.

Thus, a third and fourth risk metric can be used to evaluate a structure. In this case of four metrics, an alternative is dominated only when it is worse in all four metrics than another alternative. This is the reason for performing tradeoff analysis.

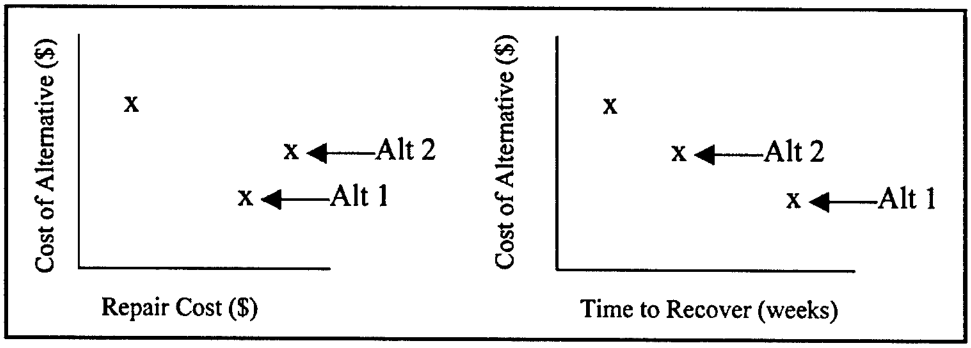


Figure 3.6. Example of multiple risk metrics

3.8.6 Pareto optimal alternatives with multiple scenarios

Now consider the case of evaluating alternatives under multiple scenarios, as shown in Figure 3.7. This case shows the construction costs and repair costs of three alternatives under both a barge impact and an earthquake scenario.

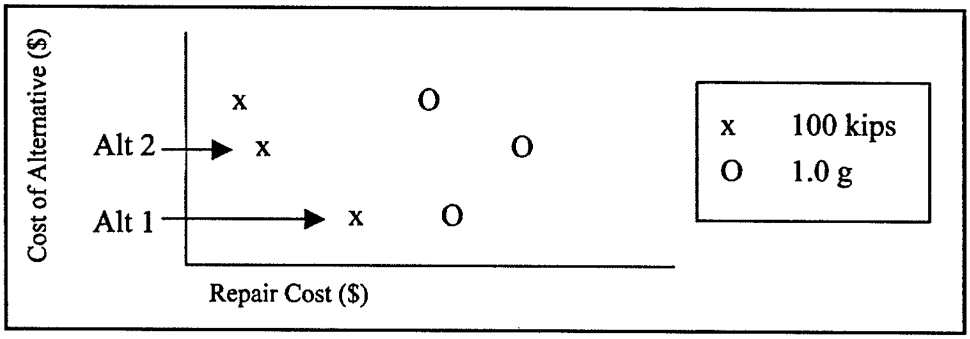


Figure 3.7. Example with multiple scenarios

For the 100-kip collision scenario, all three alternatives shown are Pareto optimal with respect to that specific scenario. For the 1-g earthquake, Alternative 2 is dominated by Alternative 1. Assuming that only one risk metric and two scenarios are used, the alternatives are then considered Pareto optimal.

3.8.7 Considerations in tradeoff analysis

When choosing among construction alternatives, there are several considerations. First, it is important to look for any dominated alternatives. For example, if Alternative A lies vertically above Alternative B in the tradeoff graphs for all criteria of interest, then Alternative A is dominated. The presence of dominated alternatives may suggest that either a different, more competitive set of alternatives be chosen because one alternative appears inferior to another on all the criteria, or there should be a more severe extreme event scenario for the analysis. This latter suggestion is especially true when the values of the criteria for the dominated and dominating pair of alternatives under the chosen scenarios are zero or very small.

After checking for dominated alternatives, a lock wall designer can consider the tradeoffs under the barge impact and earthquake scenarios for the different risk metrics (e.g., repair cost). The designer can weigh the tradeoffs among the alternatives with respect to the four risk metrics. The considerations above will be used to analyze some of the tradeoff graphs shown in Chapter 5.

4 Development of Input Section of an Automated Tool for Lock Wall Design Aid

This section describes the software that has been developed to assist in making multiple-criteria decisions for innovative lock walls. The spreadsheet tool was developed in Microsoft Excel and has multiple worksheets that take input from the user and display results of tradeoff analysis. The first worksheet is the **Welcome** worksheet with the name of the tool, its purpose, and information for correspondence (Figure 4.1).

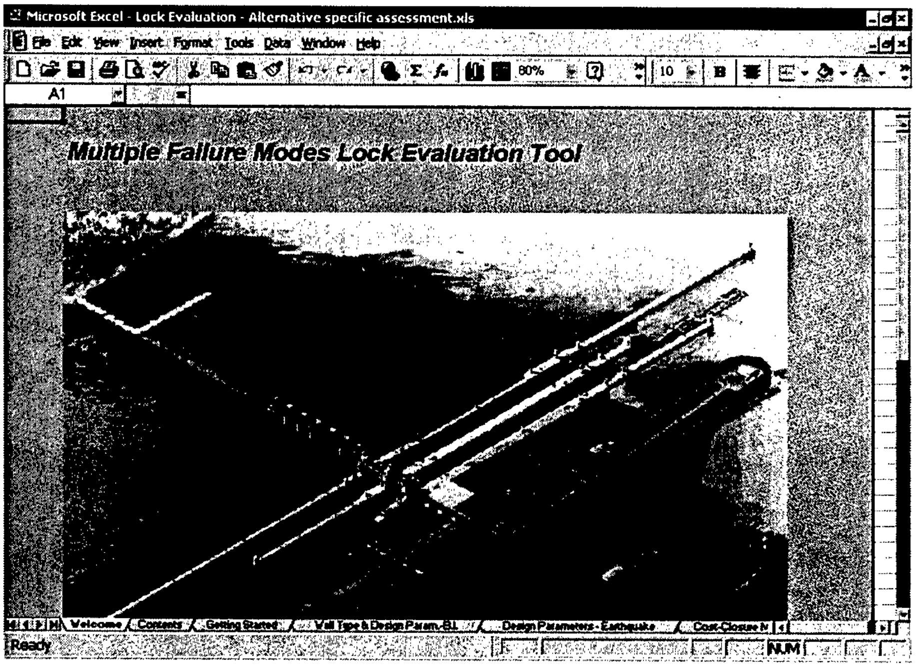
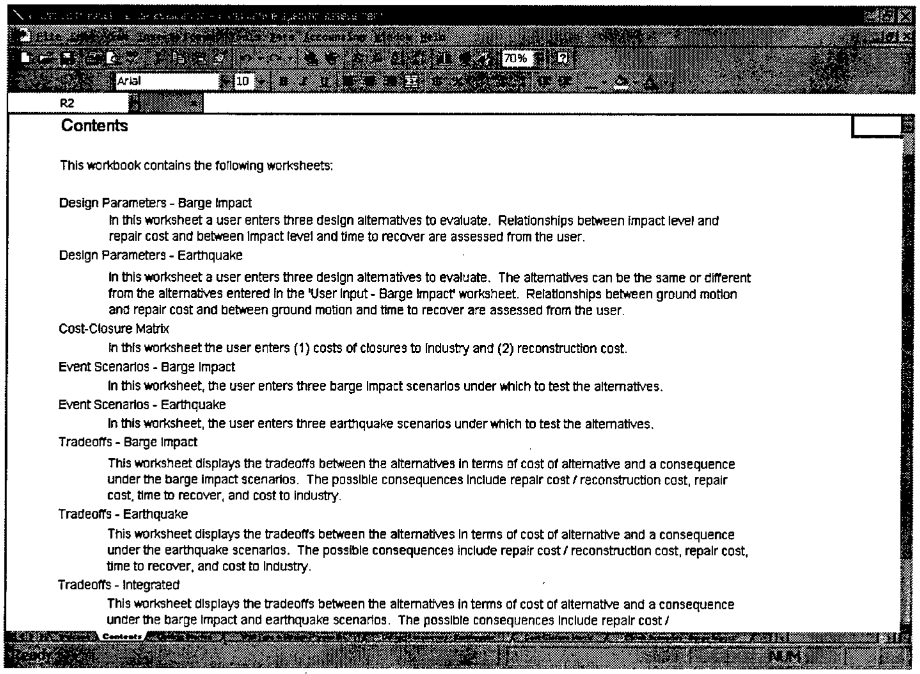


Figure 4.1. **Welcome** worksheet

A **Contents** worksheet has a description of each worksheet in the analysis tool. The **Contents** worksheet is shown in Figure 4.2.



Contents

This workbook contains the following worksheets:

Design Parameters - Barge Impact
In this worksheet a user enters three design alternatives to evaluate. Relationships between impact level and repair cost and between impact level and time to recover are assessed from the user.

Design Parameters - Earthquake
In this worksheet a user enters three design alternatives to evaluate. The alternatives can be the same or different from the alternatives entered in the 'User Input - Barge Impact' worksheet. Relationships between ground motion and repair cost and between ground motion and time to recover are assessed from the user.

Cost-Closure Matrix
In this worksheet the user enters (1) costs of closures to industry and (2) reconstruction cost.

Event Scenarios - Barge Impact
In this worksheet, the user enters three barge impact scenarios under which to test the alternatives.

Event Scenarios - Earthquake
In this worksheet, the user enters three earthquake scenarios under which to test the alternatives.

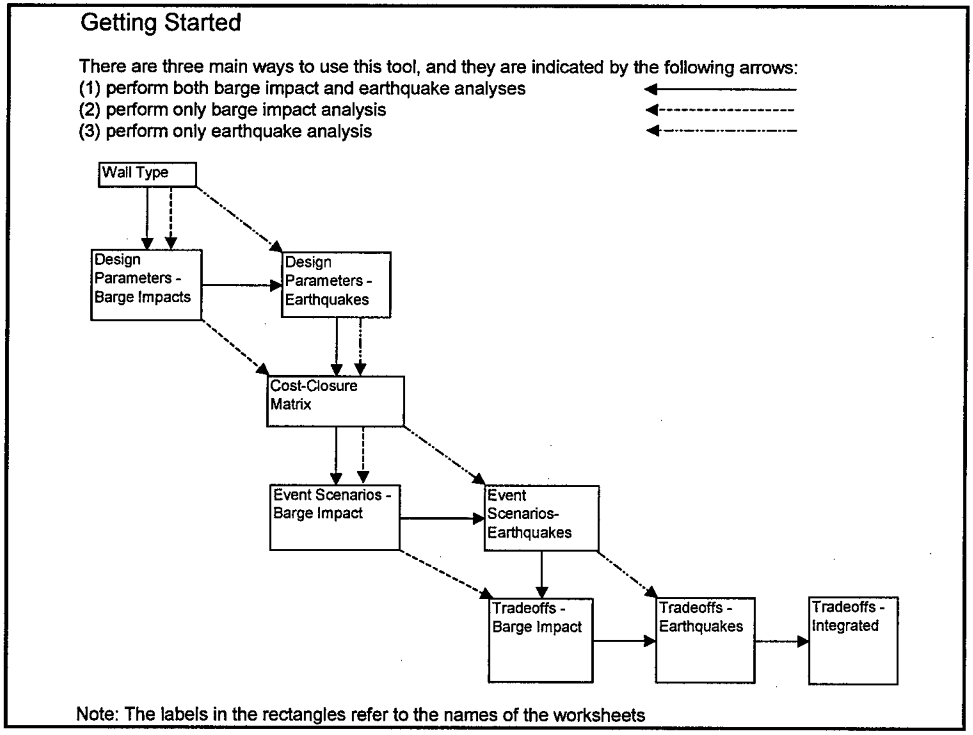
Tradeoffs - Barge Impact
This worksheet displays the tradeoffs between the alternatives in terms of cost of alternative and a consequence under the barge impact scenarios. The possible consequences include repair cost / reconstruction cost, repair cost, time to recover, and cost to industry.

Tradeoffs - Earthquake
This worksheet displays the tradeoffs between the alternatives in terms of cost of alternative and a consequence under the earthquake scenarios. The possible consequences include repair cost / reconstruction cost, repair cost, time to recover, and cost to industry.

Tradeoffs - Integrated
This worksheet displays the tradeoffs between the alternatives in terms of cost of alternative and a consequence under the barge impact and earthquake scenarios. The possible consequences include repair cost /

Figure 4.2. **Contents** worksheet

A **Getting Started** worksheet has a flow diagram that clearly shows the worksheets that the user should use depending upon which analyses (barge impact, earthquake, or both) are desired. The flow diagram is shown in Figure 4.3.



There are three main ways to use this tool, and they are indicated by the following arrows:
(1) perform both barge impact and earthquake analyses ←———
(2) perform only barge impact analysis ←-------
(3) perform only earthquake analysis ←-·-·-·-

Note: The labels in the rectangles refer to the names of the worksheets

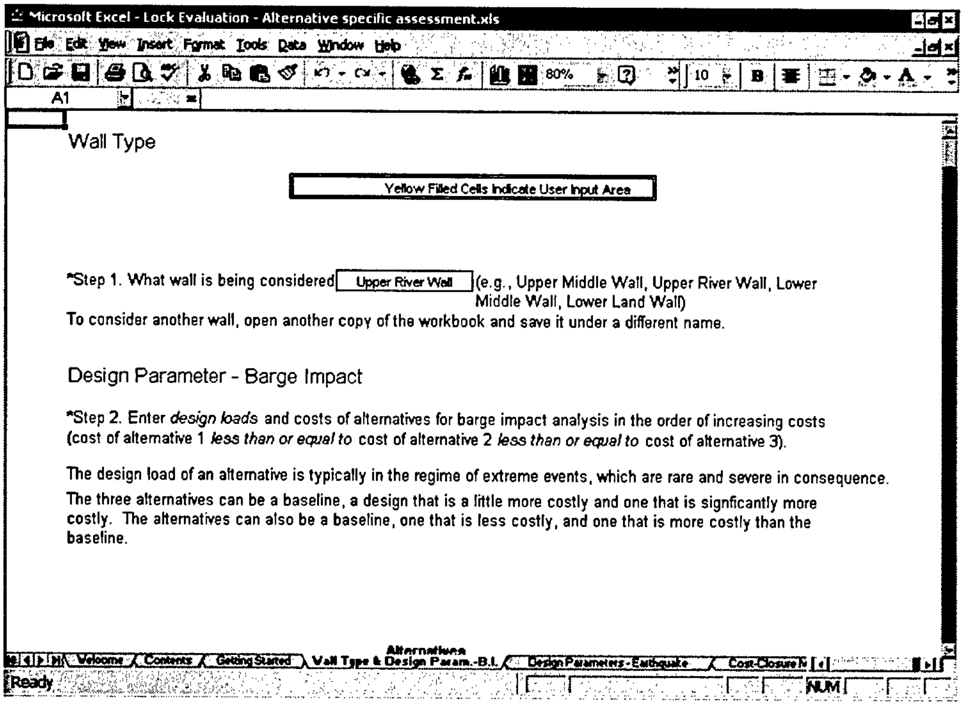
Figure 4.3. Flow diagram in **Getting Started** worksheet

4.1 Data Input for Barge Impact Analysis

A **Wall Type & Design Parameters – Barge Impact** worksheet allows for the input of the type of wall to consider, the design alternatives to compare, the information needed to estimate repair costs and the *Time to recover*, and the historical data on actual barge impacts and the associated damage. Figure 4.4 shows the top of the input worksheet.

The worksheet has an area to enter the wall type to consider. This is Step 1. In the area for entering wall location, the user will input the wall location that is under consideration (upper middle, upper river, lower middle, lower river, lower land). The other worksheets in the tradeoff workbook are automatically populated with that wall location.

There are several issues with coming to the decision to analyze each wall location separately instead of defining the whole lock project as an alternative. First, if an alternative defines the entire wall system with all the wall locations, there would be too many possible alternatives. Second, although the final layout of the software analyzes particular wall locations, the usual practice of lock wall designers is to choose the similar kinds of design (e.g., pontoon, fixed) for all the lock walls at a site. Third, with the final layout, a user who wants to consider another wall location could open up another copy of the software and save it under a different name. The user then has multiple copies of the software workbook for analyzing multiple wall locations.



Wall Type

Yellow Filled Cells Indicate User Input Area

*Step 1. What wall is being considered Upper River Wall (e.g., Upper Middle Wall, Upper River Wall, Lower Middle Wall, Lower Land Wall)

To consider another wall, open another copy of the workbook and save it under a different name.

Design Parameter - Barge Impact

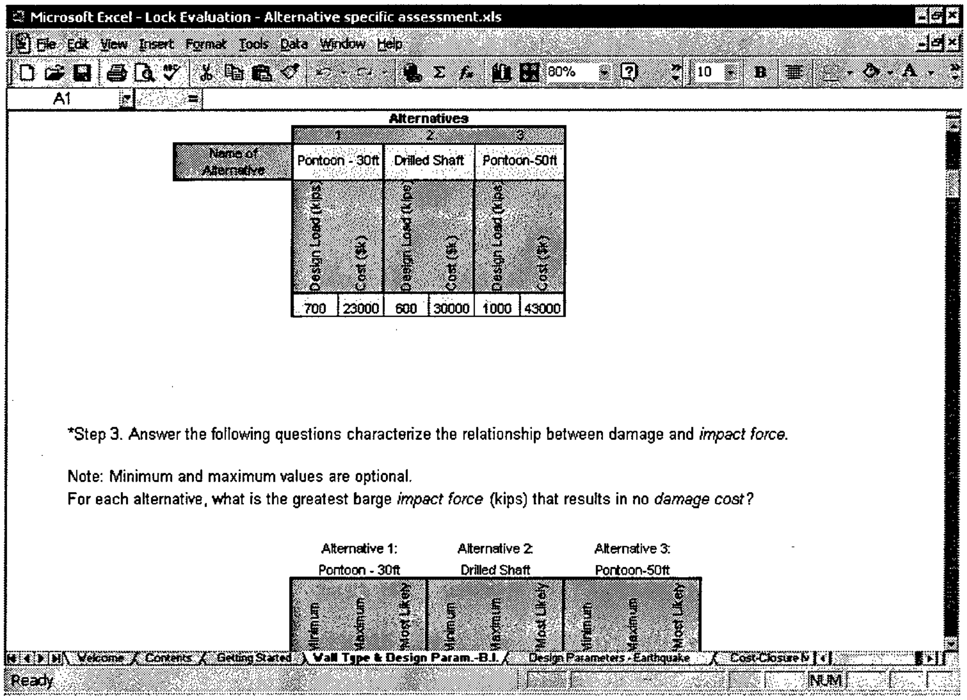
*Step 2. Enter *design loads* and costs of alternatives for barge impact analysis in the order of increasing costs (cost of alternative 1 *less than or equal to* cost of alternative 2 *less then or equal to* cost of alternative 3).

The design load of an alternative is typically in the regime of extreme events, which are rare and severe in consequence.

The three alternatives can be a baseline, a design that is a little more costly and one that is signficantly more costly. The alternatives can also be a baseline, one that is less costly, and one that is more costly than the baseline.

Figure 4.4. **Wall Type & Design Parameters – Barge Impact** worksheet

Figure 4.5 shows the input area for Step 2, which involves entering the construction design alternatives. For each design alternative, the user needs to supply the name, the cost of construction, and the design load. Since the purpose of the tool is to analyze designs for their performance under extreme events, a suitable metric for design load was needed to describe the alternatives further. The design load value in this software tool may mean something slightly different from the design load that might be used for other aspects. The term design load in this application should point the user to choose a force in the regime of an extreme load case for the design load. This has no direct effect on the outcome for the tradeoffs curves but assists with keeping the normalization at or near unity.



Alternatives

	1		2		3	
Name of Alternative	Pontoon - 30ft		Drilled Shaft		Pontoon-50ft	
	Design Load (kips)	Cost ($k)	Design Load (kips)	Cost ($k)	Design Load (kips)	Cost ($k)
	700	23000	600	30000	1000	43000

*Step 3. Answer the following questions characterize the relationship between damage and *impact force.*

Note: Minimum and maximum values are optional.
For each alternative, what is the greatest barge *impact force* (kips) that results in no *damage cost?*

Alternative 1: Pontoon - 30ft			Alternative 2: Drilled Shaft			Alternative 3: Pontoon-50ft		
Minimum	Maximum	Most Likely	Minimum	Maximum	Most Likely	Minimum	Maximum	Most Likely

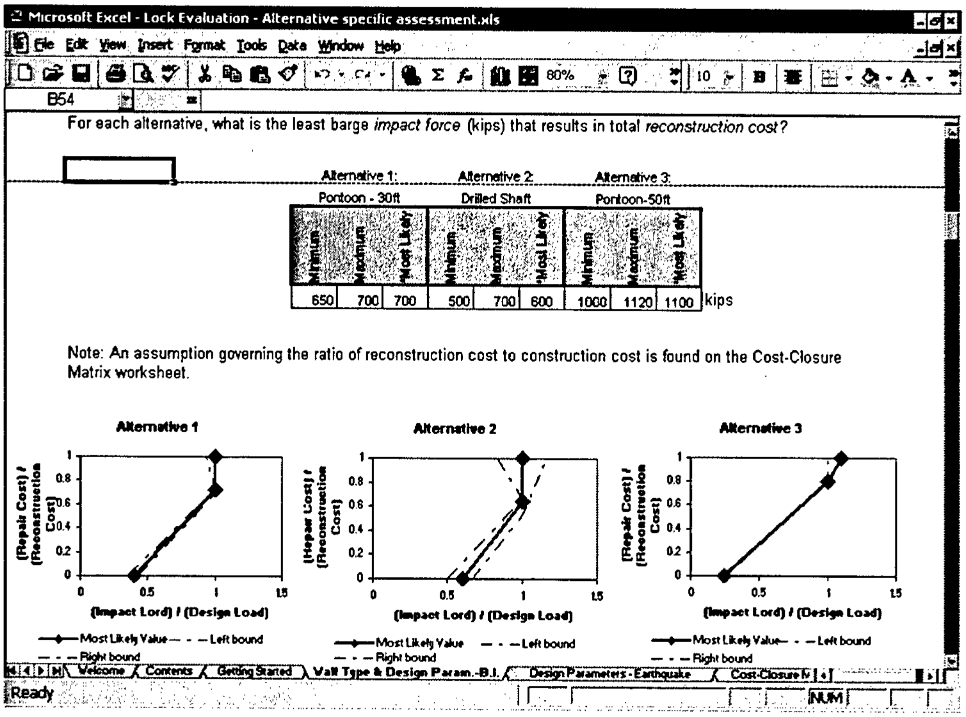
Figure 4.5. Input areas for design alternatives and expert elicitation

In Step 3 (shown in Figure 4.6), the user answers several questions to provide the required input for assessing the relationship between barge impact loads and damage:

a. For each alternative, what is the greatest barge impact force that results in no damage cost?

b. For each alternative, what is the repair cost for a barge impact equal to the design load?

c. For each alternative, what is the least barge impact force that results in total reconstruction cost?



For each alternative, what is the least barge *impact force* (kips) that results in total *reconstruction cost?*

Alternative 1: Pontoon - 30ft			Alternative 2: Drilled Shaft			Alternative 3: Pontoon-50ft			
Minimum	Maximum	Most Likely	Minimum	Maximum	Most Likely	Minimum	Maximum	Most Likely	
650	700	700	500	700	600	1000	1120	1100	kips

Note: An assumption governing the ratio of reconstruction cost to construction cost is found on the Cost-Closure Matrix worksheet.

Figure 4.6. Graphs of assessed relationships for damage from barge impact

The answers to these questions define three points on a graph of *(Repair cost)/ (Reconstruction cost)* versus *(Impact force)/(Design load)* for each alternative as shown in Figure 4.6. With respect to the graphs, the answer to the first question gives a point on the horizontal axis from which the function begins to increase linearly. The next question locates a point at which the horizontal coordinate is 1, because the impact force is equal to the design load. The answer to the question gives the value for the vertical component of the point. Answering the third question locates the point where the vertical component is always 1 but the horizontal component depends on the answer.

No empirical information is available on the relationships between the metrics (e.g., *Repair cost, Time to recover*) and the extreme events. Therefore, such relationships need to be assessed from experts. Allowing the possibility of nonlinear relationships, three points of assessment are chosen. The choice of the three assessment points is not arbitrary. Physically meaningful points needed to be found. Also, these points must adequately describe the relationship. Therefore, the final choice includes a point at zero repair cost, one at the highest, and one in the middle. The questions need to be easily answered by a lock wall designer. The first question, which asks for the magnitude of impact (or earthquake) at which repair is necessary (or lock must be closed), seems to be physically meaningful. So are the second and third questions, which ask for the associated repair cost (or *Time to recover*) due to a barge impact equal to the design load and the minimum magnitude of impact (or earthquake) at which the repair cost is equal to the reconstruction cost. For the case of estimating *Time to recover*, the third assessment point is the magnitude of impact that results in a *Time to recover* of 1 year or more.

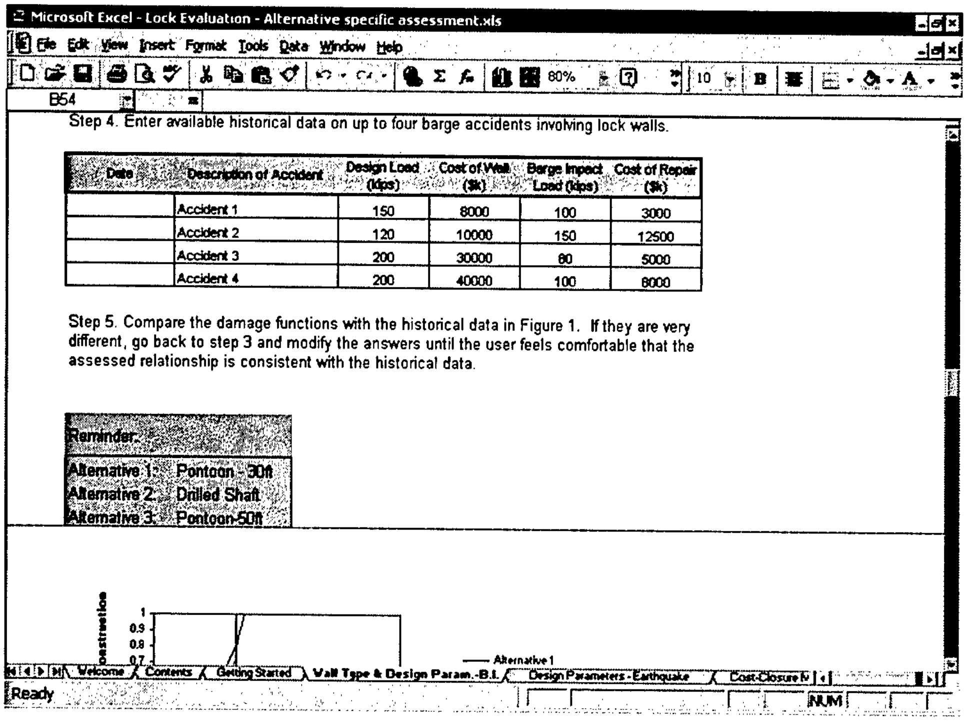
Initially, an attempt was made to assess a normalized relationship that applied to all alternatives between *(Repair cost)/(Reconstruction cost)* and *(Impact load)/(Design load)*, between *(Repair cost)/(Reconstruction cost)* and *(Actual ground motion)/(Design ground motion)*, between *Time to recover* and *(Impact load)/(Design load)*, and between *Time to recover* and *(Actual ground motion)/(Design ground motion)*. For example, the *(Repair cost)/(Reconstruction cost)* versus *(Impact load)/(Design load)* relationship gives the *(Repair cost)/ (Reconstruction cost)* ratio for any alternative given a certain barge impact. Given an alternative with a known design load and construction cost, and thereby reconstruction cost (obtained through a user-defined ratio of reconstruction cost to construction cost), the resulting repair cost can be estimated using the relationship.

However, later it was thought that alternatives could be different enough (e.g., pontoon design versus drilled shaft design) that the normalized relationships mentioned previously were not common to all alternatives. Therefore, it was decided to assess separate relationships for each alternative.

The questions ask experts for minimum, most likely, and maximum numerical estimates. Supplying the three types of answers characterizes the uncertainty of the assessment. However, it is not absolutely necessary to enter minimum and maximum estimates, as these are used only to create the graphs shown in Figure 4.6. Only the most likely estimates are used in the mathematical model for calculating damage. It would have been helpful for the minimum or maximum to be automatically used in the calculations. However, as it stands, a user could replace the most likely value with the minimum or maximum to get an idea of how the output would change.

Step 4, shown in Figure 4.7, asks the user to enter any historical data on actual barge impacts. Since barge impacts and earthquake seldom occur, there are few to no data on damage to lock walls caused by these events. In the process of modeling, a probability model was considered. However, such a model that predicts damage based on probability density functions of barge impact load or earthquake load seems very difficult because it is necessary to have historical data on damage due to impacts (or earthquakes) at the site of lock wall design. Collecting such data might be impossible or too costly. Therefore, it was decided to make use of the little data by allowing the use of historical incidents of impact (or earthquake for earthquake analysis) at any location, thereby pooling together the sparse data. Since these data are no longer accurate predictors of damage, statistically speaking, they are simply used as a guide as the user answers the assessment questions. There is no hard-and-fast rule on how closely the assessed relationship should lie with respect to the historical data. The comparison of the assessed relationship to the historical data is an important step of the methodology. The historical data are plotted along with the relationship assessed in Step 3. From the plot, the user can assess how close his estimated relationship is to the historical data.

Step 5, the next step, is to compare the estimated relationship (called the damage function) to the historical data and to modify the answers in Step 3 if they are too different. The historical data are not used to calculate damage directly; rather, they help in the modeling as a basis for comparison with the



Step 4. Enter available historical data on up to four barge accidents involving lock walls.

Date	Description of Accident	Design Load (kips)	Cost of Wall ($k)	Barge Impact Load (kips)	Cost of Repair ($k)
	Accident 1	150	8000	100	3000
	Accident 2	120	10000	150	12500
	Accident 3	200	30000	80	5000
	Accident 4	200	40000	100	8000

Step 5. Compare the damage functions with the historical data in Figure 1. If they are very different, go back to step 3 and modify the answers until the user feels comfortable that the assessed relationship is consistent with the historical data.

Reminder:
Alternative 1: Pontoon - 30ft
Alternative 2: Drilled Shaft
Alternative 3: Pontoon-50ft

Figure 4.7. Historical data on barge impact accidents and repair costs and comparison with assessed relationships

estimated relationship. It is assumed that a straight-line interpolation of the points assessed in Step 3 is sufficiently accurate to describe the relationship. Figure 4.8 shows the graph. If the historical data are mostly lying outside the left and right bounds, then the user may decide to reconsider the answers to the questions in Step 3. However, the historical data may not lie close to the real relationship when there are few relevant data on actual barge impacts.

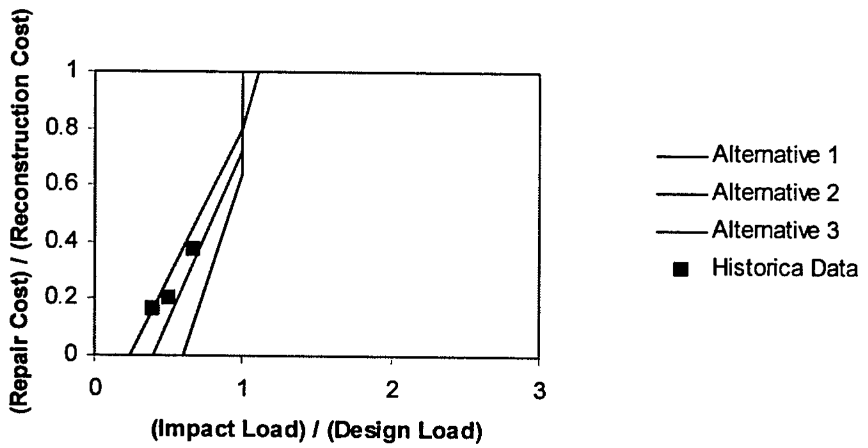


Figure 4.8. Damage function plotted along with historical data for user to modify the estimates entered in Step 3 accordingly if necessary

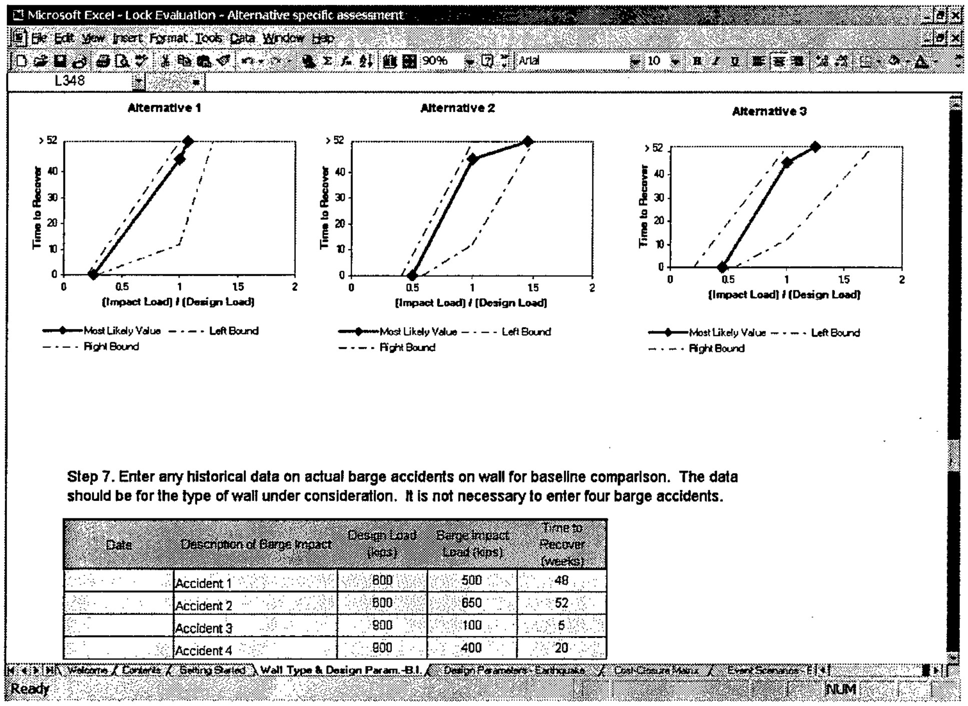
In Step 6 the user is asked several questions in order to assess the relationship between barge impact load and *Time to recover*. These questions are as follows:

a. For each alternative, what is the greatest barge impact force (kips) that results in no closure of the lock?

b. For each alternative, what is the duration of closure (weeks) that results from a barge impact equal to the design load?

c. For each alternative, what is the least barge impact force (kips) that results in a lock closure for 1 year or more?

In Step 7, there is the opportunity to enter any historical data on the *Time to recover* after actual barge impacts (up to four accidents), as shown in Figure 4.9.

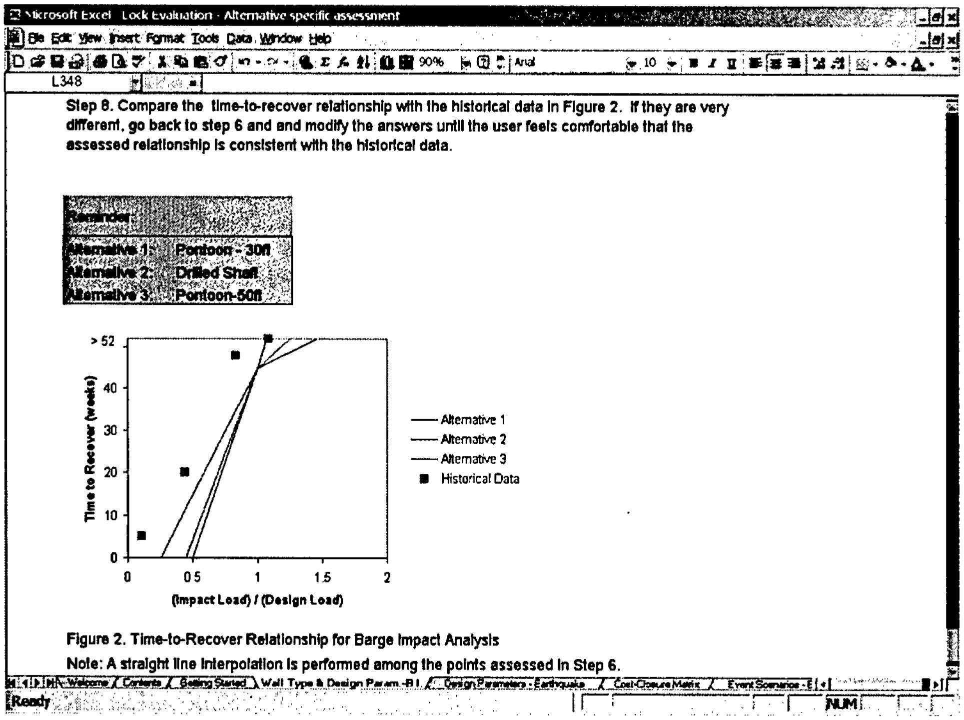


Step 7. Enter any historical data on actual barge accidents on wall for baseline comparison. The data should be for the type of wall under consideration. It is not necessary to enter four barge accidents.

Date	Description of Barge Impact	Design Load (kips)	Barge Impact Load (kips)	Time to Recover (weeks)
	Accident 1	800	500	48
	Accident 2	800	650	52
	Accident 3	800	100	5
	Accident 4	800	400	20

Figure 4.9. Historical data on barge impact accidents and *Time to recover*

In Step 8, a plot is displayed for the user to check whether the input in Step 6 is close to the historical data (see Figure 4.10). Similar to the relationship between *(Repair cost/(Reconstruction Cost)* and *(Impact load)/(Design load)*, a straight-line assumption is made on the points assessed previously. The historical data are plotted along with the relationship assessed in Step 6. From the plot, the user can assess how close his estimated relationship is to the historical data. Step 8 compares the estimated relationship to the historical data, and allows the user to modify the answers in Step 6 if they are too different. The historical data are not used to calculate damage directly, but help in the modeling only as a basis for comparison with the estimated relationship. It is assumed that a straight-line interpolation of the points assessed in Step 6 is sufficient to describe the



Step 8. Compare the time-to-recover relationship with the historical data in Figure 2. If they are very different, go back to step 6 and and modify the answers until the user feels comfortable that the assessed relationship is consistent with the historical data.

Reminder:	
Alternative 1:	**Pontoon - 30ft**
Alternative 2:	**Drilled Shaft**
Alternative 3:	**Pontoon-50ft**

Figure 2. Time-to-Recover Relationship for Barge Impact Analysis

Note: A straight line interpolation is performed among the points assessed in Step 6.

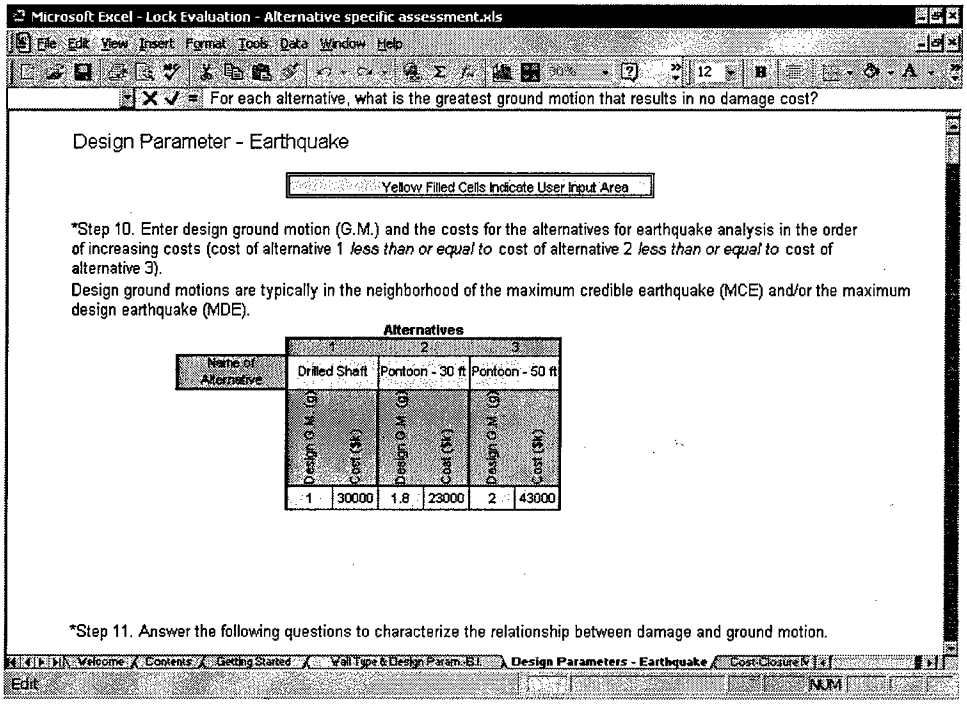
Figure 4.10. Plot of *Time to recover* versus *Impact load* for historical data and estimated relationship

relationship. The minimum and maximum estimates are also plotted in the graph. If the historical data are mostly lying outside the left and right bounds, the user may decide to reconsider the answers to the questions in Step 6. However, the historical data may actually not be very close to the real relationship when there are few relevant data on actual barge impacts.

4.2 Data Input for Earthquake Analysis

The **Design Parameters – Earthquake** worksheet involves earthquake analysis. Shown in Figure 4.11, Step 10 is for the user to enter alternatives for the analysis. For each design alternative, the user supplies the name, the cost of construction, and the design load, which is the force in kips that the structure is designed to withstand. The design alternatives for earthquakes can be the same as or different from those entered in Step 2. The option for entering different alternatives exists because there may not be information on the design ground motion for the alternatives entered for the barge impact analysis. Or, the user may not need to analyze earthquake risks to alternatives for a certain site.

In Step 11 (partially shown in Figure 4.12), the user answers questions to assess the relationship between barge impact loads and damage. In this spreadsheet, damage is expressed as the ratio of repair cost to reconstruction cost. The questions for expert elicitation are these:



For each alternative, what is the greatest ground motion that results in no damage cost?

Design Parameter - Earthquake

Yellow Filled Cells Indicate User Input Area

*Step 10. Enter design ground motion (G.M.) and the costs for the alternatives for earthquake analysis in the order of increasing costs (cost of alternative 1 *less than or equal to* cost of alternative 2 *less than or equal to* cost of alternative 3).

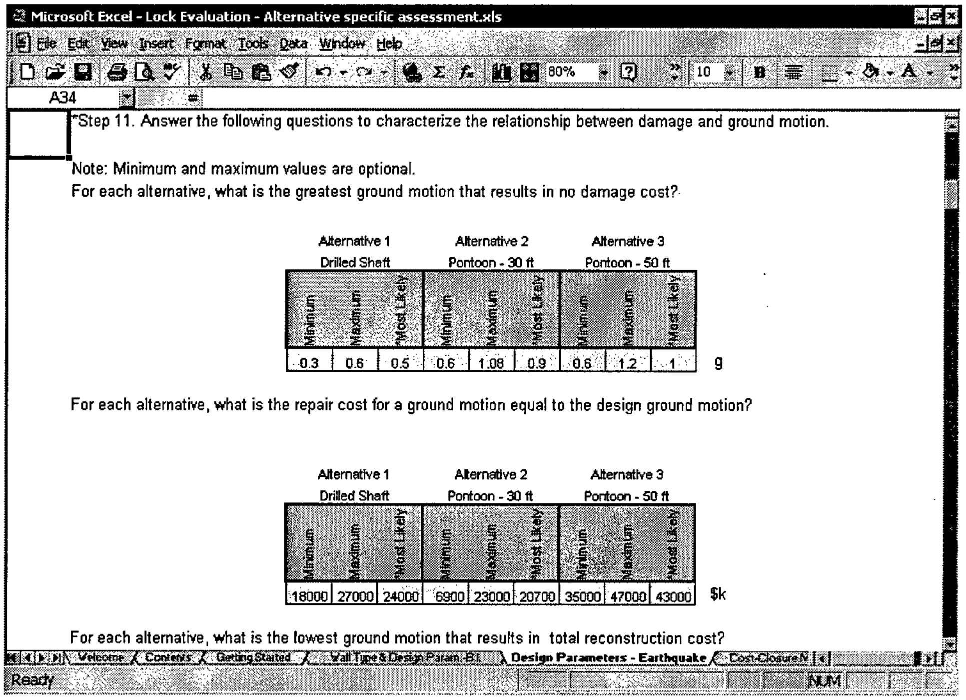
Design ground motions are typically in the neighborhood of the maximum credible earthquake (MCE) and/or the maximum design earthquake (MDE).

Alternatives

	1		2		3	
Name of Alternative	Drilled Shaft		Pontoon - 30 ft		Pontoon - 50 ft	
	Design G.M. (g)	Cost ($k)	Design G.M. (g)	Cost ($k)	Design G.M. (g)	Cost ($k)
	1	30000	1.8	23000	2	43000

*Step 11. Answer the following questions to characterize the relationship between damage and ground motion.

Figure 4.11. Design alternatives for earthquake analysis



*Step 11. Answer the following questions to characterize the relationship between damage and ground motion.

Note: Minimum and maximum values are optional.

For each alternative, what is the greatest ground motion that results in no damage cost?

Alternative 1 Drilled Shaft			Alternative 2 Pontoon - 30 ft			Alternative 3 Pontoon - 50 ft			
Minimum	Maximum	*Most Likely	Minimum	Maximum	*Most Likely	Minimum	Maximum	*Most Likely	
0.3	0.6	0.5	0.6	1.08	0.9	0.6	1.2	1	g

For each alternative, what is the repair cost for a ground motion equal to the design ground motion?

Alternative 1 Drilled Shaft			Alternative 2 Pontoon - 30 ft			Alternative 3 Pontoon - 50 ft			
Minimum	Maximum	*Most Likely	Minimum	Maximum	*Most Likely	Minimum	Maximum	*Most Likely	
18000	27000	24000	6900	23000	20700	35000	47000	43000	$k

For each alternative, what is the lowest ground motion that results in total reconstruction cost?

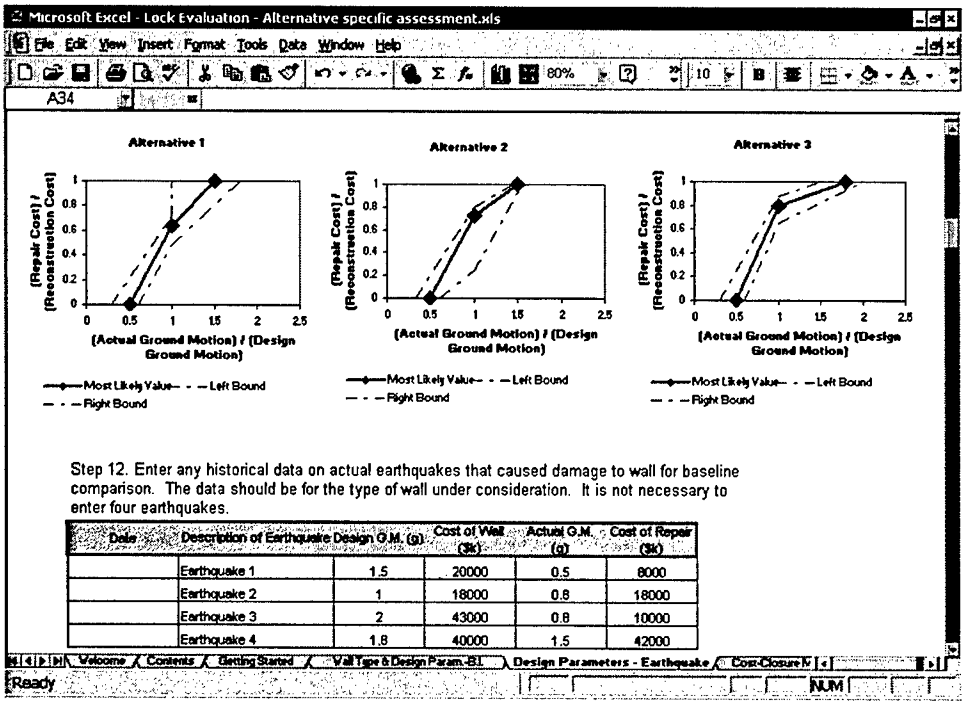
Figure 4.12. Assessment questions for a relationship between *Repair cost* and *Ground motion*

a. For each alternative, what is the greatest ground motion that results in no damage cost?

b. For each alternative, what is the repair cost for a ground motion equal to the design ground motion?

c. For each alternative, what is the lowest ground motion that results in total reconstruction cost?

For each alternative, the answers to these questions give three points on a graph of *(Repair cost)/(Reconstruction cost)* versus *(Actual ground motion)/ (Design ground motion)* as shown in Figure 4.13. With respect to Figure 4.13, the answer to the first question gives a point on the horizontal axis from which the function begins to increase linearly. The next question locates a point where the horizontal coordinate is 1.0 because the actual ground motion is equal to the design ground motion. The answer to the question gives the value for the vertical component of the point. Answering the third question locates a point where the vertical component is always 1 but the horizontal component depends on the answer.



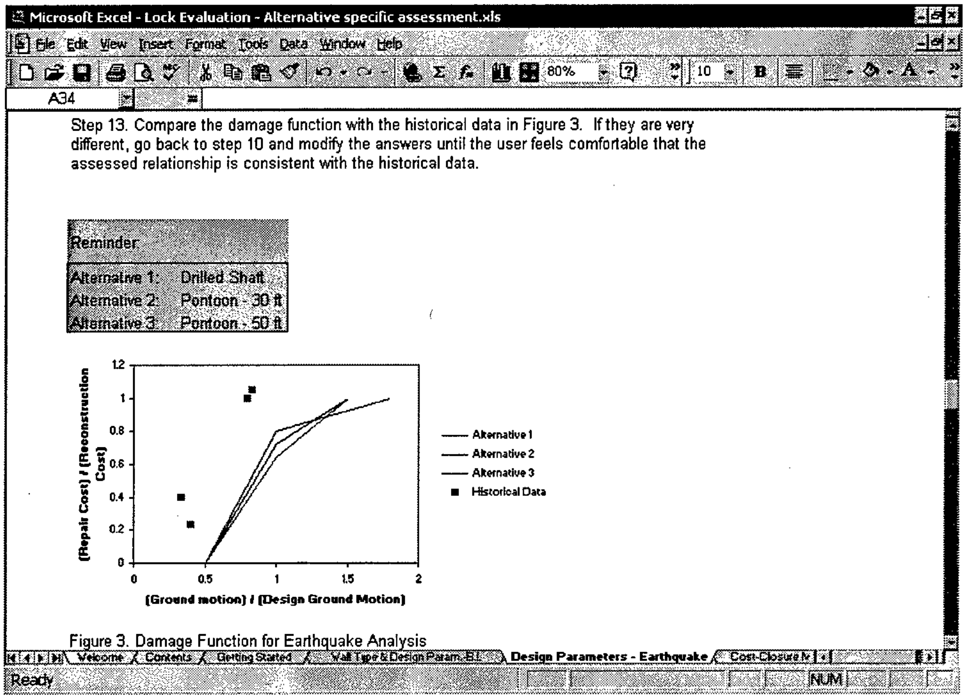
Step 12. Enter any historical data on actual earthquakes that caused damage to wall for baseline comparison. The data should be for the type of wall under consideration. It is not necessary to enter four earthquakes.

Date	Description of Earthquake	Design G.M. (g)	Cost of Wall ($k)	Actual G.M. (g)	Cost of Repair ($k)
	Earthquake 1	1.5	20000	0.5	8000
	Earthquake 2	1	18000	0.8	18000
	Earthquake 3	2	43000	0.8	10000
	Earthquake 4	1.8	40000	1.5	42000

Figure 4.13. Assessed relationships between *Repair cost* and *Ground motion* for alternatives

The questions ask for minimum, most likely, and maximum numerical estimates. Supplying the three types of answers characterizes the uncertainty of the assessment. However, it is not absolutely necessary to enter minimum and maximum estimates as these are only used to create the graph shown in Figure 4.13. Only the most likely estimates are used in the mathematical model for calculating damage.

Step 12 (shown in Figure 4.13) asks the user to enter any historical data on actual earthquakes. The historical data are then plotted along with the relationships assessed in Step 11 (see Figure 4.14). From the plot in Figure 4.14, the user can assess how close his estimated relationship is to the historical data. Shown in Figure 4.14, Step 13, the next step, is to compare the estimated relationship to the historical data, and to modify the answers in Step 11 if they are too different. The historical data are not used to calculate damage directly; it helps in the modeling only as a basis for comparison with the estimated relationship. It is assumed that a straight-line interpolation of the points assessed in Step 11 is sufficient to describe the relationship. If the historical data are mostly lying outside the left and right bounds, then the user may decide to reconsider the answers to the questions in Step 11. However, the historical data may actually not be very close to the real relationship when there are few relevant data on actual earthquakes.



Step 13. Compare the damage function with the historical data in Figure 3. If they are very different, go back to step 10 and modify the answers until the user feels comfortable that the assessed relationship is consistent with the historical data.

Reminder	
Alternative 1:	Drilled Shaft
Alternative 2:	Pontoon - 30 ft
Alternative 3:	Pontoon - 50 ft

Figure 3. Damage Function for Earthquake Analysis

Figure 4.14. Relationships plotted along with historical data for user to modify the estimates entered in Step 11 accordingly if necessary

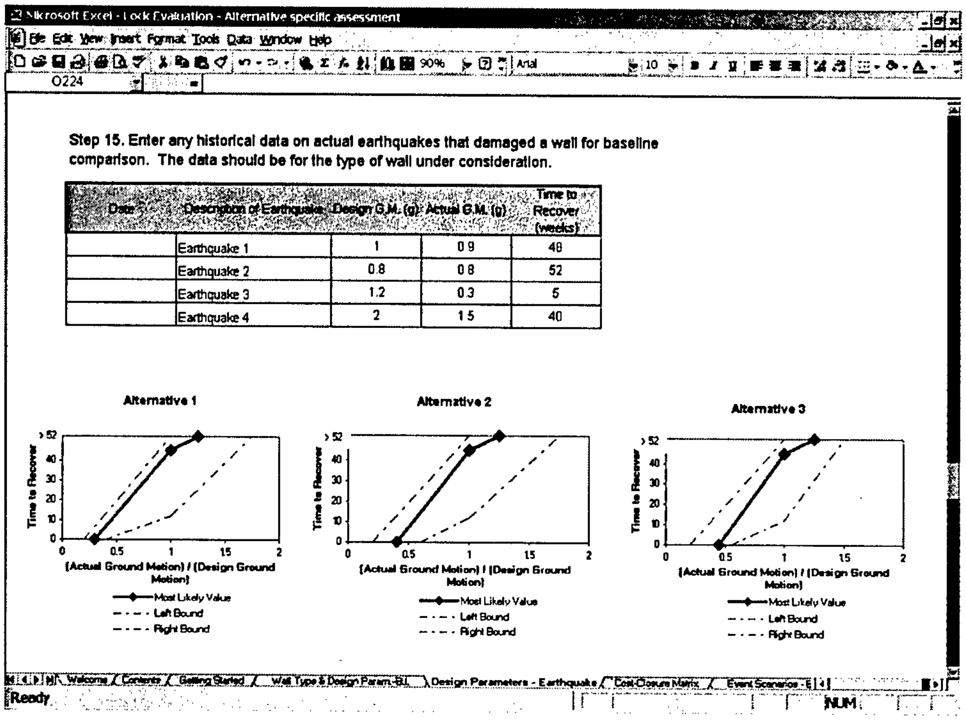
In Step 14 the expert is asked several questions to assess the relationship between ground motions and *Time to recover*. The questions are these:

a. For each alternative, what is the greatest ground motion that results in no closure of the lock?

b. For each alternative, what is the duration of closure that results from a ground motion equal to the design ground motion?

c. For each alternative, what is the least ground motion that results in a lock closure for 1 year or more?

In Step 15 (shown in Figure 4.15), there is the opportunity to enter any historical data on the *Time to recover* after actual earthquakes (up to four incidents).

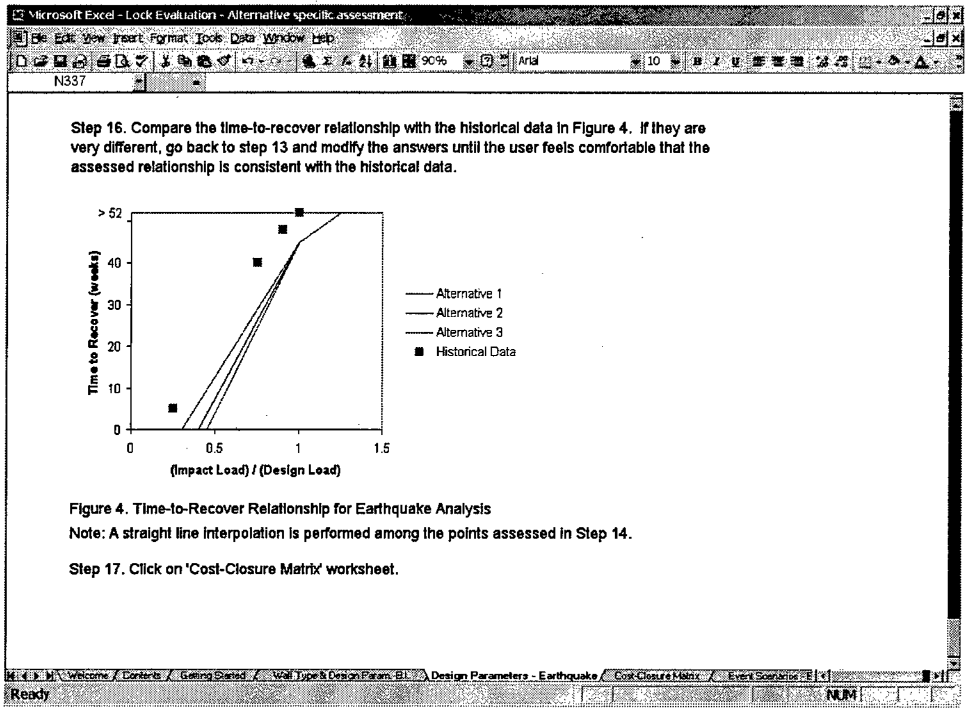


Step 15. Enter any historical data on actual earthquakes that damaged a wall for baseline comparison. The data should be for the type of wall under consideration.

Date	Description of Earthquake	Design G.M. (g)	Actual G.M. (g)	Time to Recover (weeks)
	Earthquake 1	1	0.9	48
	Earthquake 2	0.8	0.8	52
	Earthquake 3	1.2	0.3	5
	Earthquake 4	2	1.5	40

Figure 4.15. Assessed relationships between *Time to recover* and *Ground motion* for alternatives

In Step 16, a plot is displayed for the user to check whether his input in Step 13 is close to the historical data (see Figure 4.16). Similar to the damage function, a straight-line assumption is made on the points assessed previously. The historical data are then plotted along with the relationship assessed in Step 13. From the plot, the user can assess how close his estimated relationship is to the historical data. The next step is to compare the estimated relationship to the historical data, and to modify the answers in Step 13 if they are too different. The historical data are not used to calculate *Time to recover* directly, but help in the modeling as a basis for comparison with the estimated relationship. It is assumed that a straight-line interpolation of the points assessed in Step 13 is sufficiently accurate to describe the relationship. The minimum and maximum estimates are also plotted in the graph. If the historical data are mostly lying outside the left and right bounds, the user may decide to reconsider the answers to the questions in Step 13. However, the historical data may actually not be very close to the real relationship when there are few relevant data on actual earthquakes.



Step 16. Compare the time-to-recover relationship with the historical data in Figure 4. If they are very different, go back to step 13 and modify the answers until the user feels comfortable that the assessed relationship is consistent with the historical data.

Figure 4. Time-to-Recover Relationship for Earthquake Analysis

Note: A straight line interpolation is performed among the points assessed in Step 14.

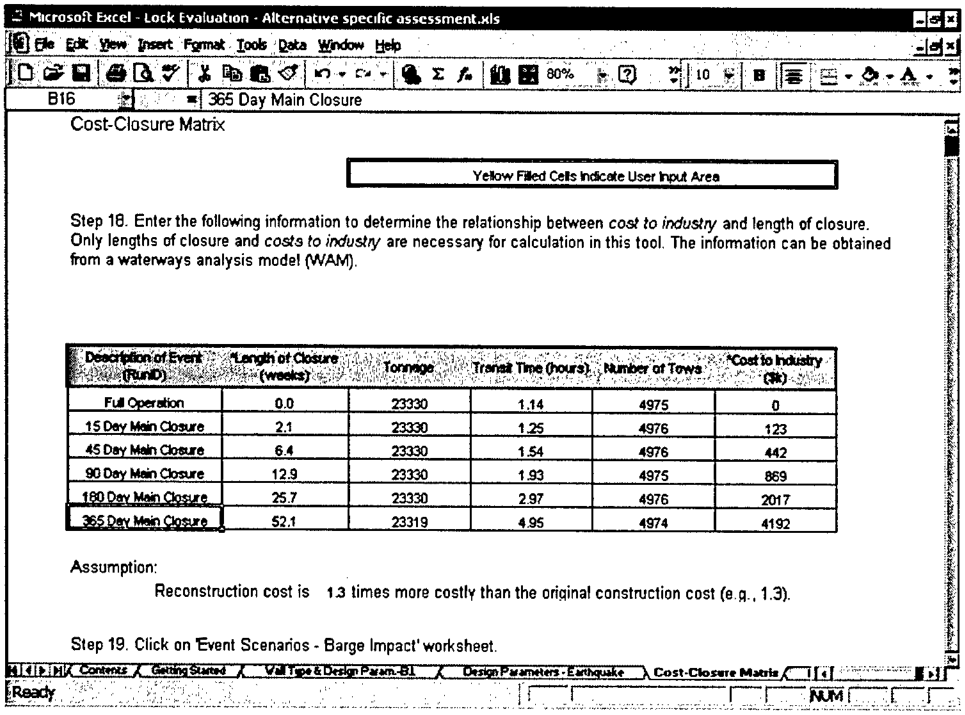
Step 17. Click on 'Cost-Closure Matrix' worksheet.

Figure 4.16. Plot of *Time to recover* versus *Ground motion* for historical data and estimated relationship

4.3 User Input for Calculations of Costs to Industry Due to Lock Closures

The **Cost-Closure Matrix** worksheet (Figure 4.17) is where the user enters information necessary for calculating *Costs to industry* due to lock closures. In addition, there is an assumption on the ratio of reconstruction cost to construction cost that can be changed by the user. Knowing this ratio is necessary for calculation of the reconstruction cost from the construction cost of a design alternative. Also, it is necessary to know the reconstruction cost to calculate the *(Repair cost)/(Reconstruction cost)* metric.

For different lengths of closure of the lock, the user can enter an estimate of the cost to industry. The USACE uses WAM (Waterways Analysis Model), a calculation cost/delay program, to obtain this cost. Curves on the relationship between length of lock closure and *Cost to industry* for Winfield and Smithland Locks were provided by the USACE Navigation Data Center. The table in Step 18 (Figure 4.17) has a layout similar to that of the spreadsheet provided by the USACE.



Cost-Closure Matrix

Yellow Filled Cells Indicate User Input Area

Step 18. Enter the following information to determine the relationship between *cost to industry* and length of closure. Only lengths of closure and *costs to industry* are necessary for calculation in this tool. The information can be obtained from a waterways analysis model (WAM).

Description of Event (RunID)	*Length of Closure (weeks)	Tonnage	Transit Time (hours)	Number of Tows	*Cost to Industry ($k)
Full Operation	0.0	23330	1.14	4975	0
15 Day Main Closure	2.1	23330	1.25	4976	123
45 Day Main Closure	6.4	23330	1.54	4976	442
90 Day Main Closure	12.9	23330	1.93	4975	869
180 Day Main Closure	25.7	23330	2.97	4976	2017
365 Day Main Closure	52.1	23319	4.95	4974	4192

Assumption:

Reconstruction cost is 1.3 times more costly than the original construction cost (e.g., 1.3).

Step 19. Click on 'Event Scenarios - Barge Impact' worksheet.

Figure 4.17. **Cost-Closure Matrix** worksheet

4.4 Event Scenario Entries for Barge Impacts

The **Event Scenarios - Barge Impact** worksheet (shown in Figure 4.18) displays the values that are calculated from the input on the **Wall Type & Design Parameters – Barge Impact** worksheet. These values are the costs of construction of the alternatives and various risk metrics. The construction cost is plotted on the vertical axis, while a risk metric is plotted on the horizontal. In this way, the user could see the present investment and the risk of a barge accident. Four risk metrics describe the consequences of barge impact occurring:

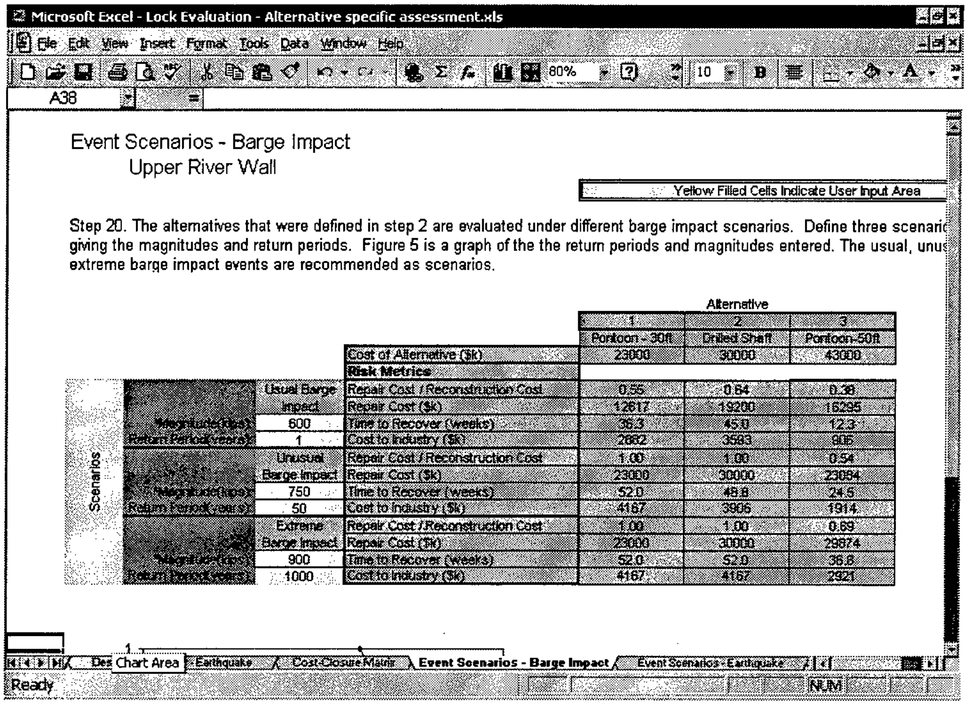
a. Ratio of *Repair cost* to *Reconstruction cost.*

b. *Repair cost.*

c. *Time to recover.*

d. *Cost to industry.*

In Step 20, the user enters three scenarios of barge impact under which to evaluate the alternatives. For each scenario, the user needs to give the magnitude of collision and the return period of the event. The magnitudes and return periods entered by the user are plotted in Figure 4.19 for the user to check the reasonableness of the entered values.



Event Scenarios - Barge Impact
Upper River Wall

Yellow Filled Cells Indicate User Input Area

Step 20. The alternatives that were defined in step 2 are evaluated under different barge impact scenarios. Define three scenari giving the magnitudes and return periods. Figure 5 is a graph of the the return periods and magnitudes entered. The usual, unu extreme barge impact events are recommended as scenarios.

				Alternative		
				1	2	3
				Pontoon - 30ft	Drilled Shaft	Pontoon-50ft
			Cost of Alternative ($k)	23000	30000	43000
			Risk Metrics			
Scenarios		Usual Barge Impact	Repair Cost / Reconstruction Cost	0.55	0.64	0.38
			Repair Cost ($k)	12617	19200	16295
	Magnitude(kips):	600	Time to Recover (weeks)	36.3	45.0	12.3
	Return Period(years):	1	Cost to Industry ($k)	2882	3583	905
		Unusual Barge Impact	Repair Cost / Reconstruction Cost	1.00	1.00	0.54
			Repair Cost ($k)	23000	30000	23084
	Magnitude(kips):	750	Time to Recover (weeks)	52.0	48.8	24.5
	Return Period(years):	50	Cost to Industry ($k)	4167	3906	1914
		Extreme Barge Impact	Repair Cost / Reconstruction Cost	1.00	1.00	0.69
			Repair Cost ($k)	23000	30000	29874
	Magnitude(kips):	900	Time to Recover (weeks)	52.0	52.0	36.8
	Return Period(years):	1000	Cost to Industry ($k)	4167	4167	2921

Figure 4.18. Top of **Event Scenarios - Barge Impact** worksheet with scenario entry boxes

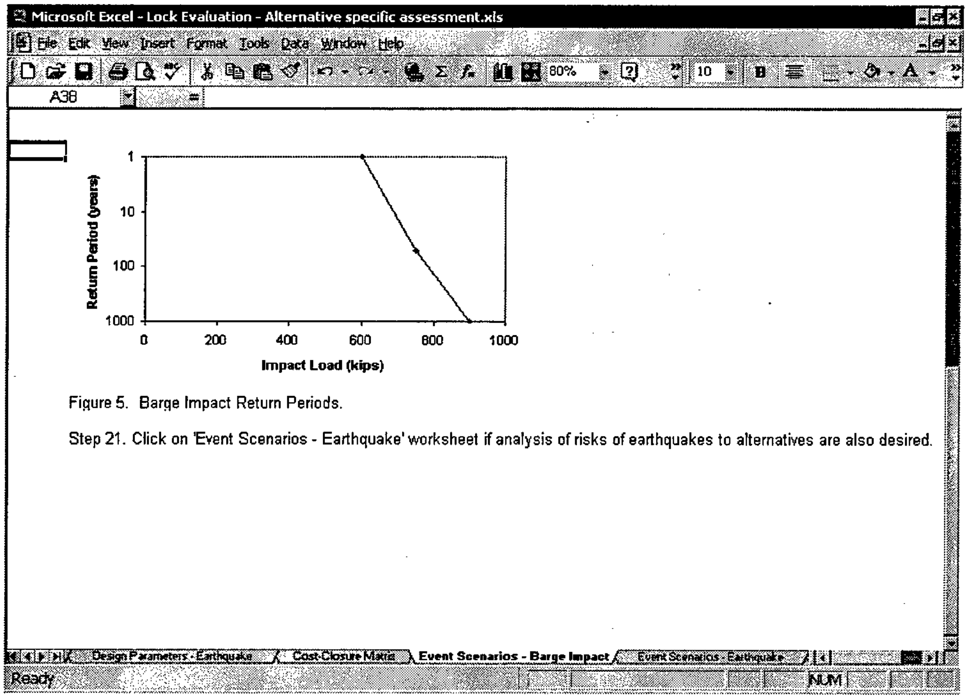


Figure 5. Barge Impact Return Periods.

Step 21. Click on 'Event Scenarios - Earthquake' worksheet if analysis of risks of earthquakes to alternatives are also desired.

Figure 4.19. Plot of barge impact magnitudes and return periods entered by user

4.5 Event Scenario Entries for Earthquakes

The **Event Scenarios - Earthquake** worksheet is similar to the **Event Scenarios - Barge Impact** worksheet. The **Event Scenarios - Earthquake** worksheet (Figure 4.20) displays the values that are calculated from the input on the **Design Parameters – Earthquake** worksheet. The values are the costs of construction of the alternatives and various risk metrics. The construction cost is plotted on the vertical axis, while a risk metric is plotted on the horizontal. In this way, the user can see the present investment and the risk of a barge accident. Four risk metrics describe the consequences of an earthquake occurring:

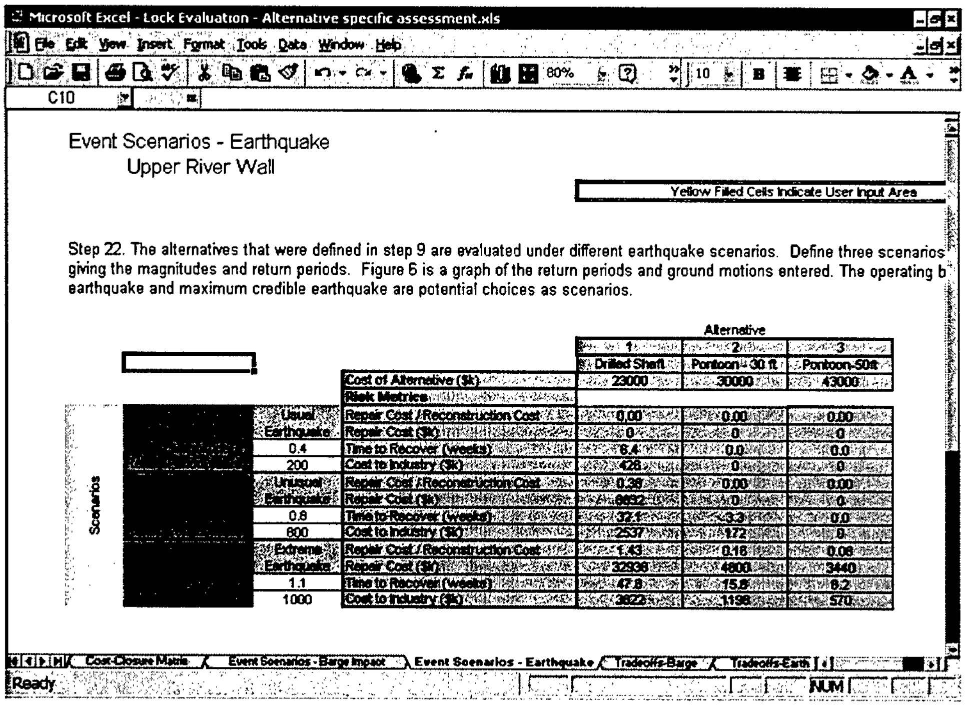
a. Ratio of *Repair cost* to *Reconstruction cost.*

b. *Repair cost.*

c. *Time to recover.*

d. *Cost to industry.*

In Step 22, the user enters three scenarios of earthquakes under which to evaluate the alternatives. For each scenario, the user needs to give the ground motion of earthquake and the return period of the event. The magnitudes and return periods entered by the user are plotted for the user to check the reasonableness of the values. Figure 4.21 shows the plot.



Event Scenarios - Earthquake
Upper River Wall

Yellow Filled Cells Indicate User Input Area

Step 22. The alternatives that were defined in step 9 are evaluated under different earthquake scenarios. Define three scenarios giving the magnitudes and return periods. Figure 6 is a graph of the return periods and ground motions entered. The operating b earthquake and maximum credible earthquake are potential choices as scenarios.

Scenarios		Alternative 1	2	3
		Drilled Shaft	Pontoon - 30 ft	Pontoon-50ft
	Cost of Alternative ($k)	23000	30000	43000
	Risk Metrics			
Usual Earthquake	Repair Cost / Reconstruction Cost	0.00	0.00	0.00
	Repair Cost ($k)	0	0	0
0.4	Time to Recover (weeks)	6.4	0.0	0.0
200	Cost to Industry ($k)	428	0	0
Unusual Earthquake	Repair Cost / Reconstruction Cost	0.38	0.00	0.00
	Repair Cost ($k)	8692	0	0
0.8	Time to Recover (weeks)	32.1	3.3	0.0
800	Cost to Industry ($k)	2537	172	0
Extreme Earthquake	Repair Cost / Reconstruction Cost	1.43	0.16	0.08
	Repair Cost ($k)	32936	4800	3440
1.1	Time to Recover (weeks)	47.8	15.8	8.2
1000	Cost to Industry ($k)	3822	1198	570

Figure 4.20. Top of **Event Scenarios - Earthquake** worksheet with scenario entry boxes

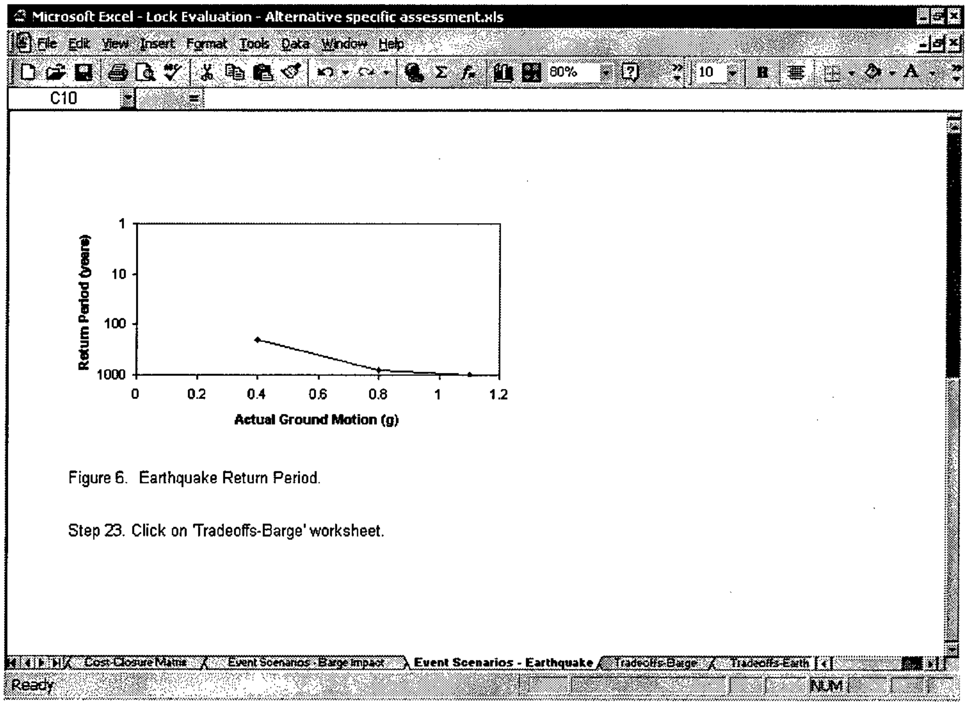


Figure 6. Earthquake Return Period.

Step 23. Click on 'Tradeoffs-Barge' worksheet.

Figure 4.21. Plot of ground motions and return periods entered by user

5 Development of Output Section of an Automated Tool for Multiple-Criteria Lock Wall Design

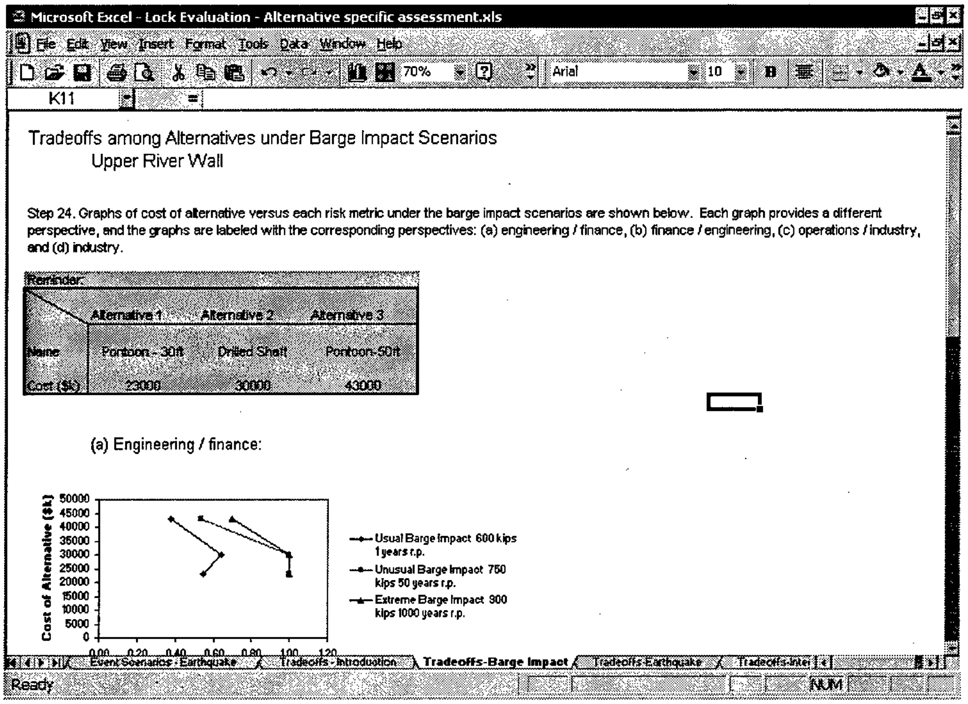
5.1 Tradeoffs Among Alternatives Under Barge Impact Scenarios

The **Tradeoffs – Barge Impact** worksheet contains graphs that show the tradeoffs between the alternatives under the barge impact scenarios. Figure 5.1 shows the top of the worksheet including the first graph, *Cost of alternative* versus *(Repair cost)/ (Reconstruction cost)*. Figure 5.2 shows a larger version of the graph. The approach to interpret the curves in the graphs is to view the cost of an alternative on the vertical axis as the present investment for that alternative and the value on the horizontal axis as a consequence of a barge impact incident provided that the alternative was chosen. The consequence can be any of the risk metrics, such as *(Repair cost)/(Reconstruction cost)*, *Repair cost, Time to recover*, or *Cost to industry.* The three curves are associated with the three scenarios entered previously in Step 20. These three scenarios are three probable barge impact incidents that have different probabilities of occurrence, and therefore different return periods. For example, referring to the graph in Figure 5.2, the user can determine the ratio of repair to reconstruction cost for different levels of investment under the different barge impact scenarios.

The following section depicts one possible sequence of decisions based on Figure 5.2 that leads to selection of an alternative. The decisions are an illustration of a barge impact example using the workbook.

Assumptions regarding the design situation, including the nature of the site and the preferences of the lock wall designer, are as follows:

- The user is interested only in the risk metric *(Repair cost)/ (Reconstruction cost).*
- The site for construction of the lock does not lie in an earthquake zone. Therefore, consideration of earthquake scenarios is not necessary.



Tradeoffs among Alternatives under Barge Impact Scenarios
Upper River Wall

Step 24. Graphs of cost of alternative versus each risk metric under the barge impact scenarios are shown below. Each graph provides a different perspective, and the graphs are labeled with the corresponding perspectives: (a) engineering / finance, (b) finance / engineering, (c) operations / industry, and (d) industry.

Reminder:

	Alternative 1	Alternative 2	Alternative 3
Name	Pontoon - 30ft	Drilled Shaft	Pontoon-50ft
Cost ($k)	23000	30000	43000

(a) Engineering / finance:

Figure 5.1. Top of **Tradeoffs - Barge Impact** worksheet

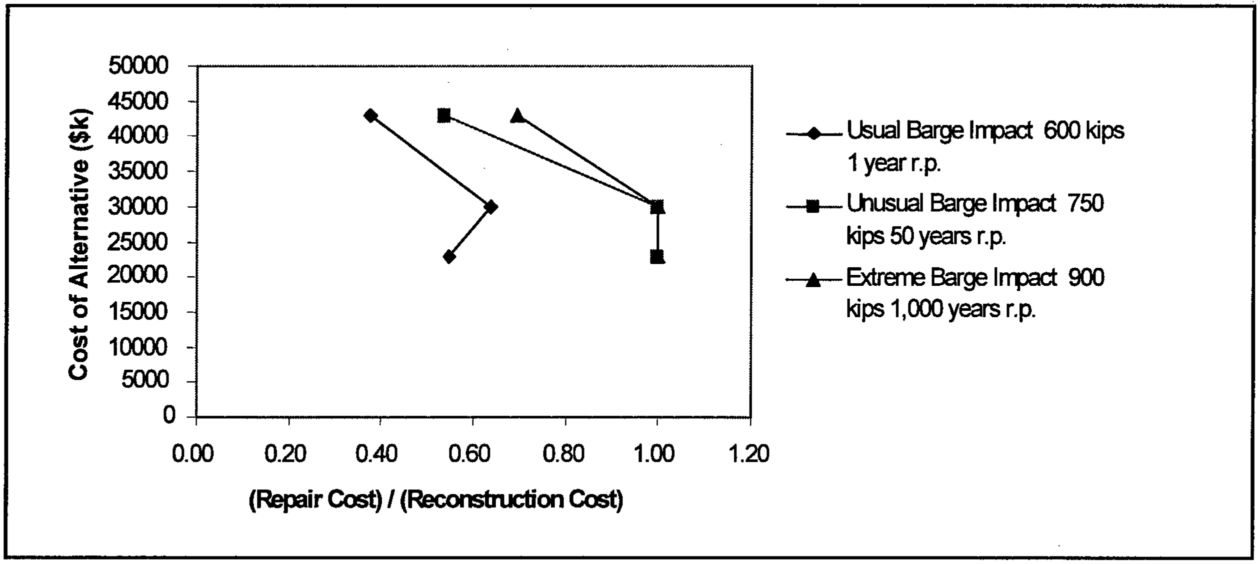


Figure 5.2. Tradeoffs of *Cost of alternative* versus (*Repair cost*)/(*Reconstruction cost*) between designs in different barge impact scenarios (Note: r.p. = return period)

- The user does not want to consider alternatives over $30M. The user believes that the two alternatives are enough options from which to choose.
- The set of barge impact scenarios truly represents the usual, unusual, and extreme cases.

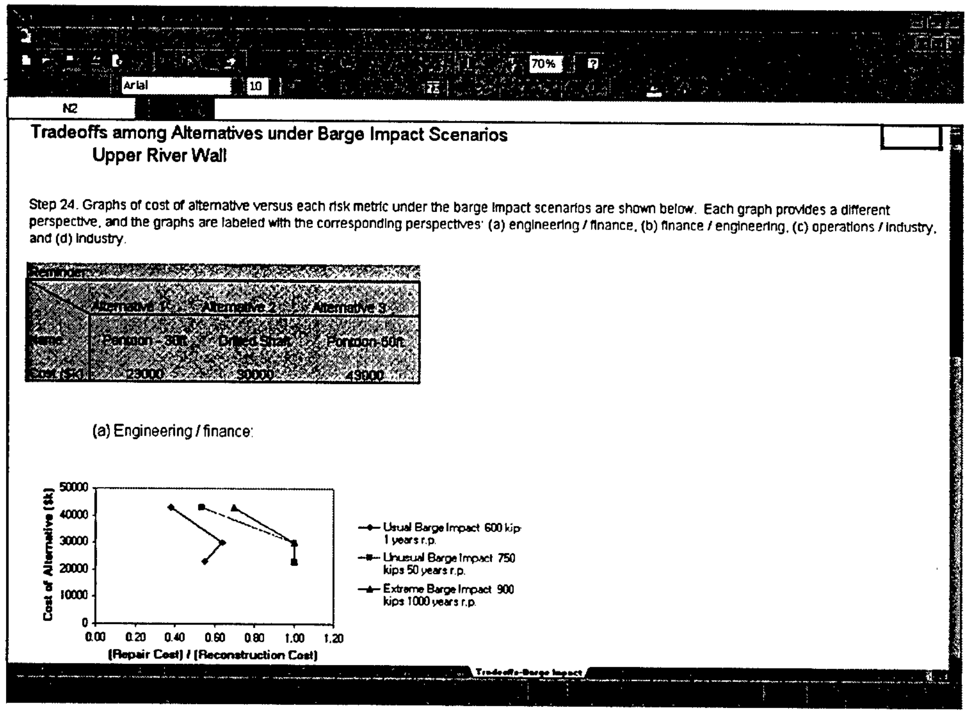
The tradeoffs among alternatives are as follows:

- For the unusual and extreme scenarios, the \$30M and \$23M alternatives have the same *(Repair cost)/(Reconstruction cost)*. Therefore, a \$7M increase in cost does not have a benefit in this particular risk metric.
- For the usual scenario, the \$30M alternative actually has a greater *(Repair cost)/(Reconstruction cost)* than the \$23M alternative. Therefore, there is really no tradeoff, and the \$30M design is dominated.

The following conclusion can be drawn:

- The \$23M pontoon alternative is chosen.

Lambert (2001) shows that there can be multiple perspectives on impacts in multiple-criteria tradeoff analysis. Each graph on the worksheet presents tradeoffs from a unique perspective. The graph with *(Repair cost)/(Reconstruction cost)* is of an engineering and finance perspective (see Figure 5.3). Primarily, the graph gives an engineering perspective because the ratio of the costs gives an idea of the structural damage. The monetary components of the graph can also give a financial point of view.



Tradeoffs among Alternatives under Barge Impact Scenarios
Upper River Wall

Step 24. Graphs of cost of alternative versus each risk metric under the barge impact scenarios are shown below. Each graph provides a different perspective, and the graphs are labeled with the corresponding perspectives: (a) engineering / finance, (b) finance / engineering, (c) operations / industry, and (d) industry.

Reminder:

	Alternative 1	Alternative 2	Alternative 3
Name	Pontoon - 30ft	Drilled Shaft	Pontoon-50ft
Cost ($k)	23000	30000	43000

(a) Engineering / finance:

Figure 5.3. Engineering/finance perspective on tradeoffs among lock wall alternatives

Second, the graph with repair cost primarily shows a financial perspective and gives an engineering point of view because repair cost is closely related to physical damage. Therefore, the perspective of Figure 5.4 with repair cost is finance and engineering.

Third, the graph with *Time to recover* (Figure 5.4) has an operations and industry perspective. The time that a lock is closed is when the lock cannot be operated. The industries that rely on the lock are very naturally concerned about the length of the *Time to recover*.

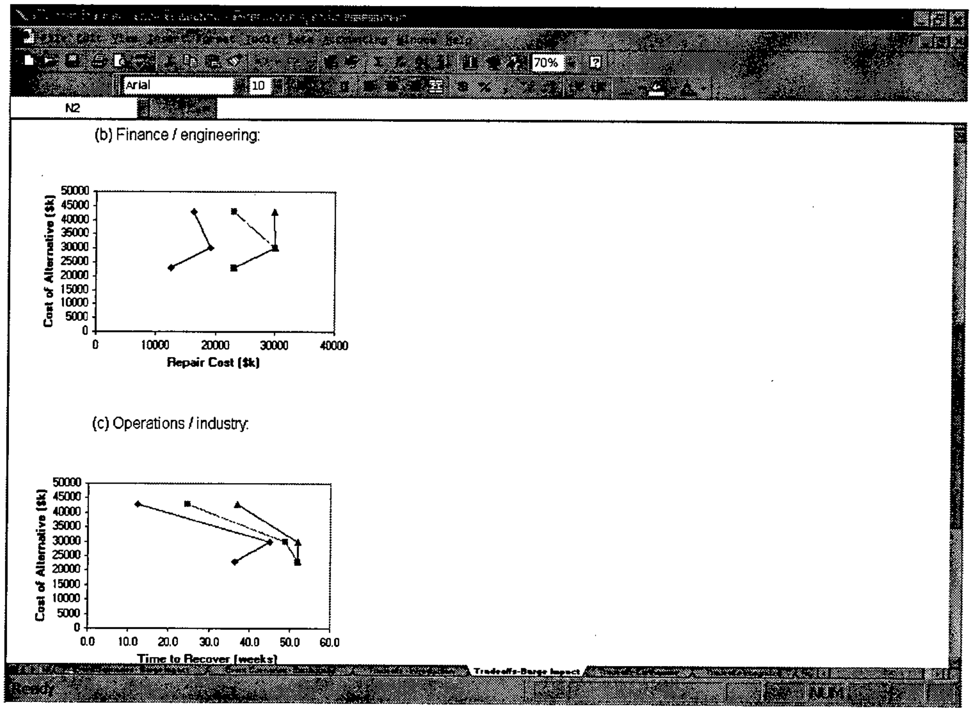
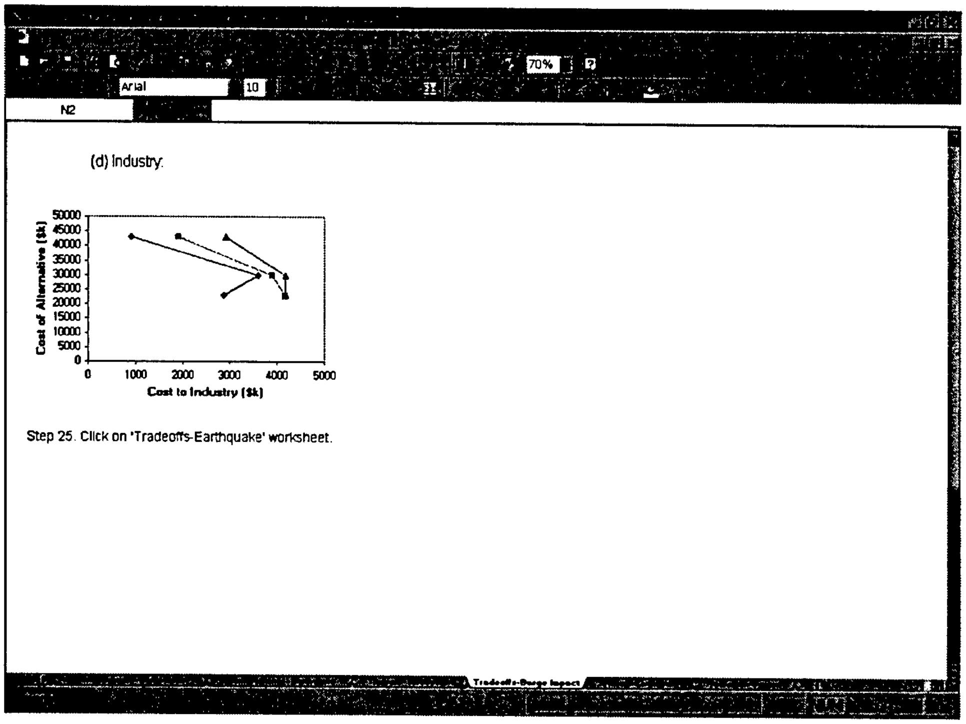


Figure 5.4. Finance/engineering and operations/industry perspectives on tradeoffs among lock wall alternatives

Fourth, the graph with *Cost to industry*, shown in Figure 5.5, has an industry perspective.

5.2 Tradeoffs Among Alternatives Under Earthquake Scenarios

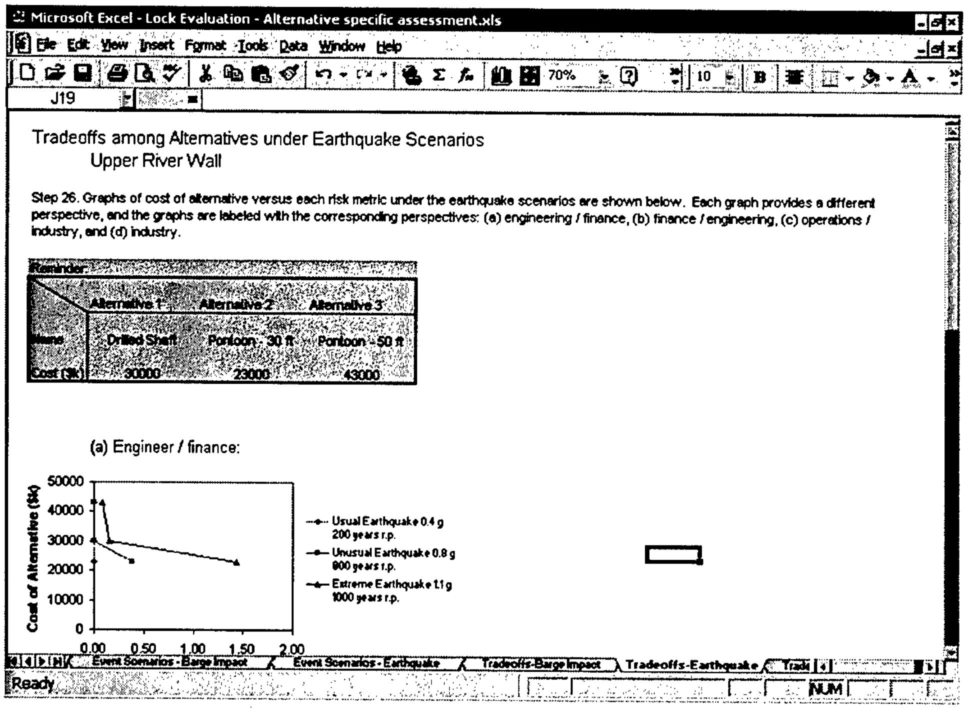
The **Tradeoffs – Earthquakes** worksheet contains graphs that show the tradeoffs among the alternatives under the earthquake scenarios. Figure 5.6 shows the top of the worksheet including the first graph, *Cost of alternative* versus (*Repair cost*)/(*Reconstruction cost*). Figure 5.7 shows a larger version of the graph. The way to interpret the curves in the graphs is to view the cost of an alternative on the vertical axis as the present investment for that alternative and the value on the horizontal axis as a consequence of an earthquake provided the alternative were chosen. The consequence can be any of the risk metrics, such as (*Repair cost*)/(*Reconstruction cost*), *Repair cost, Time to recover*, or *Cost to industry*. The three curves are associated with the three scenarios entered previously in Step 22. These three scenarios are three probable earthquake events that have different probabilities of occurrence, and therefore different return periods. For example, referring to the graph in Figure 5.7, the user can determine the ratio



(d) Industry:

Step 25. Click on 'Tradeoffs-Earthquake' worksheet.

Figure 5.5. Industry perspective on tradeoffs among lock wall alternatives



Tradeoffs among Alternatives under Earthquake Scenarios
Upper River Wall

Step 26. Graphs of cost of alternative versus each risk metric under the earthquake scenarios are shown below. Each graph provides a different perspective, and the graphs are labeled with the corresponding perspectives: (a) engineering / finance, (b) finance / engineering, (c) operations / industry, and (d) industry.

Reminder:

	Alternative 1	Alternative 2	Alternative 3
Name	Drilled Shaft	Pontoon - 30 ft	Pontoon - 50 ft
Cost ($k)	30000	23000	43000

(a) Engineer / finance:

Figure 5.6. Top of **Tradeoffs - Earthquake** worksheet

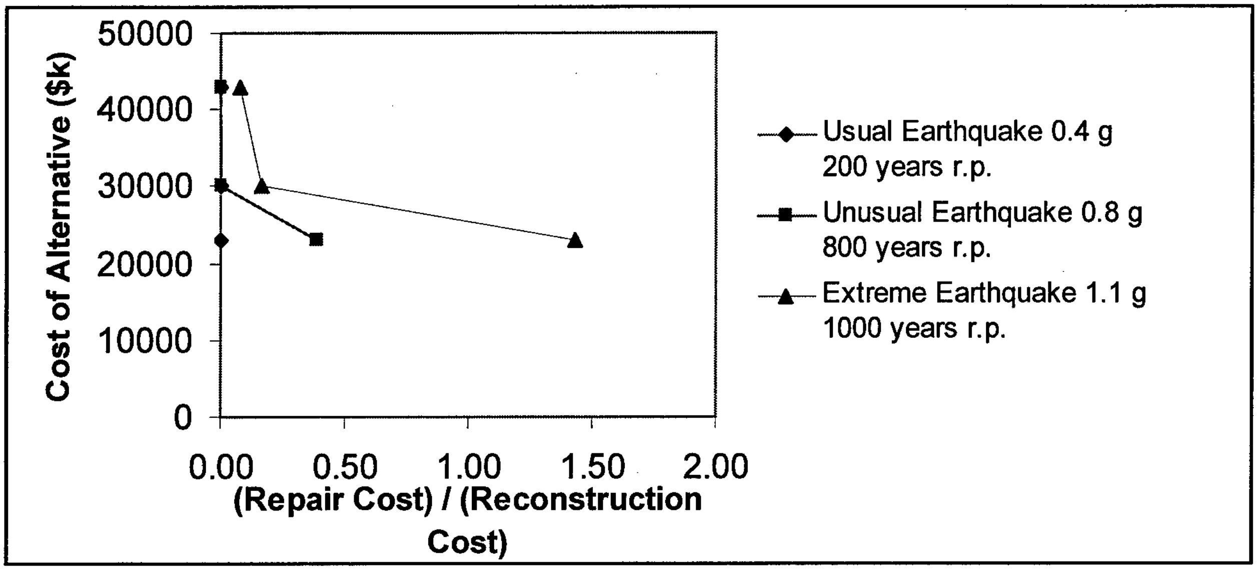


Figure 5.7. Tradeoffs of *Cost of alternative* versus (*Repair cost*)/(*Reconstruction cost*) between designs in different earthquake scenarios

of repair to reconstruction cost for different levels of investment under the different earthquake scenarios.

One possible sequence of decisions based on Figure 5.7 that leads to selection of an alternative is described below. The decisions are an example of an earthquake analysis using the tool. Assumptions on the design situation, including the nature of the site and preferences of the lock wall designer, are as follows:

- The user is interested only in the risk metric *(Repair cost)/ (Reconstruction cost)*.
- The user is only interested in earthquake risks to the alternatives. Therefore, consideration of barge impact scenarios is not necessary.
- The set of alternatives is agreeable to the user.
- The usual earthquake has a reasonable recurrence rate, but the unusual and extreme earthquakes have such large return periods that their risks are negligible.

The tradeoffs among alternatives are as follows:

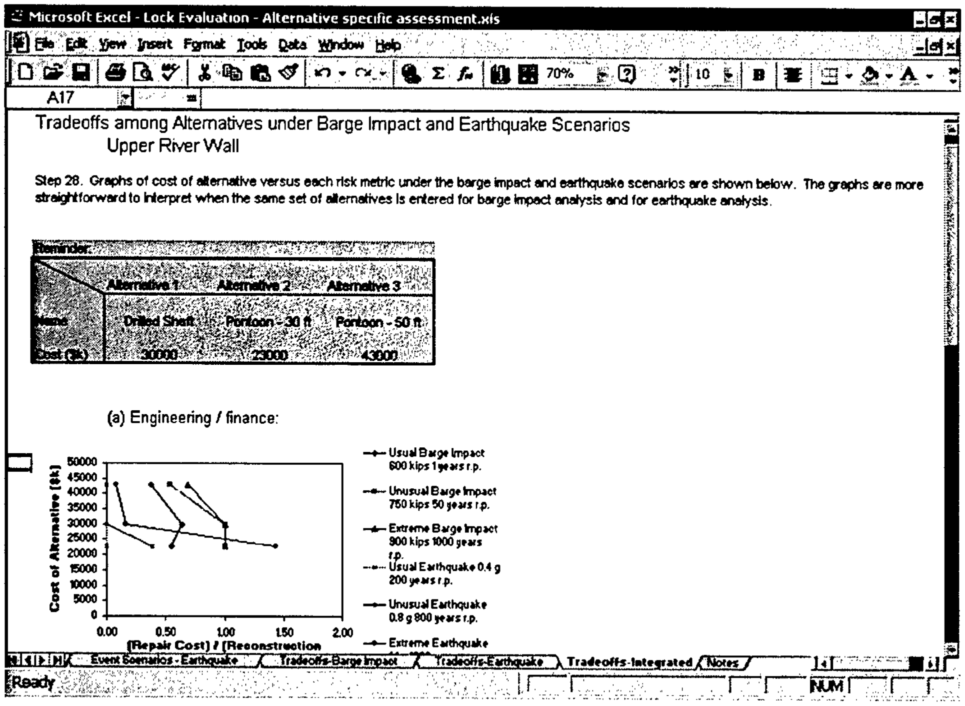
- Since only the usual scenario is of interest to the user, there is no benefit in *(Repair cost)/(Reconstruction cost)* in choosing the $30M or $43M alternative over the $23M alternative. Therefore, there is no tradeoff among the three alternatives.

The following conclusion can be drawn:

- The $23M alternative is chosen.

5.3 Tradeoffs Among Alternatives Under Barge Impacts and Earthquake Scenarios

The **Tradeoffs – Integrated** worksheet contains graphs that show the tradeoffs between the alternatives under the barge impact and earthquake scenarios. Figure 5.8 shows the top of the worksheet including the first graph, *Cost of alternative* versus (*Repair cost*)/(*Reconstruction cost*). Figure 5.9 shows a larger version of the graph. The way to interpret the curves in the graphs is to view the cost of an alternative on the vertical axis as the present investment for that alternative and the value on the horizontal axis as a consequence of a barge impact incident or earthquake provided the alternative were chosen. The consequence can be any of the risk metrics such as (*Repair cost*)/ (R*econstruction cost*), *Repair cost, Time to recover*, or *Cost to industry*. The six curves are associated with the three scenarios entered previously in Steps 20 and 22. These six scenarios are three probable earthquake events and three probable barge impact incidents that have different probabilities of occurrence, and therefore different return periods. For example, referring to the graph in Figure 5.9, the user can determine the ratio of repair to reconstruction cost for different levels of investment under the different earthquake scenarios.



Tradeoffs among Alternatives under Barge Impact and Earthquake Scenarios
Upper River Wall

Step 28. Graphs of cost of alternative versus each risk metric under the barge impact and earthquake scenarios are shown below. The graphs are more straightforward to interpret when the same set of alternatives is entered for barge impact analysis and for earthquake analysis.

Reminder:

	Alternative 1	Alternative 2	Alternative 3
Name	Drilled Shaft	Pontoon - 30 ft	Pontoon - 50 ft
Cost ($k)	30000	23000	43000

(a) Engineering / finance:

Figure 5.8. Top of **Tradeoffs - Integrated** worksheet

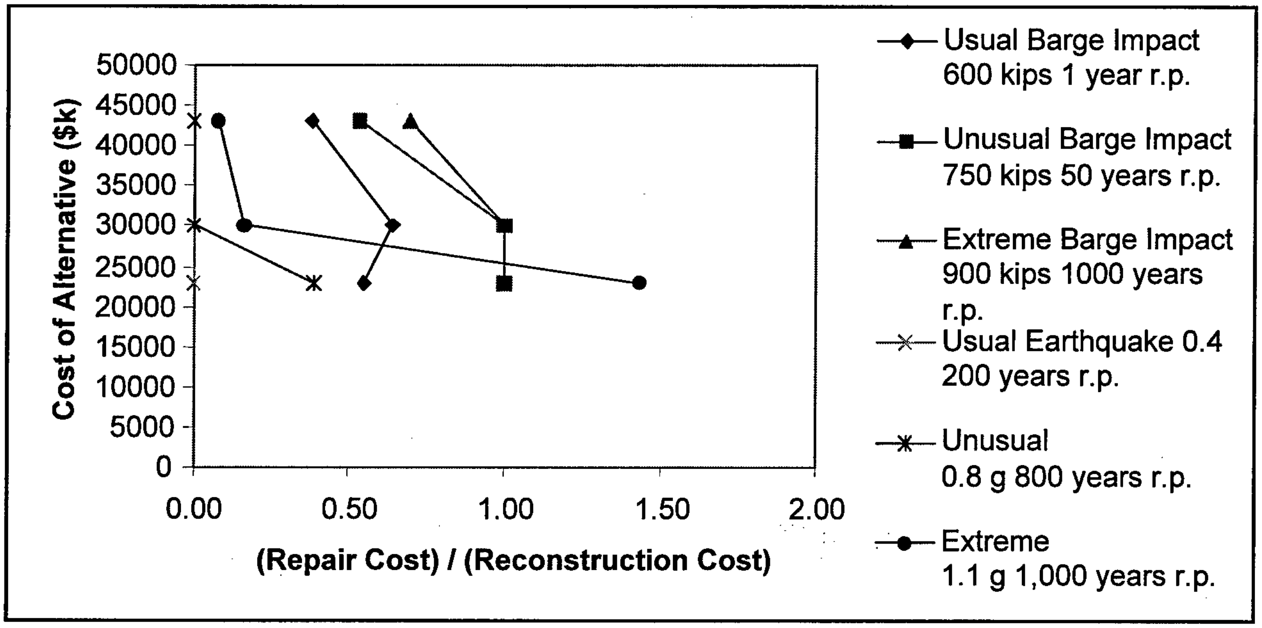


Figure 5.9. Tradeoffs of *Cost of alternative* versus (*Repair cost*)/(*Reconstruction cost*) between designs in different barge impact and earthquake scenarios

One possible sequence of decisions based on Figure 5.9 that leads to selection of an alternative is described below. The decisions are an example of an integrated analysis using the tool. Assumptions on the design situation, including the nature of the site and the preferences of the lock wall designer, are as follows:

- The user is interested only in the risk metric *(Repair cost)/ (Reconstruction cost)*.

The three alternatives are representative of the possible design options.The tradeoffs among alternatives are as follows:

- Comparing the $30M and $23M alternatives, tradeoffs exist in the unusual and extreme earthquake cases.
    - In the usual barge impact case, which occurs once a year on average, the $30M alternative actually has a 10 percent greater *(Repair cost)/ (Reconstruction cost)* than the $23M alternative. If reconstruction cost is equal to construction cost, the extra repair cost for the more costly alternative is ($30M* 0.6 - $23M*0.5), or $6.5M. Although there are tradeoffs between the two alternatives if an unusual or extreme earthquake occurred, these events have return periods of 800 and 1,000 years. In comparison to the much more likely event of a usual barge impact, the disadvantage under the barge impact scenario outweighs the benefits under earthquake scenarios. Therefore, given only these two alternatives, the $23M one will be chosen.

    - There is a more drastic tradeoff of *(Repair cost)/(Reconstruction cost)* for *Cost of alternative* in the extreme case than in the unusual case.

- Comparing the $43M and $30M alternatives, tradeoffs exist in the extreme earthquake case and in all three barge impact cases. More severe cases have larger tradeoffs.
- Comparing the $43M and $23M alternatives, tradeoffs exist in the unusual and extreme earthquake cases and in all three barge impact cases.
    - In the usual barge impact case with a return period of 1 year, there is a reduction of 0.15 in the *(Repair cost)/(Reconstruction cost)* going from the $23M alternative to the $43M alternative.
    - In the unusual barge impact case, there is a reduction of 0.45 in the *(Repair cost)/(Reconstruction cost)* going from $23M alternative to the $43M alternative.
    - In the unusual earthquake, there is a reduction from 0.4 to 0 in the *(Repair cost)/(Reconstruction cost)* when the more costly alternative is chosen.

The following conclusions can be drawn:

- It seems that the $30M alternative is inferior to the $23M alternative. So, the $23M and $43M alternatives remain in consideration.
- If the tradeoffs between *Cost of alternative* and *(Repair cost)/ (Reconstruction cost)* going from the $23M alternative to the $43M alternative are not desirable, the less costly alternative will be chosen. Otherwise, the more costly alternative will be chosen. Neither alternative is better than another objectively. After viewing the tradeoffs, the final choice of an alternative depends on the institutional preferences.

6 Example Multiple-Criteria Design Evaluation

An example of multiple-criteria design scenarios for a fictitious lock wall design is performed using data that exist from two actual lock designs. The issue for the design is what design alternative should be chosen for the upper river wall of the fictitious lock. The input data are taken from two locks that have been recently designed and are in the process of construction by Corps of Engineers districts. The purpose of this example is to show the reader the types of input required and the output results that may be obtained using this software for a hypothetical design example. This example is not made to define the criteria for real or existing lock design. Unfortunately, complete data were not available at the time of this report to perform such an analysis on an existing facility.

6.1 Design Alternatives

Three alternatives for the barge impact analysis of the upper river wall are considered: a) pontoon design–30 ft (9 m) in diameter, b) drilled shaft design, and c) pontoon design–50 ft (15 m) in diameter. Table 6.1 shows the name, cost, and design load of each alternative evaluated.

The same three alternatives are analyzed for vulnerability to earthquakes. Table 6.2 shows the names, costs, and design ground motions of the alternatives.

6.2 Design Load

The possible design loads for the final, chosen design of the fictitious lock walls (called "Pontoon–50 ft" in the tool) are shown in Table 6.3. The design load to be entered in the tool is the extreme impact force because it is at such a force that significant damage is expected. The design loads constitute only one design alternative for each wall type. Design loads for the other alternatives are determined by the user.

Table 6.1
Alternatives Considered in Example Evaluation, Showing Names, Costs, and Design Loads (Step 1)

	Alternatives					
	1		2		3	
Name of Alternative	Pontoon - 30ft		Drilled Shaft		Pontoon-50ft	
	Design Load (kips)	Cost ($k)	Design Load (kips)	Cost ($k)	Design Load (kips)	Cost ($k)
	700	23000	600	30000	1000	43000

Table 6.2
Alternatives Considered in Example Evaluation, Showing Names, Costs, and Design Ground Motions (Step 10)

	Alternatives					
	1		2		3	
Name of Alternative	Drilled Shaft		Pontoon - 30 ft		Pontoon - 50 ft	
	Design G.M. (g)	Cost ($k)	Design G.M. (g)	Cost ($k)	Design G.M. (g)	Cost ($k)
	1	30000	1.8	23000	2	43000

Table 6.3
Design Impact Forces for Lock Walls

Wall Type	Impact Force (kips)		
	Usual	Unusual	Extreme
Upper river wall (URW)	600	900	1,000
Upper middle wall (UMW)	300	600	800
Lower River Wall (LRW)	300	450	500
Lower Middle Wall (LMW)	300	450	500

NOTE: Impact force chosen as the design load in this example is for the extreme case (1,000 kips).

6.3 Determination of Cost of Baseline Alternative

The tradeoff analysis methodology is designed to evaluate design alternatives for each type of lock wall, such as upper river wall (URW). Therefore, it is necessary to obtain the costs of the alternatives for each wall type. One way to estimate the construction costs of the walls of the chosen design is by finding the cost per foot of lock wall and multiplying this cost rate by the length of the wall to be constructed. This way is somewhat of a back-tracking calculation because it requires that the cost of the entire lock wall system be estimated already. However, while estimating this cost, it might have been possible to obtain the cost of the individual walls, if the engineers knew that such costs were needed. It is important to note that the approximation is meaningful when all the lock wall types have a similar design. For example, all the lock wall types—URW, LRW, UMW, LMW, and LLW—are of the pontoon design.

The cost of the i^{th} lock wall:

$$C_t = C_f L_i$$

where

$$C_f = C_t / L_t$$

and

C_f = cost per foot of lock wall, dollars

C_t = cost of all lock walls of a lock, dollars

L_t = total length of lock walls of a lock, feet

L_i = length of i^{th} lock wall

The total estimated cost of the approach lock walls is \$73,013,913. The total length of the lock walls is 3,714 ft. Therefore, the cost per foot is \$73,013,913 ÷ 3,714 ft, or \$19,659 per foot. Table 6.4 shows the costs of different types of wall.

Table 6.4
Cost of Some Olmsted Lock Walls

Type of Wall	Length (ft)	Cost of Wall ($)
Upper river wall	1,167	22,942,053
Upper middle wall	767	15,078,453
Lower river wall	112	2,201,808
Lower middle wall	159	3,125,781

Due to the changes during wall design, the final design for these lock walls has pontoons with a 50-ft width. The approximate additional cost to the URW was about \$20M. Therefore, \$43M is entered as the design cost of the 50-ft pontoon design.

The costs for other pontoon and drilled shaft alternatives for the URW would need to be determined with an approach other than estimating the cost, by taking a fraction of the total estimated cost of the chosen designs for lock wall system.

6.4 Database for the Automated Tool for Lock Wall Design Aid

Data have been collected from design reports, personal interviews, electronic mail correspondence, telephone correspondence, and databases on the Internet. Of the data used for the example, the costs and design loads of the pontoon alternatives come directly from design reports. Also, the data for cost to industry may come directly from the USACE. The data on the drilled shaft alternative and the earthquake analysis data are consistent with general estimates given by different designs. For example, a typical range for the values of *(Repair cost)/ (Reconstruction cost)* due to usual, unusual, and extreme barge impacts might be 0.01-0.1, 0.2-0.5, and 0.5-1.0 for the usual, unusual, and extreme cases, respectively. The same ranges for the ratio apply to usual, unusual, and extreme earthquakes.

General estimates on *Time to recover* were also given for the three cases. For both barge impacts and earthquakes, the *Time to recover* values for the usual, unusual, and extreme cases are 1-7, 7-90, and 90-365+ days, respectively. Estimates on the peak ground accelerations of the operating basis earthquake and maximum credible earthquake were give as 0.25 and 1.0 g's, respectively. The design ground motion in the software is synonymous with peak ground acceleration. Just as the extreme load case was selected as the design load in the barge impact analysis, the design ground motion should be in the neighborhood of the maximum design earthquake and the maximum credible earthquake. Nevertheless, it does not seem crucial that the design load and design ground motion be taken from the extreme load case. However, it is very important that, once the lock wall designer decides which case from which to take a value for the design load (thereby defining the meaning of design load), he is consistent to take a value from the same case (e.g., extreme load case) for every alternative. The designer also needs to be consistent in picking a value for ground motion for each alternative also, but the case does not need to be the same as the barge impact case.

Table 6.5 shows the input for the barge impact analysis of the alternatives for the fictitious lock wall.

Table 6.6 shows hypothetical values as input for historical barge impact data. The data include the dates, descriptions, and impact loads of accidents, design loads, costs of construction, and costs of repair of lock walls.

Table 6.7 contains hypothetical historical data on barge impacts. The data include the dates, descriptions, and impact loads of accidents and *Time to recover* of lock walls.

Table 6.5
Input Values for Barge Impact Analysis of Alternatives and Answers to Assessment Questions

Step Number	Item or Question	Value
1	Wall to consider	Upper river wall
2	Name of Alt. 1	Pontoon–30 ft
2	Design load of Alt. 1 (kips)	700
2	Cost of Alt. 1 ($K)	23000
2	Name of Alt. 2	Drilled shaft
2	Design load of Alt. 2 (kips)	600
2	Cost of Alt. 2 ($K)	30000
2	Name of Alt. 3	Pontoon–50 ft
2	Design load of Alt. 3 (kips)	1,000
2	Cost of Alt. 3 ($K)	43000
3	Greatest barge impact force that results in no damage cost for Alt. 1 (kips)	(min, max, most likely) = (250, 300, 280)
3	Greatest barge impact force that results in no damage cost Alt. 2 (kips)	(300, 400, 360)
3	Greatest barge impact force that results in no damage cost Alt. 3 (kips)	(230, 250, 240)
3	Repair cost for a barge impact equal to design load for Alt. 1 ($K)	(20000, 21000, 20700)
3	Repair cost for a barge impact equal to design load for Alt. 2 ($K)	(20000, 25000, 24000)
3	Repair cost for a barge impact equal to design load for Alt. 3 ($K)	(42500, 43000, 43000)
3	Least barge impact force that results in reconstruction cost for Alt. 1 (kips)	(650, 700, 700)
3	Least barge impact force that results in reconstruction cost for Alt. 2 (kips)	(500, 700, 600)
3	Least barge impact force that results in reconstruction cost for Alt. 3	(1000, 1120, 1100) (kips)
6	Greatest barge impact force that results in no closure of the lock for Alt. 1	(min, max, most-likely) = (140, 200, 180) (kips)
6	Greatest barge impact force that results in no closure of the lock for Alt. 2	(250, 350, 300) (kips)
6	Greatest barge impact force that results in no closure of the lock for Alt. 3	(200, 550, 450) (kips)
6	Duration of closure that results from a barge impact equal to the design load for Alt. 1	(12, 52, 45) (weeks)
6	Duration of closure that results from a barge impact equal to the design load for Alt. 2	(12, 52, 45) (weeks)
6	Duration of closure that results from a barge impact equal to the design load for Alt. 3	(12, 52, 45) (weeks)
6	Least barge impact force that results in a lock closure for 1 year or more for Alt. 1	(570, 900, 750) (kips)
6	Least barge impact force that results in a lock closure for 1 year or more for Alt. 2	(800, 900, 875) (kips)
6	Least barge impact force that results in a lock closure for 1 year or more for Alt. 3	(950, 1750, 1250) (kips)

Table 6.6
Hypothetical Historical Data on Barge Impacts to Lock Walls: Impact Loads of Accidents, Design Loads, Costs of Construction, and Repair Costs of Lock Walls (Input for Step 4)

Date	Description of Accident	Design Load (kips)	Cost of Wall ($K)	Barge Impact Load (kips)		Cost of Repair ($K)
	Accident 1	150	8,000	100		3,000
	Accident 2	120	10,000	150		12,500
	Accident 3	200	30,000	80		5,000
	Accident 4	200	40,000	100		8,000

Table 6.7
Hypothetical Values for Historical Data on Barge Impacts on Lock Walls: Impact Loads of Accidents, Design loads, and *Time to Recover* of Lock Walls (Input for Step 7)

Date	Description of Barge Impact	Design Load (kips)	Barge Impact Load (kips)	Time to Recover (weeks)
	Accident 1	600	500	48
	Accident 2	600	650	52
	Accident 3	900	100	5
	Accident 4	900	400	20

Table 6.8 shows the input values for earthquake analysis of the alternatives, the answers to the assessment questions, and the *(Reconstruction cost)/ (Construction cost)* ratio. The values are hypothetical because no data were easily available.

Table 6.9 displays the magnitudes and return periods of barge impact and earthquake scenarios for evaluating the alternatives. The barge impact scenarios are typical examples for navigation locks.

For testing purposes, Table 6.10 shows hypothetical and reasonable values for historical data on earthquakes that have occurred near locks. The data include the ground motions of the earthquakes, the design ground motions, costs of construction, and repair costs of the lock walls.

Table 6.11 shows hypothetical values for historical data on earthquakes that have occurred near locks. The data include the ground motions of the earthquakes, the design ground motions, costs of construction, and *Time to recover* of the lock walls.

Table 6.12 displays data from WAM (Waterways Analysis Model) studies that are input to the cost to industry model. The input includes different lengths of closure and the associated tonnage, transit times, and *Costs to industry.*

Table 6.8
Input Values for Earthquake Analysis of Alternatives and Answers to Assessment Questions

Step Number	Item or Question	Value
10	Name of Alt. 1	Drilled Shaft
10	Design GM [ground motion] of Alt. 1 (g's)	1
10	Cost of Alt. 1 ($K)	30,000
10	Name of Alt. 2	Pontoon–30 ft
10	Design GM of Alt. 2 (g's)	1.8
10	Cost of Alt. 2 ($K)	23,000
10	Name of Alt. 3	Pontoon–50 ft
10	Design GM of Alt. 3 (g's)	2
10	Cost of Alt. 3 ($K)	43,000
11	Greatest ground motion that results in no damage cost for Alt. 1 (g's)	(min, max, most likely) = (0.3, 0.6, 0.5)
11	Greatest ground motion that results in no damage cost for Alt. 2 (g's)	(0.6, 1.08, 0.9)
11	Greatest ground motion that results in no damage cost for Alt. 3 (g's)	(0.6, 1.2, 1)
11	Repair cost for a ground motion equal to the design ground motion for Alt. 1 ($K)	(18000, 27000, 24000)
11	Repair cost for a ground motion equal to the design ground motion for Alt. 2 ($K)	(6900, 23000, 20700)
11	Repair cost for a ground motion equal to the design ground motion for Alt. 3 ($K)	(35000, 47000, 43000)
11	Lowest ground motion that results in reconstruction cost for Alt. 1 (g's)	(1, 1.8, 1.5)
11	Lowest ground motion that results in reconstruction cost for Alt. 2 (g's)	(2.6, 2.8, 2.7)
11	Lowest ground motion that results in reconstruction cost for Alt. 3 (g's)	(3, 4, 3.6)
14	Greatest ground motion that results in no closure of lock for Alt. 1 (g's)	(0.2, 0.4, 0.3)
14	Greatest ground motion that results in no closure of lock for Alt. 2 (g's)	(0.36, 1.08, 0.72)
14	Greatest ground motion that results in no closure of lock for Alt. 3 (g's)	(0.4, 1.1, 0.9)
14	Duration of closure that results from a ground motion equal to the design ground motion for Alt. 1 (weeks)	(12, 52, 45)
14	Duration of closure that results from a ground motion equal to the design ground motion for Alt. 2 (weeks)	(12, 52, 45)
14	Duration of closure that results from a ground motion equal to the design ground motion for Alt. 3 (weeks)	(12, 52, 45)
14	Least ground motion that results in a lock closure for 1 year or more for Alt. 1 (g's)	(0.95, 1.75, 1.25)
14	Least ground motion that results in a lock closure for 1 year or more for Alt. 2 (g's)	(1.7, 3.15, 2.25)
14	Least ground motion that results in a lock closure for 1 year or more for Alt. 3 (g's)	(2, 3, 2.5)
18	(Reconstruction cost)/(Construction cost)	1.25

Table 6.9
Barge Impact and Earthquake Scenario Input: Magnitudes and Return Periods

Step Number	Item or Question	Value
20	Magnitude of usual barge impact	600 kips
20	Return period of usual barge impact	1 year
20	Magnitude of unusual barge impact	750 kips
20	Return period of unusual barge impact	50 years
20	Magnitude of extreme barge impact	900 kips
20	Return period of extreme barge impact	1,000 years
22	Magnitude of usual earthquake	0.4 g
22	Return period of usual earthquake	200 years
22	Magnitude of unusual earthquake	0.8 g
22	Return period of unusual earthquake	800 years
22	Magnitude of extreme earthquake	1.1 g
22	Return period of extreme earthquake	1,000 years

Table 6.10
Hypothetical Historical and Reasonable Data on Earthquakes: Ground Motions of Earthquakes, Design Ground Motions (GM), Costs of Construction, and *Repair Costs* of Lock Walls (Input for Step 12)

Date	Description of Earthquake	Design GM (g's)	Cost of Wall ($K)	Actual GM (g's)	Cost of Repair ($K)
	Earthquake 1	1.5	20,000	0.5	8,000
	Earthquake 2	1	18,000	0.8	18,000
	Earthquake 3	2	43,000	0.8	10,000
	Earthquake 4	1.8	40,000	1.5	42,000

Table 6.11
Hypothetical and Reasonable Historical Data on Earthquakes: Ground Motions of Earthquakes, Design Ground Motions (GM), Costs of Construction, and *Time to Recover* of Lock Walls (Input for Step 15)

Date	Description of Earthquake	Design GM (g's)	Actual GM (g's)	Time to Recover (weeks)
	Earthquake 1	1	0.9	48
	Earthquake 2	0.8	0.8	52
	Earthquake 3	1.2	0.3	5
	Earthquake 4	2	1.5	40

Table 6.12
Input of Different Lengths of Closure, Transit Times, and *Cost to Industry*—Input for Step 18 (Input from a Water Analysis Model)

Description of Event (Run ID)	Length of Closure (weeks)	Transit Time (hr)	Cost to Industry ($K)
Full operation	0.0	1.14	0
15-day main closure	2.1	1.25	123
45-day main closure	6.4	1.54	442
90-day main closure	12.9	1.93	869
180-day main closure	25.7	2.97	2017
365-day main closure	52.1	4.95	4192

The rate of increase between a 15- and 45-day closure is greater than the rate between the 45- and 90-day closure. The rate then increases when going to a 180-day closure and decreases when going to a 365-day closure. The increasing and decreasing rates could be due to the following reasons. A possible reason for the initial decrease in the rate is that by the first 45 days, the initial upfront costs (e.g., insurance payments) for establishing alternative means of transporting commodities have been already been paid. Then the rate increases because perhaps the increased demand for the alternative transportation services (e.g., railroad) has driven up the price of transportation. The rate decreases again, going from a 90- to a 180- to a 365-day closure, perhaps because the total amount of commodities needing transportation varies seasonally because less grain is produced in winter months.

6.5 Barge Impact Frequency

The data for barge impact scenarios in Table 6.7 are used to plot the return periods versus impact loads. Figure 6.1 shows the plot of the return periods versus the associated magnitudes.

6.6 Earthquake Frequency

Ground motion from earthquakes is considered a noncritical factor in the design of the lock wall. Therefore, the design does not need to construct the structure to withstand the maximum credible earthquake. The data for earthquake scenarios from Table 6.7 are used to plot the return periods versus actual ground motions. The return period is plotted on a reverse logarithmic scale. Figure 6.2 shows the plot of the return periods versus the associated ground motions.

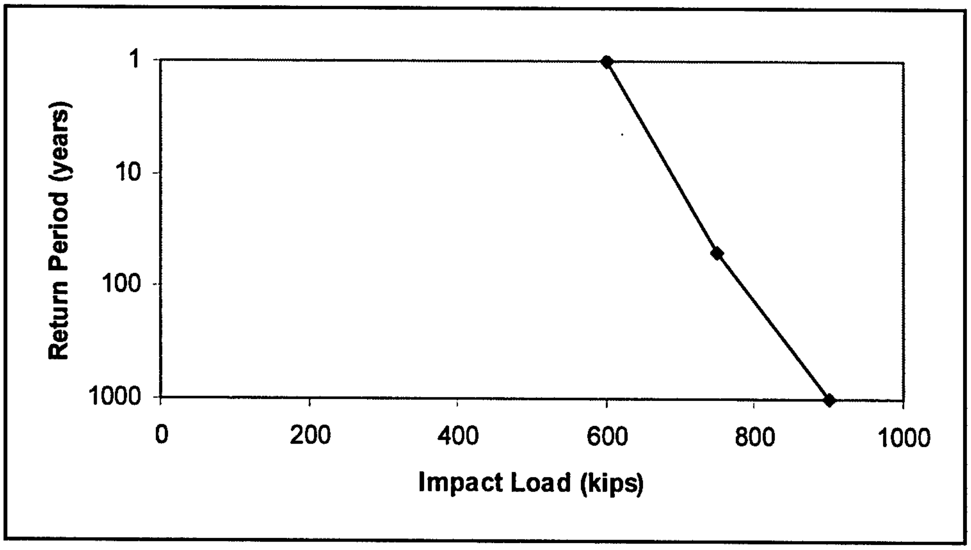


Figure 6.1. Reverse log plot of return periods and impact loads of barge impact scenarios

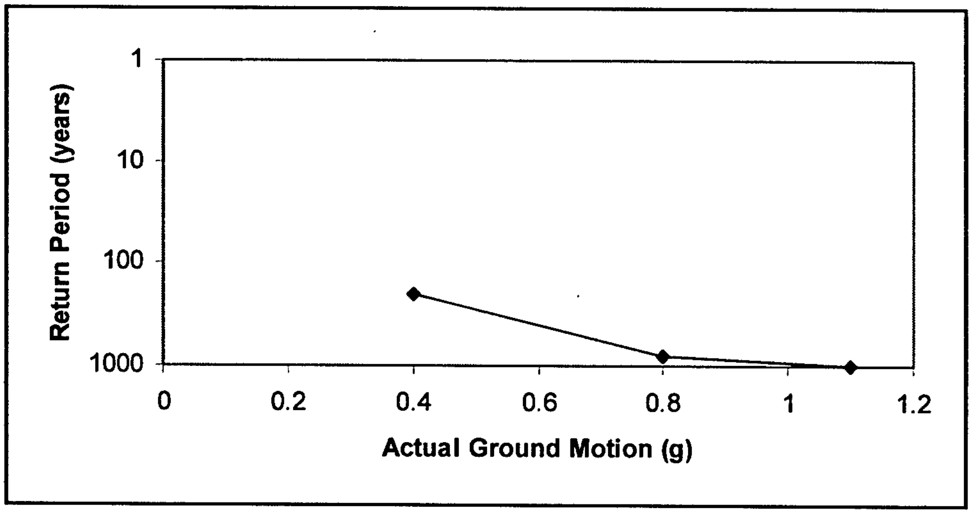


Figure 6.2. Reverse log plot of return periods and impact loads of earthquake scenarios

6.7 Commodities That Will Travel Through the Lock

The following information on commodities that are transported through the navigation system is obtained from the Navigation Data Center (USACE 2001). The commodity with the greatest quantity that passed through nearby locks is coal, followed by crude material and farm products. In the month of January 1999, 7,412.1 Ktons of commodity passed through the locks. More commodity was shipped upstream than downstream, with a difference of about 500 Ktons in January 1999. For more information on the breakdown of the tonnage based on commodity types for a typical lock example, see Appendix C.

6.8 Relationship Between Closure Length and Cost to Industry

The USACE Navigation Data Center provided data, as shown in Table 6.13, from curves relating closure length to cost to industry. It is determined that the appropriate scenario under which cost to industry is estimated is where only the main chamber is closed, with no closure of the auxiliary chamber or dual closures. The costs are calculated using a 95-Kton family and based on 50 runs of WAM.

Table 6.13
Closure cost and *Cost to Industry*

Run ID	Tons	Transit Time (hr)	Cost to Industry ($)
Full operation	23,330	1.14	NA
15-day main closure	23,330	1.25	122,740
45-day main closure	23,330	1.54	441,727
90-day main closure	23,330	1.93	869,488
180-day main closure	23,330	2.97	2,017,242
365-day main closure	23,319	4.95	4,192,091

A straight-line interpolation is used to determine the *Cost to industry* of any length of closure.

6.9 Tradeoffs and Analysis

Since the main purpose of the study is to develop a methodology, not every tradeoff graph of the example design evaluation is interpreted. Some interpretation is made, as described in Sections 5.7-5.9. From the tool, the *Cost to industry* caused by a usual barge impact with a 1-year return period is $906,000. However, the *Cost to industry* estimated from historical data is only $43,550. The estimate from the tool is much higher than the historical data. Also, there are many more closures from the historical data than the tool examines. That the tool produces a greater *Cost to industry* is a result of the nature of the methodology. The methodology uses *Time to recover* to calculate *Cost to industry*. The methodology might consider the *Time to recover* of relatively small barge impacts as zero if the "greatest barge impact that results in no closure of the lock" (Step 6) is greater than the small barge impacts.

6.10 Sensitivity Analysis

To assess how sensitive results are to input to the model that supports the tradeoff analysis, a sensitivity analysis is performed. The input for "the greatest barge impact force (kips)" to Alternative 1 "that results in no damage cost" is increased by 50 percent, from 280 to 420. The rest of the input and parameter values remain the same as those shown in Section 6.3. This change affects only the output in the tradeoff graphs of *Cost of alternative* versus *(Repair cost)/ (Reconstruction cost)* and *Cost of alternative* versus *Repair cost*. Also, there is a difference in the usual barge impact scenario only when the input is changed. *(Repair cost/(Reconstruction cost)* decreases from 0.55 to 0.46 with the change. The decrease is 16 percent of the original value. Once the impacts of changing different input individually are calculated, they are organized in a table similar to Table 6.14. Figure 6.3 shows the graphs of *Cost of alternative* versus *(Repair cost)/(Reconstruction cost)* for the original and modified set of input.

Table 6.14
Percentage Impact on (Repair Cost)/(Reconstruction Cost)

Change in Input Parameter	Input Parameter			
	A	Greatest barge impact that results in no damage cost	C	D
+5%	--[1]	--	--	--
+10%	--	--	--	--
+50%	--	–16%	--	--
+5%	--	--	--	--
+10%	--	--	--	--
+50%	--	--	--	--

[1] Denotes values not of interest in this study.

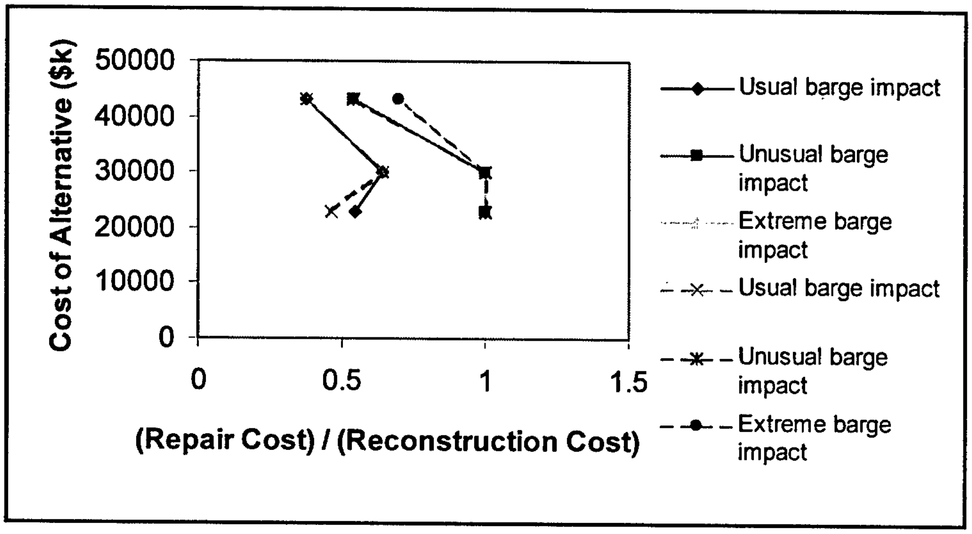


Figure 6.3. Impact of increasing "the greatest barge impact that results in no damage cost" by 50 percent (the impact is indicated by an arrow)

7 Conclusions

7.1 Contributions of the Study

The contributions of the study reported herein are as follows:

- Development of methodology for multiple-criteria tradeoff analysis of lock wall designs vulnerable to extreme events.
- Identification of metrics and interpretation of metrics from engineering/finance, finance/engineering, operations/industry, and industry perspectives.
- Incorporation of both barge impact and earthquake loads within the methodology.
- Development of assessment techniques for elicitation of expert evidence for 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.*
- Data collection needs for lock systems.
- Demonstration of methodology and software using a realistic example with data from actual locks.
- Development, design, and documentation of software.
- Survey of literature relevant to multiple-criteria decision-making, benefit-cost analysis, risk analysis, multiple failure modes, and navigation structural design.

7.2 Further Work

Further work related to the study is as follows:

- Extend the methodology to consider other extreme events such as terrorism.
- Enlarge the scope to study impacts on a system level (e.g., multiple dependent locks).

- Extend extreme events and tradeoff analysis to other components of the lock and navigation system.
- Explore consistency with engineering-economic considerations of efficiency (e.g., benefit-cost ratios and expected net benefits).

8 References

American Society of Civil Engineers. (1998). *Inland navigation: Locks, dams, and channels*. Reston, VA.

Ang, A. H., and Tang, W. H. (1984). *Probability concepts in engineering planning and design; II, Decision, risk, and reliability*. John Wiley, New York.

Beim, G. K., and Hobbs, B. F. (1997). Event tree analysis of lock closure risks, *Journal of Water Resources Planning and Management* (May/June), 1-10.

Diewald, W. (1987). "Risk analysis in public works facilities planning, design, and construction." *Proceedings; Risk analysis and management of natural and man-made hazards*. Y. Y. Haimes and E. Z. Stakhiv, ed., American Society of Civil Engineers, Santa Barbara, CA, 331-40.

Ellingwood, B. R. (1995), "Event combination analysis for design and rehabilitation of U.S. Army Corps of Engineers navigation structures," Contract Report ITL-95-2, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Glosten Associates, Inc. (1995). "Winfield Lock and Dam upper approach guardwall: Barge impact loads," prepared for U.S. Army Engineer District, Huntington, Huntington, WV.

Green, R. A., and Hall, W. J. (1996). "A review (and comparison) of DSHA and PSHA." *Proceedings; Natural disaster reduction*. G. W. Housner and R. M. Chung, ed. American Society of Civil Engineers, Washington, DC, 125-26.

Haimes, Y. Y. (1991). "Total risk management," *Risk Analysis* 11(2), 168-71.

INCA Engineers, Inc. (1999), Olmsted Locks and Dam, upper and lower approach walls, design report," U.S. Army Engineer District, Louisville, Louisville, KY.

Institute for Water Resources. (1992a). "Guidelines for risk and uncertainty analysis in water resources planning; I, Principles and technical appendices," IWR Report 92-R-1, Fort Belvoir, VA.

Institute for Water Resources. (1992b). "Guidelines for risk and uncertainty analysis in water resources planning; II, Examples," IWR Report 92-R-2, Fort Belvoir, VA.

Kaplan, S., and Garrick, B. J. (1981). "On the quantitative definition of risk," *Risk Analysis* 1(1), 11-26.

Lambert, J. H. (2001). "Selection of extreme scenarios and protection alternatives supportive of cost/benefit/risk analyses. *Proceedings; Risk-based decision making in water resources*. Engineering Foundation Conference, Santa Barbara, CA.

Lambert, J. H., Haimes, Y. Y., Tsang, J. L., Jiang, P., and Patev, R.C. (2001). "Multiple-criteria decision-making in the design of innovative lock walls for barge impact," ERDC/ITL TR-01-8, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Lindbergh, C., Harlan, M. R., and Lafrenz, J. L. (1996). "Structural evaluation of existing buildings for seismic and wind loads." *Proceedings; Natural disaster reduction*. G. W. Housner and R. M. Chung, ed. American Society of Civil Engineers, Washington, DC, 317-18.

Loucks, D. P., Stedinger, J. R., and Haith, D. A. (1981). *Water resource systems planning and analysis*. Prentice-Hall, New Jersey.

Lowrance, R. (1976). *Of acceptable risk: Science and determination of safety*. William Kaufmann, Inc., California.

Moser, D. A. (1996). "The use of risk analysis by the U.S. Army Corps of Engineers,"_*Water Resources Update* 103, 27-34.

Moser, D. A., and Stakhiv, E. Z. (1987). "Risk-cost evaluation of coastal protection projects with sea level rise and climate change." *Proceedings; Risk analysis and management of natural and man-made hazards*. Y. Y. Haimes and E. Z. Stakhiv, ed. American Society of Civil Engineers, Santa Barbara, CA, 222-39.

Patev, R. C. (2000). "Probabilistic barge impact analysis of the upper guide and guard walls at Marmet Locks and Dam," ERDC/ITL TR-00-4, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Pomerol, J., and Barba-Romero, S. (2000). *Multicriterion decision in management; Principles and practice*. Kluwer Academic Publishers, Boston, MA.

Taylor, D. B., Hofseth, K. D., Shabman, L. A., and Moser, D. A. (1991). "Moving toward a probability-based risk analysis of the benefits and costs of major rehabilitation projects" (V). *Proceedings, Risk-based decision making in water resources*. Y. Y. Haimes, D. A. Moser, and E. Z. Stakhiv, ed. American Society of Civil Engineers, Santa Barbara, CA, 148-73.

USACE. (1995a). "Planning and design of navigation locks," Engineer Manual 1110-2-2602, Washington, DC. http://www.usace.army.mil/inet/usace-docs/eng-manuals/em1110-2-2602/toc.htm.

__________. (1995b). "Planning and design of navigation dams," Engineer Manual 1110-2-2607, Washington, DC. http://www.usace.army.mil/inet/usace-docs/eng-manuals/em1110-2-2607/toc.htm.

__________. (1995c). "Earthquake design and evaluation for Civil Works projects," Engineer Regulation 1110-2-1806, Washington, DC. http://www.usace.army.mil/inet/usace-docs/eng-regs/er1110-2-1806/toc.htm.

__________. (1996). "Risk-based analysis for evaluation of hydrology/hydraulics, geotechnical stability, and economics in flood damage reduction studies," Engineer Regulation 1105-5-101, Washington, DC. http://www.usace.army.mil/inet/usace-docs/eng-regs/er1105-2-101/toc.htm.

__________. (1999). "Response spectra and seismic analysis for concrete hydraulic structures," Engineer Manual 1110-2-6050, Washington, DC. http://www.usace.army.mil/inet/usace-docs/eng-manuals/em1110-2-6050/toc.htm.

__________. (2000). "Time-history dynamic analysis of concrete hydrualic structures," Engineer Circular 1110-2-6051, Washington, DC. http://www.usace.army.mil/inet/usace-docs/eng-circulars/ec1110-2-6051/toc.htm.

__________. "Welcome to the U.S. Army Corps of Engineers: Navigation Data Center." http://www.iwr.usace.army.mil/ndc (6 May 2002).

U.S. Army Engineer District, St. Paul. (2000). "Regulating Mississippi River navigation pools," St. Paul, MN. http://www.mvp-wc.usace.army.mil/projects/general/ld_brochure.html.

Walker, W. W. (1997). "Toward a risk-based assessment of shallow-draft navigation investment." *Proceedings, Risk-based decision making in water resources* (VIII). Y. Y. Haimes, D. A. Moser, and E. Z. Stakhiv, ed. American Society of Civil Engineers, Santa Barbara, CA, 33-43.

Yoe, C. (1987). The construction cost/risk cost trade-off in public works projects: navigation channel width determination. *Proceedings, Risk analysis and management of natural and man-made hazards*. Y. Y. Haimes and E. Z. Stakhiv, ed. American Society of Civil Engineers, Santa Barbara, CA, 315-30.

Appendix A
Frequency Analysis of Ground Motions

This appendix describes a probability model used by the USACE for determining the frequency of ground motions.

A Poisson probability model for the ground motion has been used. The following description comes from Engineer Manual 1110-2-6050 (USACE 1999). When using a Poisson model, one is interested in how many times an event occurs during a certain time duration. Therefore, the model takes on countable numbers or discrete values. Yet the model is a function of time, a continuous variable. A Poisson model has the form

$$P\{X(t)=n\}=\frac{(\alpha t)^n e^{-\alpha t}}{n!}$$

where

$X(t)$ = an event that is a function of time
n = number of occurrences of the event by time t; $n = 0,1,2,\ldots$
α = mean rate at which the events occur

In the context of earthquake analysis, the event X is

X = a ground motion below level k

Therefore, the probability that a ground motion of level k occurring in a certain length of time, t, is when $n = 0$ and

$$P\{X(t)=0\}=e^{-\alpha t}$$

The complement, or opposite, of this event is

X^c = a ground motion of at least k in magnitude

Therefore, the probability of X^c occurring in time t is

$$P\left\{X^c(t)=0\right\}=1-e^{-\alpha\, t}$$

where

α = mean rate at which the events $X(t)$ occur

The model used by the Corps is in the same form:

$$P(z)=1-e^{-V_z t}$$

where

$P(z)$ = exceedance probability

$z(t)$ = the event that a ground motion of at least k in magnitude occurs by time t

V_z = mean rate at which ground motions of less than k in magnitude occur

To obtain the annual exceedance probability, t should be measured in the unit of years. In this case, $P(z)$ in the above equation becomes the annual exceedance probability for ground motions for the magnitude k.

Appendix B
Length of Closure and Cost to Industry

This appendix explains how to use data collected by the USACE to determine annual *Cost to industry* due to lock closures.

Lock Performance:

USACE collects data on the number of closures and the average length of the closures on each lock that it operates. Table B1 presents the "Calendar year summary of lock statistics" report from the Lock Performance Monitoring System of the Navigation Data Center (USACE 2001).

Table B1
Length of Closure, Number of Closures, and Tonnage at Smithland Lock (USACE 2001)

Year	Average Length of Lock Closure (hr)		Number of Closures per year		Total Tonnage per year (Ktons)	
	Main	Aux1	Main	Aux1	Main	Aux1
1999	0.67	2.40	130	16	36106	46005
1998	0.94	11.49	161	24	42166	42435
1997	2.46	14.88	209	26	45391	39496
1996	0.95	5.08	215	46	45780	39251

Therefore, another method to approximate *Cost to industry* is used. The method is a rule of thumb obtained from USACE that every hour of lock closure costs industries \$400 to \$600. Using \$500 as the cost per hour of lock closure, Table B2 shows the calculation for *Costs to industry.*

Table B2
Components for Calculation of *Cost to Industry* (USACE 2001)

Year	Average Length of Main Chamber Closure (hr)	Number of Main Chamber Closure per Year	Cost to Industry ($)
1999	0.67	130	43,550
1998	0.94	161	75,670
1997	2.46	209	257,070
1996	0.95	215	102,125

Appendix C
Commodity Data on Olmsted and Winfield Locks

This appendix displays example data collected by the USACE (2001) on the commodities that are shipped through the Winfield Lock and Lock 52 (which will be replaced by Olmsted Lock).

Key Lock Report

River: Ohio **Division: LRD** **Data MO/YR : Jan 1999**
Lock : 52 **District: LRL** **Report Date: 03/02/99**

Commod (Ktons)	Up(MO)	Dn(MO)	Tot(MO)	MO/DF/PY	Up(YTD)	Dn(YTD)	Tot(YTD)	YTD/DF/PY
10 Coal	1241	1051.7	2292.7	-125.3	1241	1051.7	2292.7	-125.3
20 Petroleum	510.4	58.9	569.3	30	510.4	58.9	569.3	30
30 Chemicals	789.9	116.5	906.4	61.4	789.9	116.5	906.4	61.4
40 Crude mat.	718.7	1060.1	1778.8	12.5	718.7	1060.1	1778.8	12.5
50 Procd. mat.	421.7	126.3	548	-43.5	421.7	126.3	548	-43.5
60 Farm Prod.	156.7	957.2	1113.9	-5.9	156.7	957.2	1113.9	-5.9
70 Mfrd Equi.	0.6	28.2	28.8	8.4	0.6	28.2	28.8	8.4
80 Waste Mat	0	0	0	0	0	0	0	0
99 Unknown	100.4	73.8	174.2	101.2	100.4	73.8	174.2	101.2
	------	------	------	------	------	------	------	------
Total Ktons	3939.4	3472.7	7412.1	38.8	3939.4	3472.7	7412.1	38.8
Empty Brgs	1262	1379	2641	-112	1262	1379	2641	-112
Loaded Brgs	2365	2268	4633	-7	2365	2268	4633	-7
	------	------	------	------	------	------	------	------
Tot Number	3627	3647	7274	-119	3627	3647	7274	-119

% MO/DF(Ktns) = +0.5
% YTD/DF(Ktns) = +0.5

Key Lock Report

River: Ohio **Division: LRD** **Data MO/YR: Jan 1999**
Lock: 52 aux1 **District: LRL** **Report Date: 03/02/99**

Commod (Ktons)	Up(MO)	Dn(MO)	Tot(MO)	MO/DF/PY	Up(YTD)	Dn(YTD)	Tot(YTD)	YTD/DF/PY
10 Coal	0	3	3	0.1	0	3	3	0.1
20 Petroleum	25.3	0	25.3	8.3	25.3	0	25.3	8.3
30 Chemicals	27.1	0	27.1	-12.3	27.1	0	27.1	-12.3
40 Crude mat.	0	6.5	6.5	-37.8	0	6.5	6.5	-37.8
50 Procd. mat.	10.9	0	10.9	0.5	10.9	0	10.9	0.5
60 Farm Prod.	0	4.5	4.5	-1.1	0	4.5	4.5	-1.1
70 Mfrd Equi.	0	0	0	0	0	0	0	0
80 Waste Mat	0	0	0	0	0	0	0	0
99 Unknown	0	0	0	0	0	0	0	0
	------	------	------	------	------	------	------	------
Total Ktons	63.3	14	77.3	-42.3	63.3	14	77.3	-42.3
Empty Brgs	12	12	24	-33	12	12	24	-33
Loaded Brgs	26	8	34	-26	26	8	34	-26
	------	------	------	------	------	------	------	------
Tot Number	38	20	58	-59	38	20	58	-59

% MO/DF(Ktns) = -35.4
% YTD/DF(Ktns) = -35.4

Key Lock Report

River: Kanawha **Division: LRD** **Data MO/YR : Jan 1999**
Lock: Winfield Main 800 **District: LRH** **Report Date: 03/02/99**

Commod (Ktons)	Up(MO)	Dn(MO)	Tot(MO)	MO/DF/PY	Up(YTD)	Dn(YTD)	Tot(YTD)	YTD/DF/PY
10 Coal	1.5	1324.2	1325.7	-28	1.5	1324.2	1325.7	-28
20 Petroleum	73.3	0.7	74	-1.1	73.3	0.7	74	-1.1
30 Chemicals	57.7	3.3	61	-0.5	57.7	3.3	61	-0.5
40 Crude mat.	117	0	117	-12.7	117	0	117	-12.7
50 Procd. mat.	4.6	0	4.6	-3.9	4.6	0	4.6	-3.9
60 Farm Prod.	0	0	0	0	0	0	0	0
70 Mfrd Equi.	0.9	1.9	2.8	-0.1	0.9	1.9	2.8	-0.1
80 Waste Mat	0	0	0	-3.3	0	0	0	-3.3
99 Unknown	0	0	0	0	0	0	0	0
	------	------	------	------	------	------	------	------
Total Ktons	255	1330.1	1585.1	-49.6	255	1330.1	1585.1	-49.6
Empty Brgs	897	108	1005	0	897	108	1005	0
Loaded Brgs	152	1026	1178	-27	152	1026	1178	-27
	------	------	------	------	------	------	------	------
Tot Number	1049	1134	2183	-27	1049	1134	2183	-27

% MO/DF(Ktns) = -3.0
% YTD/DF(Ktns) = -3.0

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
December 2002

2. REPORT TYPE
Final report

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Multiple-Criteria Decision-Making in the Design of Innovative Lock Walls for Barge Impact; Phase 2, Implementation Methodologies

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Joshua L. Tsang, James H. Lambert, Robert C. Patev

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
WU 33143

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

University of Virginia, Center for Risk Management of Engineering Systems
P.O. Box 400736, Charlottesville, VA 22904-4736;
U.S. Army Engineer District, New England
696 Virginia Road, Concord, MA 01742-2751

8. PERFORMING ORGANIZATION REPORT NUMBER

ERDC/ITL TR-02-5

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Corps of Engineers, Washington, DC 20314-1000;
U.S. Army Engineer Research and Development Center, Information Technology Laboratory, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The goal of this research is to develop and implement a methodology for multiple-criteria tradeoff analysis supportive of lock wall design subject to extreme events. The work is the first effort for the U.S. Army Corps of Engineers toward performing tradeoff analysis for lock wall design and considering very rare and severe damages such as barge impacts and earthquakes.

In designing lock walls, engineers consider different levels of the extreme events for which to design (e.g., a 50-, 100-, or 500-year return-period event). In the past, lock walls may have been designed for the conservative and extreme scenario. Looking at tradeoffs among design alternatives may reasonably lower costs without sacrificing significant performance.

Several criteria or metrics are identified for considering tradeoffs among different designs, including construction cost, the ratio of repair cost to reconstruction cost, repair cost, time to recover, and cost to industry. These metrics reflect the degree of severity of a barge impact or earthquake. In the methodology, three scenarios each of possible barge impacts or earthquakes are selected by a lock wall designer for evaluating the alternatives. By studying the metrics, a decision-maker can see the tradeoffs among different designs. Graphs with the cost of alternative on the vertical axis and the value of a risk metric (e.g., repair cost) on the horizontal axis show the tradeoffs among the alternatives under the extreme event scenarios. A software workbook is developed for the methodology. The implemented methodology is tested using a realistic design situation, making use of data from actual lock projects. Sensitivity analysis is performed to assess the robustness of the model results.

15. SUBJECT TERMS
See reverse.

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(include area code)*
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED		77	

15. (Concluded)

Barge impact
Decision-making
Earthquake
Hazard
Innovative
Lock walls
Multiple-criteria
Reliability
Risk
System reliability
Tradeoff analysis