CHAPTER 6 ECONOMIC / RISK ANALYSIS

Introduction

The 1990's represent a period in which both government and industry are attempting to reduce expenditures, focusing on economics of operation as a priority problem. Both are undergoing a downsizing to eliminate unnecessary functions and personnel with an increased emphasis on cost effectiveness and maximization of return on investment. All construction has a purpose and the economics of use is involved in the decision process to build or upgrade. Commercial and industrial construction are categories of investment which generally are designed to serve in an income-producing role. The user commits to the expenditure of an amount of resources to establish an operating environment to meet a specific objective. In the corporate world, the objective may be an industrial complex designed to produce a product. For this application the objective of the investment is a marine oil terminal designed to serve as a means of transferring oil from a ship or barge to a shore based facility. The facility represents a costly investment to the owner/operator. It also represents a vital resource to the State of California as a means of supplying the fuel needs of the State. In addition to the economics of operation there is the additional concern of protection of the environment.

The California State Lands Commission has oversight of over sixty marine oil terminals, some of which are over eighty years old and built to unknown standards. Typically, they were built to resist minor earthquake intensity. New earthquake hazard information from recent events such as Loma Prieta (1989) and Northridge (1994) indicate that much higher intensities are possible. It is prudent that these facilities be evaluated and unsafe deficiencies corrected. The criteria uses the factor to relate the seismic exposure period of existing construction to that of new construction. In effect is the main factor which determines the seismic upgrade level for an existing facility. The choice of what to use is an economic decision on the part of the owner and a risk acceptance decision on the part of the State. Although there is need of definition of a minimum value of from a regulatory perspective, the decision of what to use should be based on maximization of benefits and minimization of risk. The CSLC goals are to:

Ensure safe and pollution-free transfer of petroleum products between the ship and land based facilities.

Ensure the best achievable protection of the public health, safety and the environment

Maximize the utilization of limited resources

The development of guidelines in part involves prescription of a set of constraints to minimize the size and frequency of an oil spill. This imparts some design requirements and imposes some expenditure of money to build a system to which will not fail under some prescribed load conditions. An important issue is the degree of severity of the design requirements. This must be viewed in terms of the consequences of the resulting failure. Over the last forty years, the evaluation of risk and consequences has been advanced starting with work on nuclear power plant safety. Risk analysis and economics have been utilized in transportation both in the design of automobiles and highways. From this certain norms have evolved. Society is much more adverse to a single catastrophic event than equivalent damage spread over a number of events, such as a plane crash versus highway deaths. The following table illustrates society's aversion to events perceived as catastrophic.

	Catastrophic	**Critical**	**Marginal**	**Negligible**
Frequent $X > 10^{-1}$	Unacceptable	Unacceptable	Unacceptable	OK
Probable $10^{-1} > X > 10^{-2}$	Unacceptable	Unacceptable	Undesirable	OK
Occasional $10^{-2}>X>10^{-3}$	Unacceptable	Undesirable	Undesirable	OK
Remote $10^{-3}>X>10^{-6}$	Undesirable	Undesirable	OK	OK
Improbable $10^{-6}> X$	OK	OK	OK	OK

40 CFR 300.5 (NCP) defines a major spill as in excess of 10,000 gallons (238 barrels). A consensus of persons contacted from agencies such as the Coast Guard, Minerals Management Service, and oil removal contractors indicate that in excess of 1000 barrels constitutes a large spill of potentially enormous consequences if it reaches a shoreline. Most people would say that a spill of 1200 barrels would constitute at least critical consequences. A few might say that under the most adverse circumstances, catastrophic consequences might occur. The extent of the damage depends on a number of factors including the nature of the shoreline, the composition of the oil, wind speeds and temperature etc.

1200 barrels is a large critical spill

The federal government has in some instances taken a position ignoring risk and acting as a self-insurer. This is possible chiefly because of its huge size. Other entities both state and private do not have this ability. Risk must be considered as an integral part of decision making. A prudent investor does not always seek the highest yield alone; rather one must also consider the volatility (riskiness) of the investment decision.

This chapter will introduce techniques which had there origins in the evaluation of alternatives largely based on economic issues and expands on those techniques to include risk of adverse consequences.

Cost of an Oil Spill

The cost of an oil spill involves several elements. There is the direct cleanup cost involving the expenditures on removal of the oil. There is the cost of damage to the coastline and the environment in the form of the destruction of wild life and natural resources. There are third-party damages consisting of individuals who suffered property damage from contact with the oil. Additionally there are factors such as loss of use.

The State of California Office of Oil Spill Prevention and Response estimates the cost of an oil spill based on an average of 108 oil spill incidents as follows:

Cleanup cost	$150 /gallon
Third-part cost	$100 /gallon
Natural resource damage	$200 /gallon
Total Cost	$450/gallon

Noting that there are 42 gallons per barrel, the cost of a 1200-barrel spill would be $22,680,000. The 1990 Oil Pollution Act establishes a level of financial responsibility for a 1000-barrel oil spill in federal waters at $35 million.

Potential damage from a 1200-barrel spill is very large

The costs associated with an oil spill must be factored into the decision making process for selecting the design for a seismic upgrade.

Economic Analysis

In the 1980's the Naval Civil Engineering Laboratory, now named the Naval Facilities Engineering Service Center, developed a procedure for the economic analysis of seismic design levels and lateral force resisting systems, Ferritto (1982, 1983, 1984a and 1984b). That work led to the development of Chapter 7 of NAVFAC P355.2, Seismic Design Guidelines For Upgrading Existing Buildings. The procedures have been adopted for use by the engineering community and used to analyze the seismic upgrade of several hospitals. Recently the State of California passed SB920 which mandates an economic analysis be conducted when new earthquake hazard mitigation technology such as base isolation or viscoelastic dampers are proposed for use in State construction projects. The State of California has adopted for use the economic analysis procedures developed by the Navy referenced above. New data on damage was added. The State of California procedures for conducting an economic analysis are contained in “Earthquake Hazard Mitigation Technology Guidelines”, Way (1995). This section will present the general procedure which although developed for buildings is directly applicable to any waterfront structure.

Economic analysis techniques have been used extensively in business and engineering. There has been investigation of the cost of seismic construction upgrading in a number of documents such as FEMA 157 (1988). FEMA 228 (1992) and 229 (1992) discuss a benefits-cost model for the rehabilitation of buildings. A significant study was performed by the Applied Technology Council, ATC-13 (1985). These studies took a macro-level perspective looking at the decision process for large inventories of buildings, expressing costs on a per square foot basis, and developing guidelines for application to classes of construction. The models for estimating cost and damage focused only on evaluating the lateral force resisting system. There have been a number of studies of damageability and a good summary of this topic is found in Taylor ed. (1992). Harris and Harmon (1986) performed an economic analysis using techniques very similar to those outlined in Ferritto (1984a), but the work was unfortunately oversimplified to the point where its results are limited. They related damage only to drift and failed to include story force/acceleration as a separate damage mechanism. Ductility demand alone can not represent all damage since direct force/acceleration effects on elements mounted to floors or ceilings and damage to building contents would not be included. One would erroneously conclude that simply stiffening a building would reduce all damage when in effect we find that induced floor accelerations are increased by stiffening. One would never be able to completely assess the cost - benefits of base isolation if acceleration damage were omitted. Their damage function for the total building consisted of interpolating between yield and collapse ductility levels for only the lateral force resisting element neglecting the possibilities of different level of damage to the other building elements and subsystems.

There is an increased emphasis on post-earthquake facility functionality by the engineering community. In this light, it is essential to be able to evaluate the extent and location of expected building damage. Are there any weak links in the facility system design which will preclude operability? Operability demands that the facility be viewed as a total system not just a structural system. Utilities and the other elements must function to have operability. It is necessary to know what other facility system elements are damaged in addition to the damage to the lateral force resisting system. This section presents a detailed analysis procedure which can evaluate the economics of seismic design for a building system.

The purpose of this analysis procedure is to perform an economic comparison of alternative designs of a structure considering initial construction expenditures and expected earthquake induced damage over the life of the structure. It may compare different types of construction or different design levels. It is thus intended to assist the user and the design engineer in obtaining cost effective seismic construction. The procedure referenced above is a process of estimating earthquake damage based on both displacement and acceleration. As such it recognizes that the facility system is composed of components, some structural, some nonstructural and some mechanical and electrical, which are affected by displacement or drift. It also recognizes the damage induced in some facility system components which are mounted to floors or ceilings are damaged by the transmitted story accelerations. The procedure of including both drift and acceleration is a significant factor in this procedure which is an improvement over other techniques which focused only on drift. As noted above, failure to include the acceleration induced damage leads to erroneous conclusions that mere stiffening which reduces drift is fully effective. For every dollar that is invested in stiffening a structure, a portion of it may be wasted because stiffening results in increased floor accelerations which can cause additional damage to acceleration sensitive components like contents.

The methodology referenced above used available data at the time of its writing; since then the Loma Prieta earthquake of 1989 and the Northridge earthquake of 1994 coupled with extensive university testing have greatly increased the damage data base. In the process of developing the State of California guideline, the original damage estimation tables were updated to include the new data. This new database is now available and was used to update damage relationships, Way (1995). The procedure for conducting an economic analysis is applicable to both new and existing structures. The procedure is appropriate for larger projects which can justify a site seismicity study and the additional steps involved. The procedure is not meant for structures where the building code is design is adequate, but rather for those structures where post-earthquake performance is under consideration. It is best applied during the design process when cost estimates of the proposed structure are usually made and the performance of the structure analyzed. When only relative performance of alternatives is required, the general procedure may be shortened as will be described in following sections.

Steps for Economic Analysis

The following illustrates the steps in an economic analysis. While the procedures are illustrated in terms of a building example, they are applicable to piers and wharves and other facilities found in marine oil terminals.

Define System Components (Step 1) The system and all its component elements must be identified. This includes site location, structural plan, key facility components, utilities and lifelines. This step quantifies the operating goals and performance objectives.

Development of Alternatives and Alternative Costs(Step 2) The analysis may be applied to new construction to evaluate:

alternative structural systems
alternative materials,
alternative concepts such as conventional construction vs. new earthquake hazard mitigation technology such as seismic isolation
alternative seismic design load levels such as various design acceleration levels
alternative earthquake ground motion recurrence intervals

For existing construction, analysis may be applied to evaluate:
alternative seismic upgrade levels
alternative concepts of upgrade including conventional construction vs. new earthquake hazard mitigation methods

When an analysis is applied to a design project considering alternative concepts, it is necessary to evaluate the cost of each alternative. A preliminary structural design must be performed to determine structural member sizes for each alternative. Additionally nonstructural items affected by the seismic forces must be designed to the extent that they represent significant cost factors which vary among the alternatives. Once the structure is defined a detailed cost estimate can be completed. This is a very important step in the analysis and one which determines the level of accuracy.

As is usual practice in preparing a cost estimate, the structure should be broken down into major components and the cost of each component noted separately. The division of the facility into components is an important step since each component will be later analyzed for damage. As will be shown later, for the case of a building, it is important to separate out components which are drift sensitive from those that are force/acceleration sensitive. Equipment mounted on floors will be sensitive to the acceleration levels it receives; while, items such as vertical plumbing risers spanning between floors will be drift sensitive. Some items will fall into both categories. Where desired, a component may be subdivided into elements for a more detailed evaluation. It is required that a detailed cost estimate be compiled for each alternative being evaluated. There may significant portions of the cost estimate which do not vary among the alternatives. The amount of work involved is not as great as it might appear. Once a routine detailed cost estimate is prepared for the basic structure concept, as is standard practice, only those elements which change among alternatives need be evaluated. Use of individual components has the added benefit of showing where the damage occurs and whether there are any weak links in the system. This is especially important for systems which are expected to remain operational after an earthquake.

While the procedure is applicable to all waterfront construction, it will be illustrated by a case study of a building for which data was available. A study was performed in which a 185-foot square three-story building was designed for various steel and concrete lateral force resisting alternatives. Five lateral force-resisting alternatives were evaluated for six design acceleration levels. Figure 6-1 shows the cost increase of seismic design as a function of the design acceleration level for the various alternative lateral force-resisting systems. For this illustration, the structure was designed to be at the elastic limit at the design acceleration level to facilitate comparison. It is interesting to note that in this case, the cost of seismic strengthening is a relatively minor part of the structure's total cost.

It should be noted that in addition to the alternatives of modification of the structural design there may exist non-engineering alternative of land-use consideration (moving to a less vulnerable site), and financial and emergency response methods. In a building, use and occupancy restrictions can have significant impact on life-safety hazards. System enhancements are another possible risk reduction method (increasing the redundancy of key operational and risk-protection elements of the system)

Seismic Hazard Identification and Assessment (Step 3) Fundamental to evaluating the potential for seismic damage is quantifying of the hazard exposure. This is accomplished by a site seismicity study which determines the intensity and characteristics of ground motion shaking which pose a risk to a specific location. The method of performing a site seismicity study has become standard practice and is used by many geotechnical firms. In general, an historical epicenter database is used in conjunction with available geologic data to compute the probability distribution of site ground motion. The process of quantifying the level of hazard involves

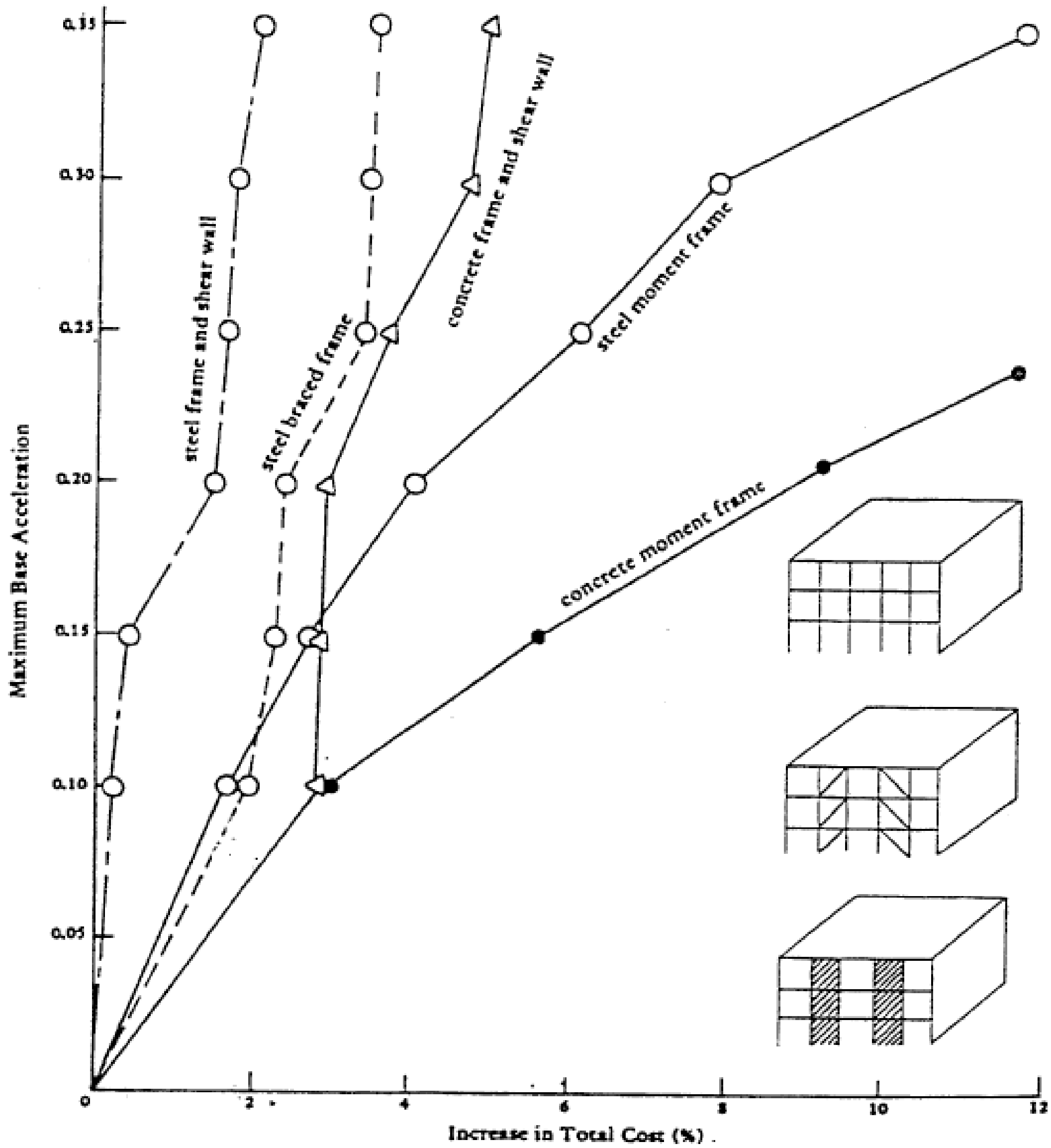


Figure 6-1. Cost of seismic resistance alternatives in new construction.

building a seismic model of the region using epicenter data, tectonics and geology. (See Chapter 2) The results of the seismicity study which are used herein include:

Definition of the site acceleration probability distribution

Definition of an array of causative (potential damage producing) events in which magnitude, separation distance, and site acceleration are defined forming a probabilistically complete set of events of significance to the facility in terms of damage causation.

Figure 6-2 illustrates a typical non-exceedance probability ground acceleration distribution for a site for a given exposure period. The word "total" is used because it represents the combined effects of all seismic source zones acting on the site. A histogram can be constructed showing the expected probabilities of various levels of ground shaking, Figure 6-3. Development of Figures 6-2 and 6-3 are the first steps in the economic analysis and are based on information available usually part of a routine seismicity study for a large facility. The use of the probability distribution and the array of discrete damaging earthquakes represent a complete set of data defining the total seismic hazard. As such it mathematically captures the exposure hazard.

Damageability Evaluation (Step 4) For waterfront construction it is necessary to consider all damage mechanisms on the structure. These include the shaking damage potential to the structures directly. They may also include other elements such as:(a) potential damage due to liquefaction and ground movement, as well as ground shaking; (b) repair cost issues for such facilities, such as possible difficulties due to lack of accessibility (e.g., to repair or replace underwater or underground piles that are damaged); (c) for major ports and marine oil terminals, the potential significance of major secondary economic losses due to interruption of operations and effects on other stakeholders; and (d) the potential for earthquake-induced environmental damage at these facilities.

Earthquake induced structural damage is caused principally by two mechanisms: drift and forces/accelerations. Drift is the mechanism usually causing damage to structural systems. There have been numerous tests conducted of lateral structural resisting systems which show the strength of these elements under cyclic load reversal. Building elements anchored to floors or suspended from ceilings feel the floor acceleration and respond as substructures. Depending upon the natural period of the structure, floor accelerations can be significantly higher than surface ground motion levels and tend to increase with height within the structure. The original Navy work, Ferritto (1984a), presented data tables relating damage of various components to drift and to acceleration. Way (1995) has updated this information based on experience over the last decade. Figure 6-4 gives the most current damage estimate data.

For each alternative it is necessary to conduct a series of analyses to compute damage over a range of possible ground motion levels. Looking at the probability histogram of occurrences of various levels of acceleration in Figure 6-2, it can be seen that the bins cover increments of 0.1 g over a range of 0 to 1.0 g for the particular site.

To illustrate the process, a set of ten dynamic analyses starting at 0.05g to 0.95g would be appropriate for this case to cover the range of possible accelerations which could produce expected damage of significance. (Note 0.95g was selected upper limit for this example and

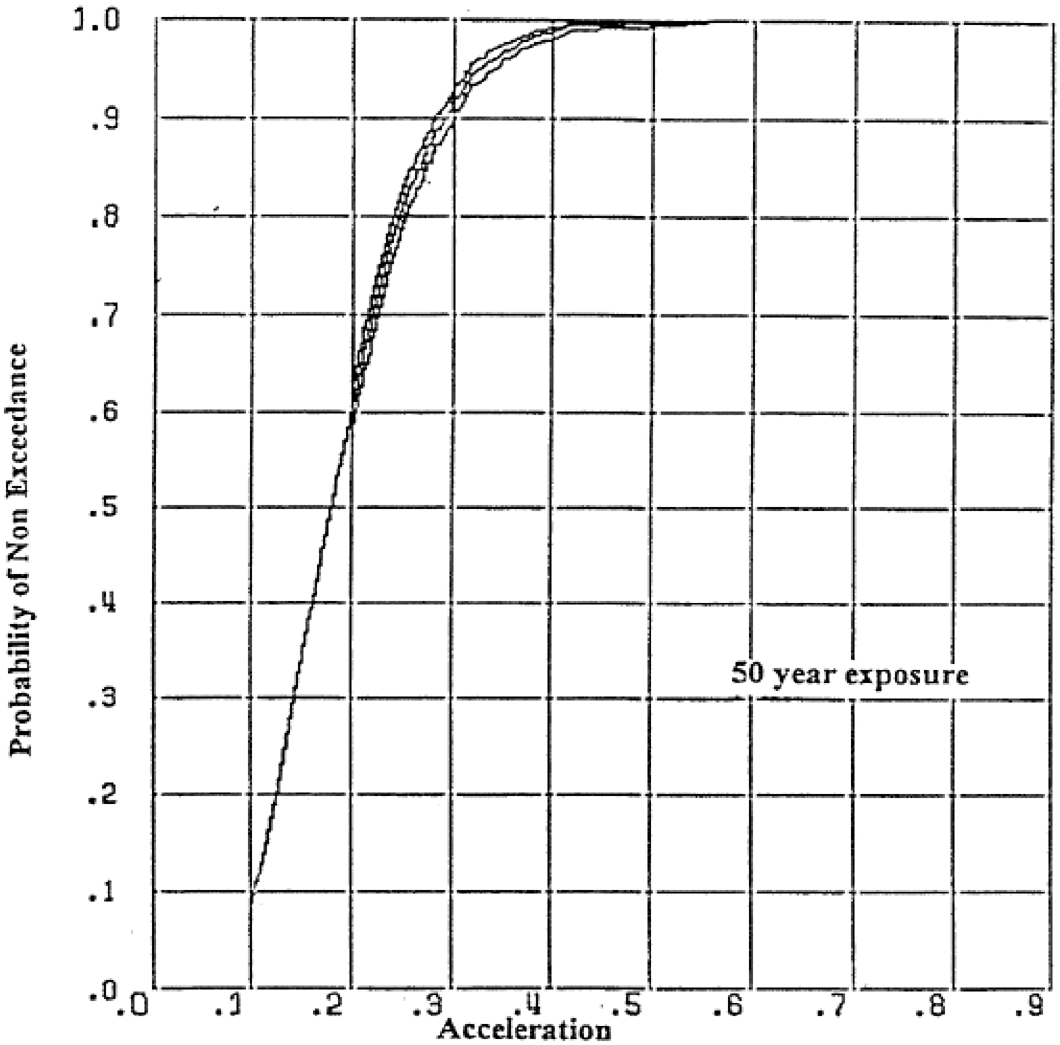


Figure 6-2. Total probability of non-exceedance of site acceleration.

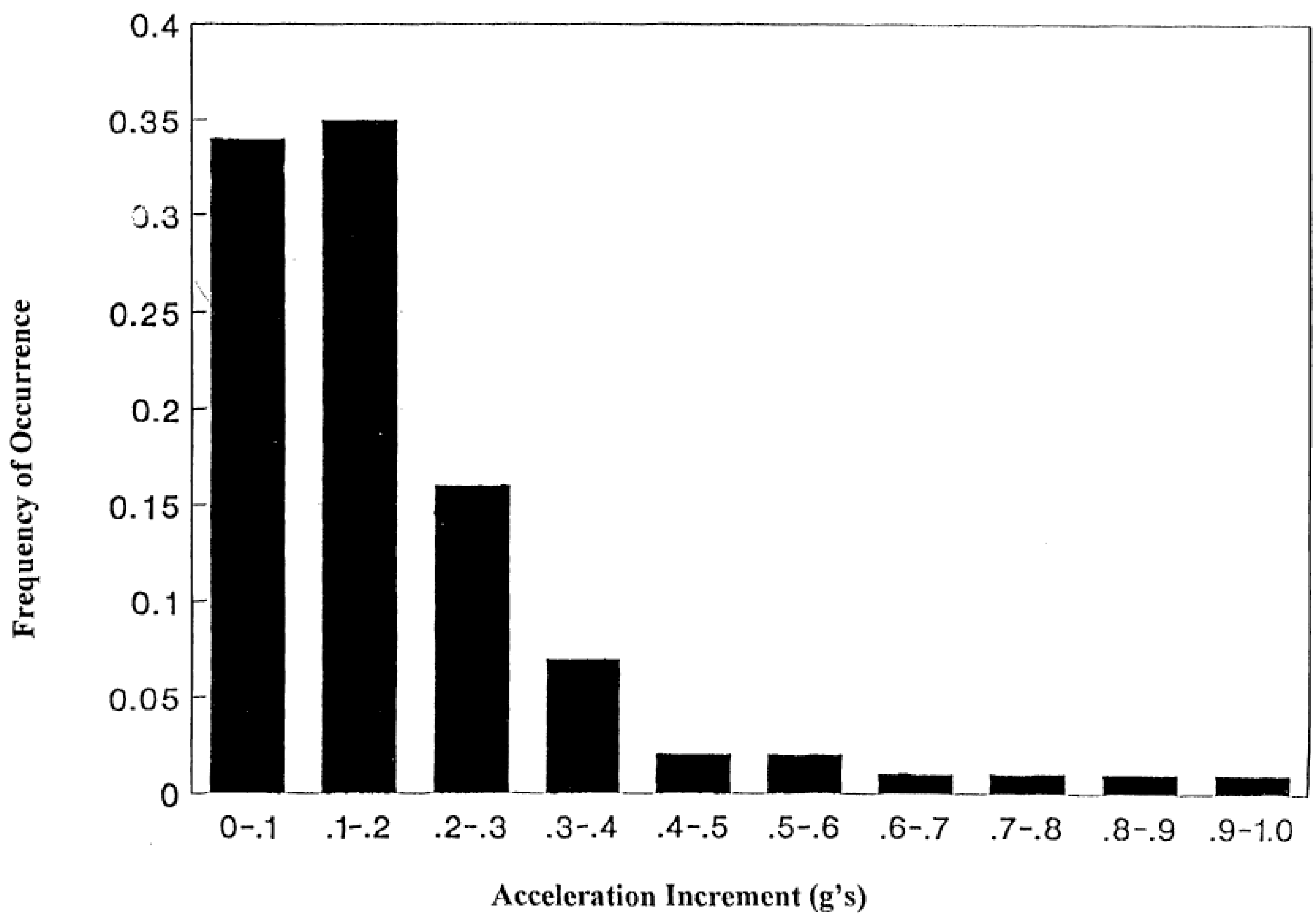
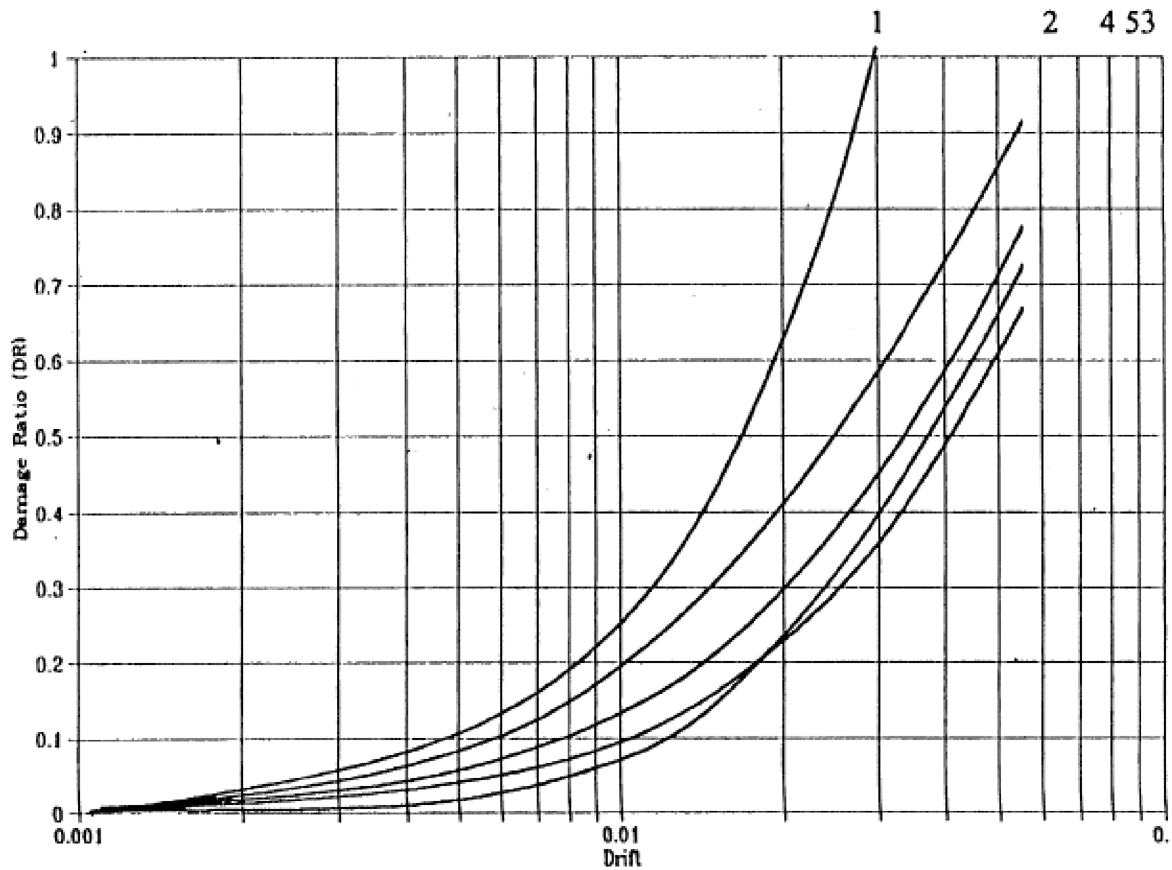
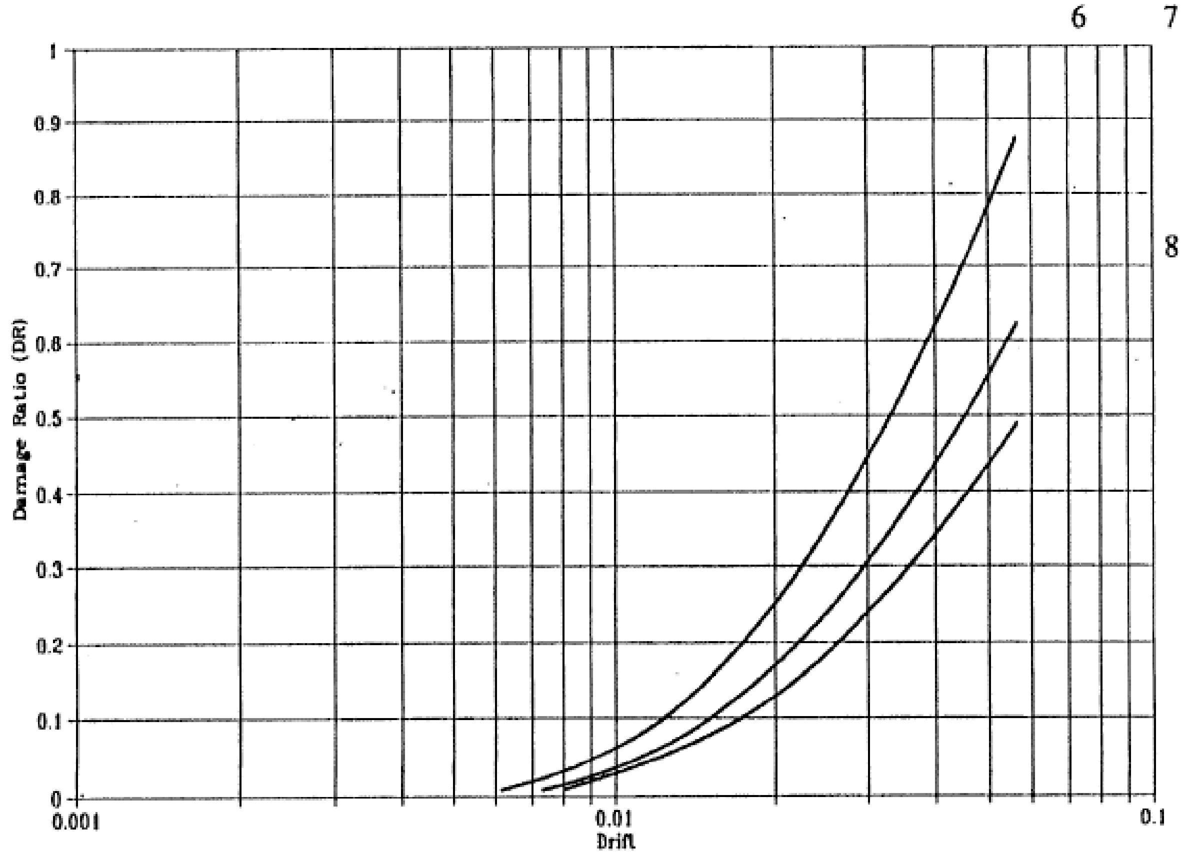


Figure 6-3.. Incremental acceleration level.



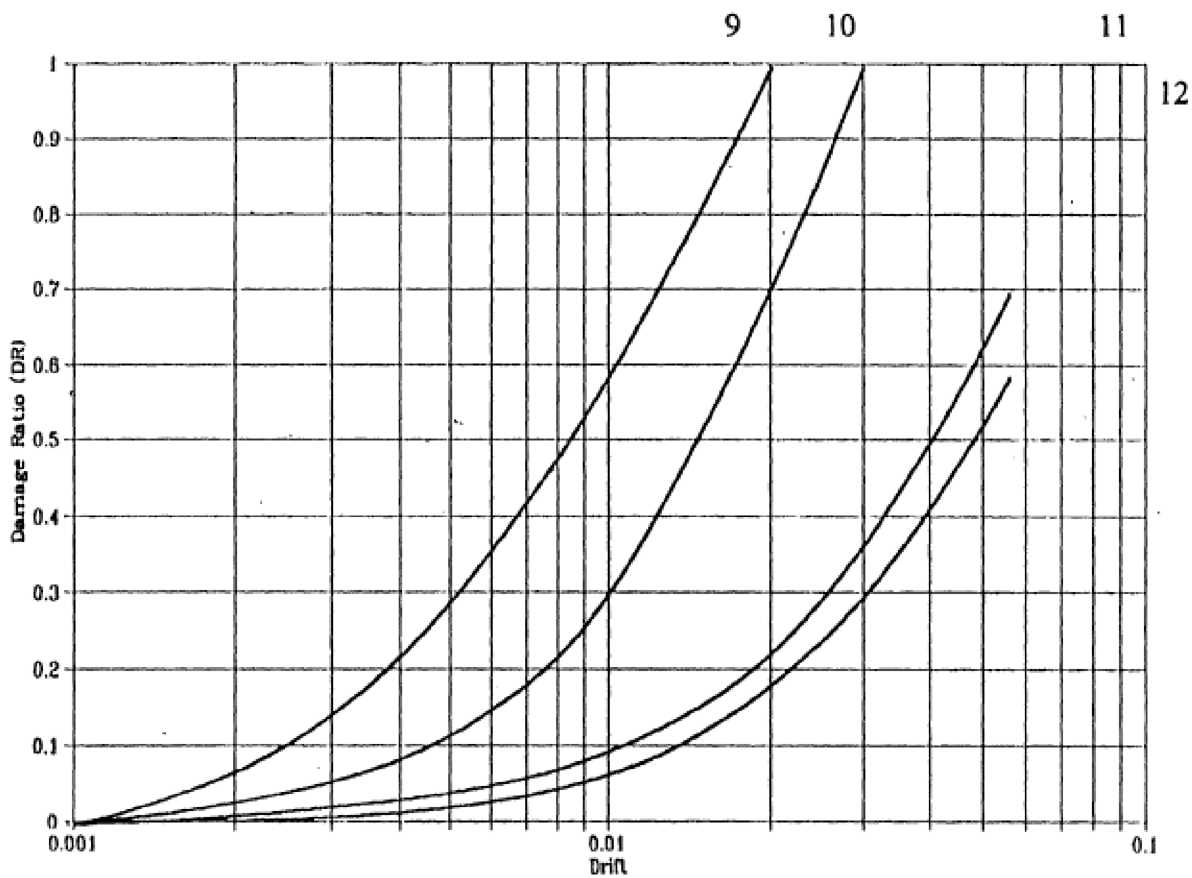
1. Masonry Walls
2. Concrete Shear Walls
3. Concrete Moment Frames
4. Steel Braced Frames
5. Steel Moment Frames

Figure 6-4. Damage as a function of drift and acceleration. (based on Way (1995))



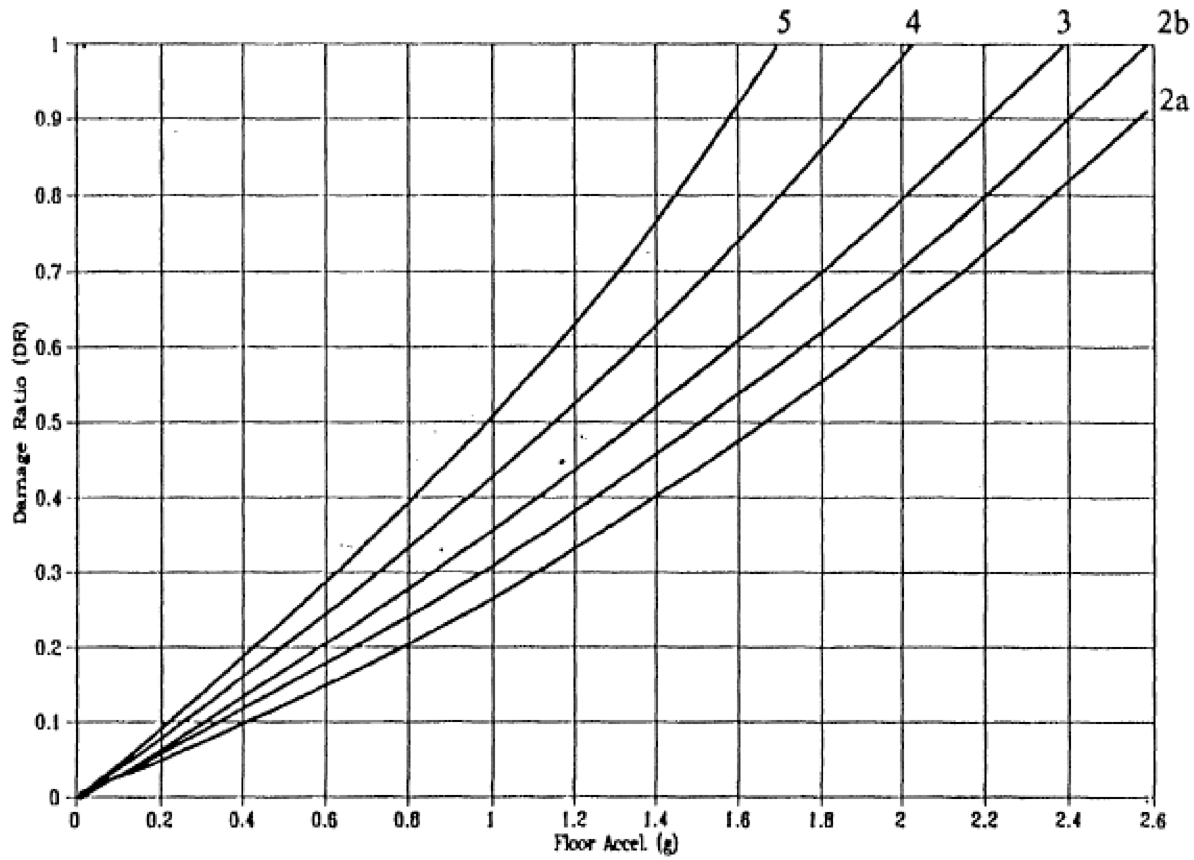
6. Structural Frames
7. Structural Floors
8. Foundations

Figure 6-4. Continued.



9. Architectural Glass
10. Partitions and Ceilings
11. Mechanical and Electrical
12. Contents

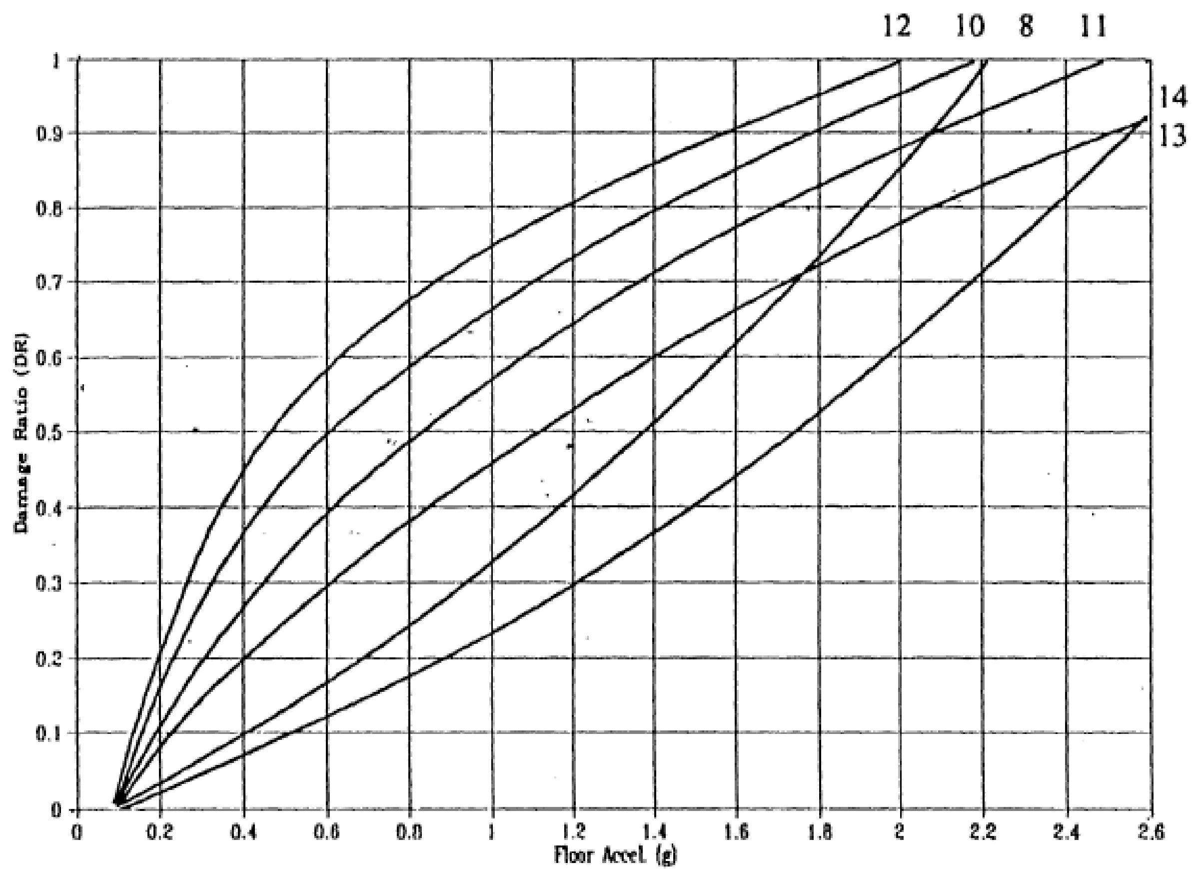
Figure 6-4. Continued.



5. Steel Moment Frames
4. Steel Braced Frames
2a. Steel Frames w/ CSW

3. Concrete Moment Frames
2b. Concrete Frames w/ CSW
CSW - Concrete Shear Walls

Figure 6- 4. Continued.



13. Floor Finish & Roof
10. Partitions & Ceilings
11. Mechanical & Electrical
9. Architectural Glass
14. Elevators
8. Foundation and Site Work
12. Contents

Figure 6- 4. Continued.

would be based on the actual site data covering the upper bound acceleration at a meaningful probability.) For a specific alternative, a basic finite element model would be constructed; then, the ten analyses of the model would be performed in which the applied load level was increased from 0.05 g to 0.95g.[1] The results of the analysis are used to establish the interstory drifts and floor accelerations at each applied load increment. These are used to compute the damage ratio for each component by using Figure 6-4, examining the individual component elements and their appropriate drift and/or floor acceleration. The damage evaluation process is repeated for each of the ten applied load levels from 0.05g to 0.95g for each alternative. This part of the analysis can be automated by a program which post-processes the output from the finite element program and computes damage to all components and then sums component damage for overall building damage at that level of applied loading. Thus to summarize:

Alternatives 1... i

Acceleration Increments 1... j

For each dynamic analysis for a given alternative, i, and applied load level, j, each of the identified components such as structural frame, mechanical equipment etc. is evaluated for damage using the drift and floor acceleration response data. Specifically, for a typical iteration the structure is defined, the load is established, a dynamic analysis is performed, displacements and accelerations are computed (drifts, interstory displacements, floor/deck accelerations, etc), for each identified component, component damage is computed using the displacement and acceleration data, damage is summed for all components giving total damage for that iteration combination.

The element damage relationship expressed in Figure 6-4 is in terms of a damage ratio; the actual element damage cost is obtained by multiplying the damage ratio from Figure 6-4 times the element cost from the cost estimate. Alternatively the element damage can be summed to a component level based on average damage ratios and then expressed as a component damage cost based on the average damage ratio times the component cost. Experience has shown that the cost of repair is greater than the original cost because elements must first be removed before the damaged component can be repaired or replaced. A component repair multiplier, R, is used to account for this increase. The repair multipliers are based on GSA data obtained from actual experience. Note that structural materials may be in short supply after an earthquake and cost more. This may also be included in the R factor. For example, when a lateral force element is damaged, the level of damage is first computed from the drift data. This level of damage is then multiplied by 1.5 to take into account that the repair process requires more work than the initial installation. Specifically, a given level of drift may represent 10 percent damage to the element which would become 15 percent of the dollar cost of the element (10% times 1.5). The following repair multipliers are suggested to increase the component costs:

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[1] The author has found that performing a nonlinear time history analyses using programs like the DRAIN2DX/DRAIN3DX computer program to be highly efficient. The amount of effort involved is not increased significantly beyond the basic analysis since repeated analyses at different load levels only involve adjusting a few parameters to change or scale the acceleration load record and the structure damping level. The topic of damping will be discussed below. No changes need be made to the structure geometry model.

Lateral force resisting system	1.5
Other structural components	1.5
Mechanical equipment	1.25
Electrical equipment	1.25
Architectural elements	1.25
Elevators	1.25
Contents	1.05

The Total Building Damage for a given iteration of acceleration load level can be expressed as:

$$\text{Total Damage} = \Sigma \text{(Damage Ratio) * (Component Cost)* (Component Repair Multiplier)}$$

Additional cost factors should be included in the Total Damage at this point, such as loss of life, injury and interruption in operations and lost revenue from the facility being out of service. Loss of functionality can be a very significant cost factor for certain types of facilities. The inclusion of these indirect costs are significant and can shape the results of an analysis.

The Expected Damage Cost is computed by multiplying the probability that the acceleration increment from the histogram will occur, such as Figure 6-2, times the damage or damage ratio for the building evaluated at that acceleration increment, and summed over all acceleration loading increments. The Expected Building Damage Cost for the specific alternative concept over the range of possible accelerations for the defined exposure period (for example 50 years) is given by:

$$\text{Expected Damage} = \Sigma \text{(Total Damage for increment “bin” of acceleration) * (Acceleration “bin” Probability)}$$

Since the damage will occur some time in the future it must be expressed in terms of the present value (PV) to relate it to the current costs of seismic strengthening or remediation.

$$\text{Current Expected Damage Costs} = \text{PV(Expected Damage Cost)}$$

In most cases, we do not have data which defines the temporal sequence of expected earthquakes over the life of the structure. It may be assumed that the risk is uniform over the exposure period. The present worth can be determined by dividing the exposure time into segments and then taking the present value of each segment.

The life cycle cost of this alternative is the sum of the initial construction cost plus the present value of the expected damage based on the preceding two equations.

$$\text{Alternative Cost} = \text{Initial Construction Cost} + \text{PV(Expected Damage Costs)}$$

Engineers have used two forms of structural dynamic analysis: response spectra procedures and time history solutions. A nonlinear time history solution is preferred because it directly computes displacements and floor accelerations taking into account structure yielding. Since there is substantial variation among earthquake records even when scaled to the same nominal peak acceleration value, the selection of an acceleration record can be a factor in establishing the maximum response of the structure. The choice of records should be examined to quantify variation in response and a series of three acceleration time histories is typically used to cover a range of response and to populate all frequency ranges of importance to the response of the structure. It is important to note that as the ratio of applied loading to design load increases, the structure undergoes increased deformation and possible nonlinear behavior. As the level of deformation increases, an increase in damping occurs which must be included in the analysis. Values for damping as a function of inelastic deformation have been discussed in the literature and are presented in Ferritto (1984a). Care must be taken at each load level iteration to select the appropriate damping for that load increment.

Decision Analysis and Alternative Selection (Step 4) At this point the owner has information which shows the cost of each alternative and the expected damage each alternative is likely to sustain over its life. The owner should examine the options in terms of the returns for investment of additional resources. Consideration of the costs of interruption of operation are essential parts of the analysis. Consideration for minimization of risk can be included and this will be further developed below.

Simple Economic Comparison - Illustrative Example

To illustrate the analysis of alternative concepts, the building discussed above will be used. The structure is a proposed three-story square building 185 feet on a side.

Problem: Consider for a new building the alternative designs of

Steel frame and concrete shear wall

Steel braced frame

The alternatives of frame/shear wall design and braced frame design will be compared for a 0.2g elastic design acceleration. The building is shown in plan view in Figure 6-5a and the two lateral force resisting alternatives are shown in Figure 6-5b. The components identified for analysis, their costs and repair multipliers are shown in Table 6-1. The components have been divided based on their susceptibility to drift or acceleration.

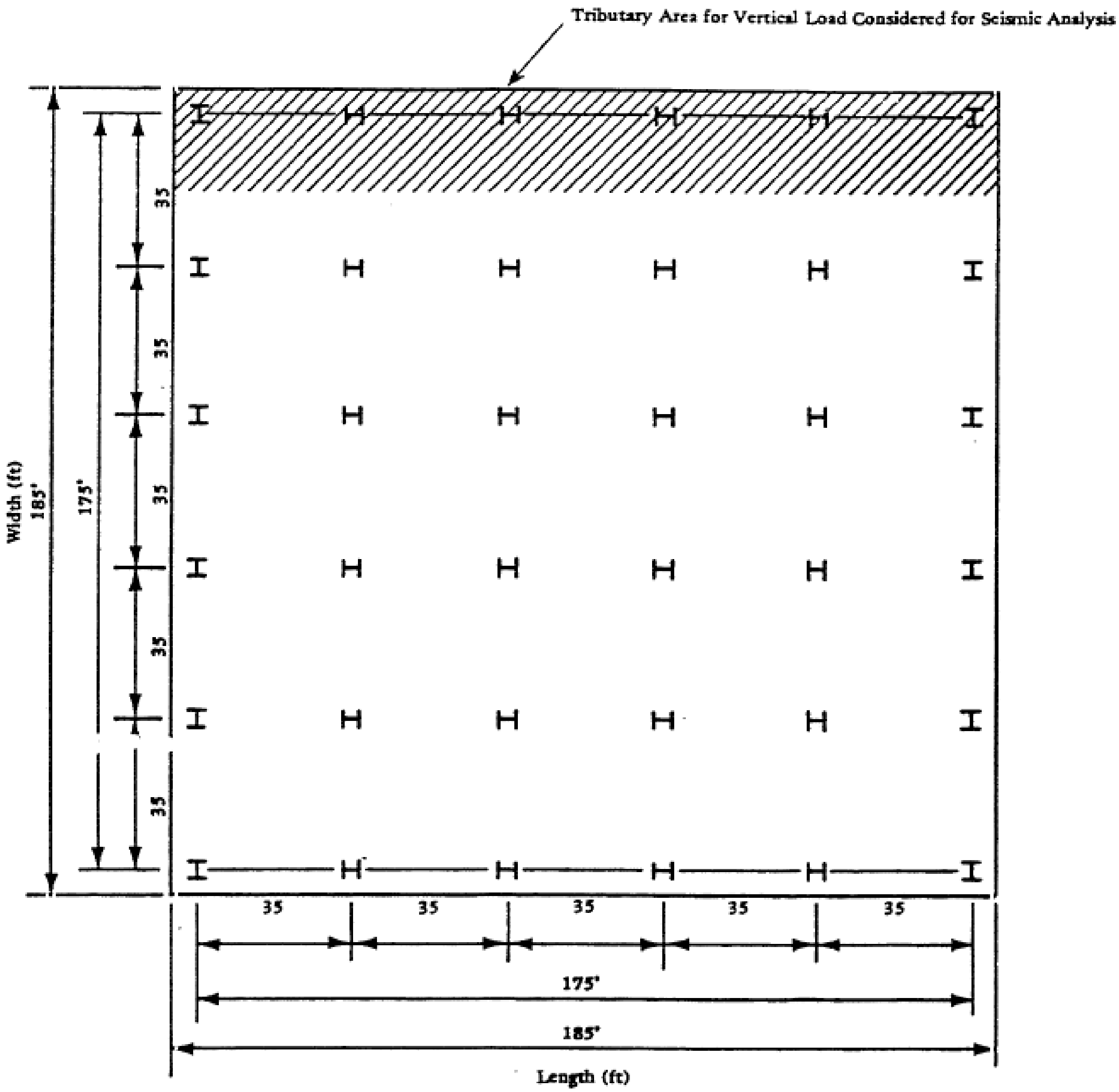
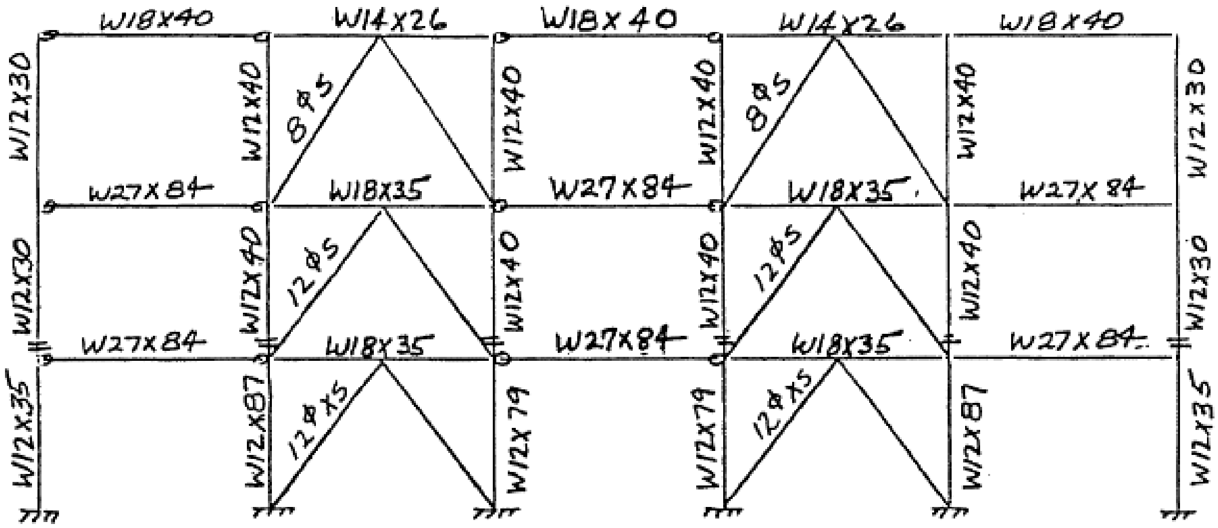
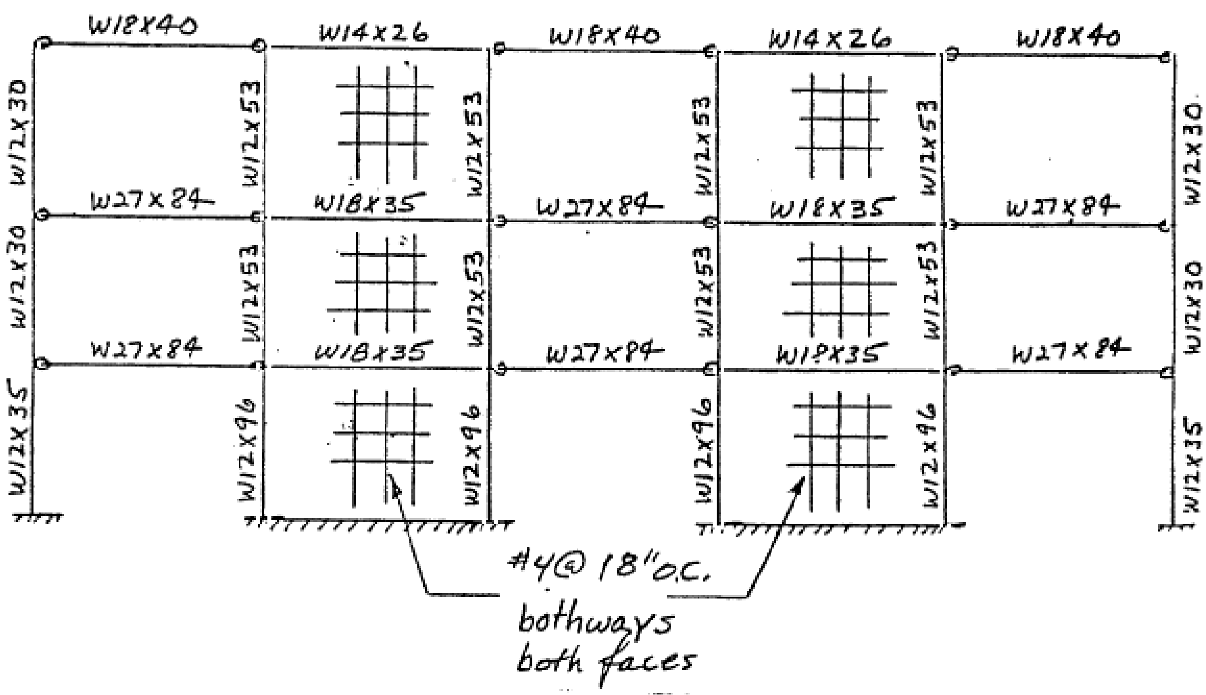


Figure 6- 5a Example building plan view.

0.20 g elastic design, $\mu = 1.0$



Braced Frame



Shear Wall

Figure 6-5b. Sections showing braced frame and shear wall alternatives.

Table 6-lA Drift Sensitive Components

Component	Cost ($)	Repair Multiplier
1. Alternatives		
a. Braced frame	126,800	2.0
b. Shear walls	107,000	2.0
2. Nonseismic structural frame	625,500	1.5
3. Masonry	417,600	2.0
4. Windows and frames	120,600	1.5
5. Partitions, architectural elements	276,200	1.25
6. Floor	301,200	1.5
7. Foundation	412,100	1.5
8. Building equipment and plumbing	731,600	1.25
9. Contents	500,000	1.05

Table 6-1A Drift Sensitive Components

Component	Cost ($)	Repair Multiplier
1. Alternatives a. Braced frame b. Shear walls	 126,800 107,000	 2.0 2.0
2. Nonseismic structural frame	625,500	1.5
3. Masonry	417,600	2.0
4. Windows and frames	120,600	1.5
5. Partitions, architectural elements	276,200	1.25
6. Floor	301,200	1.5
7. Foundation	412,100	1.5
8. Building equipment and plumbing	731,600	1.25
9. Contents	500,000	1.05

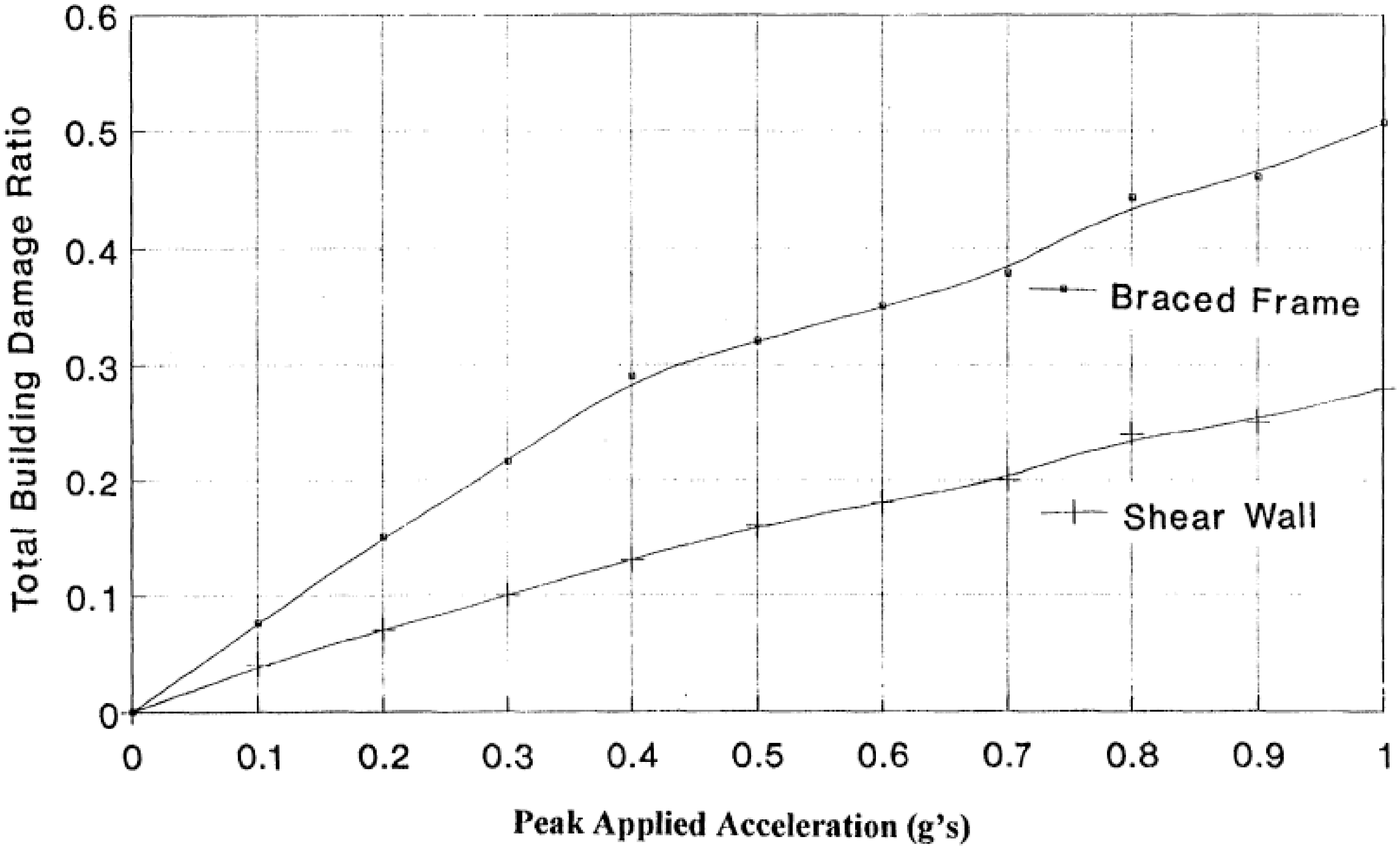


Figure 6-6. Damage ratio for alternatives.

Table 6-1B Acceleration Sensitive Components

Component	Cost ($)	Repair Multiplier
1. Alternatives a. Braced frame b. Shear walls	 126,800 107,000	 2.0 2.0
2. Floor and roof	301,200	1.5
3. Ceiling and lights	288,500	1.25
4. Building equipment and plumbing	731,600	1.25
5. Elevators	57,000	1.5
6. Foundation	412,100	1.5
7. Contents	500,000	1.05

The initial construction total costs for each alternative are

Steel Frame and Concrete Shear Wall $5876,700

Steel Braced Frame $5,928,800

For each increment in applied load acceleration between 0.05g and 0.95g a nonlinear analysis was performed and the interstory drift and floor accelerations determined. Specifically, the full range of accelerations which are possible to occur from 0 to maximum are covered in increments to represent a full set of motions and probabilities. The process of discretizing the acceleration loads in a set of increments does introduce some error which is believed small. Using drift and acceleration damage data from Figure 6-4, damage ratios were computed and are shown in Figure 6-6. The data in Figure 6-6 was combined with the data in Figure 6-2 to compute Total Building Damage. The calculations are shown in Table 6-2.

Table 6-2. Damage Ratio and present value calculation

Acceleration Increment (g's)	(1) Frequency of Occurrence		Braced Frame (2) Damage Ratio Braced Frame	Braced Frame (1) x (2) Probable Damage Ratio		Frame & Shear Wall (3) Damage Ratio Shear Wall	Frame & Shear Wall (1) x (3) Probable Damage Ratio
0-.1	0.34		0.03	0.0102		0.015	0.0051
.1-.2	0.35		0.11	0.0385		0.05	0.0175
.2-.3	0.16		0.175	0.028		0.08	0.0128
.3-.4	0.07		0.25	0.0175		0.11	0.0077
.4-.5	0.02		0.305	0.0061		0.14	0.0028
.5-.6	0.02		0.335	0.0067		0.17	0.0034
.6-.7	0.01		0.365	0.00365		0.19	0.0019
.7-.8	0.01		0.41	0.0041		0.22	0.0022
.8-.9	0.01		0.45	0.0045		0.24	0.0024
.9-1.0	0.01		0.485	0.00485		0.26	0.0026
Total Damage Ratio			BF =	0.1241		SW =	0.0584

For 50 years of equal exposure and 7 percent interest the average Present Worth factor is 0.28 (Note this value is computed by summation of PW increments over exposure or by a random simulation)

The present value of the damage costs are:

Braced Frame 0.28 * 0.1241 * $ 5,928,800 = $206,000

Shear Wall 0.28 * 0.0584 * $ 5,876,700 = $96,000

The present worth of the future damage which can occur any time in the 50-year exposure period is determined based on the average present worth factor for increments of time using a 7 percent interest rate. Note that the 0.28 used above is the present worth of a single random damage events which can occur any time in a uniform manner in the 50-year exposure. It is computed by a Monte Carlo simulation of 1000 events. As such it represents the present worth of all future damage expressed as a single event occurring in the future and brought back to today. This assumes that all damage producing events occur at some unknown set of times in the future, that they can be summed together, and that the sum can be expressed as a single time event. The interest rate was based on the approximate rate of return on long term federal bonds and is thought appropriate for federal construction. The expected damage is:

Steel Frame and Concrete Shear Wall $206,000

Steel Braced Frame $96,000

The loss of building function from an earthquake can be a significant factor and can be included at this point. Here the user develops a value for the operation of the building in terms of the value of the product produced in the building. For administrative buildings the value of the salaries paid to the occupants can be an approximate indication of the value of the operation. As an illustration consider that the out of service lost time might be estimated as follows based on the dollar value of the damage and the time to repair:

Steel Frame and Concrete Shear Wall 10 weeks

Steel Braced Frame 5 weeks

If the building housed 200 people with a total annual payroll of $10 million, one week of lost productivity would be about $200,000 times the present value factor 0.28 or $56,000. Note this is a trivial illustration relating total lost time to total damage. It should be obvious that more complex characterizations of downtime and loss of service can and should be made based on the actual circumstances.

The total cost of the two alternatives involves summing the initial construction costs plus the present worth of the total damage and lost time costs expected. In this example they are:

Steel Frame and Concrete Shear Wall $5,876,700 + $206,000 + $560,000 = $6,642,700

Steel Braced Frame $5,928,800 + $96,000, + $280,000 = $6,304,800

Up to this point the interest rate and the life of the structure have not been discussed. Both of these can affect the choice of options. It is up to the owner/user to select these values based on the value of money to him/her and the projected useful life of the structure. For federal construction the value of borrowed money such as long term Treasury Bonds is a good indication of what money is costing. One may choose to subtract the inflation rate from the long term

Treasury Bond rate to exclude the inflation or one may add an inflation rate to future repair costs. The example assumed a constant value analysis excluding inflation. Increasing the value of the interest rate makes the present value of future losses less and reduces the economic worth of damage prevention over initial savings. It becomes harder to justify seismic damage reduction technology. Conversely if borrowed money were without cost, seismic improvements would be very attractive. Buildings tend to remain in service for long periods of time. Fifty years has been used as the economic life for federal construction. Increasing the life of the structure increases its exposure to damage but also increases the time factor in present value calculations which reduces the present worth of future damage. The specifics of the problem determine the net effect. In general the life of the structure has less effect than the interest rate.

At this point the decision-maker can evaluate the reduction in losses with increased investment. Once the minimum required standard is met, the owner may decide how much additional investment is prudent based purely on commercial business investment practice. However this may not be enough when evaluating a marine oil terminal. The risk of major spills is an important factor which must be considered and will be addressed in following sections.

Simplification of General Economic Analysis

The above procedure involves three main steps: the quantification of the seismic hazard in probabilistic terms, the determination of the initial costs of seismic strengthening or remediation, and the determination of the expected damage. It was proposed to use an incremental approach in which the ground motion acceleration probability distribution is expressed as a histogram composed of incremental “bins” of acceleration and their associated probabilities of occurrence. This produces a full and complete analysis of the best estimate of the seismic exposure. However, a site seismicity study may not always be available. The engineer is free to substitute a set of earthquake events of design interest. This set is not a complete risk assessment but rather is a comparison of the proposed structural design alternatives under an assigned set of design load conditions. Having done this, the designer may choose to consider the average performance of the structure under the assigned set of events, or perhaps the worst case event, or perhaps the cumulative effect of all the events. Again it is important to note that this approach is not a total risk analysis but only a relative comparative performance of the alternatives under a set of design conditions. It was suggested that nonlinear time history finite element models of the structure be used to estimate drift and floor accelerations using sets of time histories. The engineer may substitute elastic response spectra techniques if he chooses as long as the results are adjusted for yielding.

Application Simple Economic Analysis To Piers and Wharves

As noted above the general procedure described above for performing an analysis of design alternatives may be applied to any type of structure. Data from a recent project is available to give an indication of the cost of a pier and its components. For a 120-foot wide 1460-foot long pier to be built in San Diego, a cost of $53 million was estimated. The following gives a breakdown of elements and their costs:

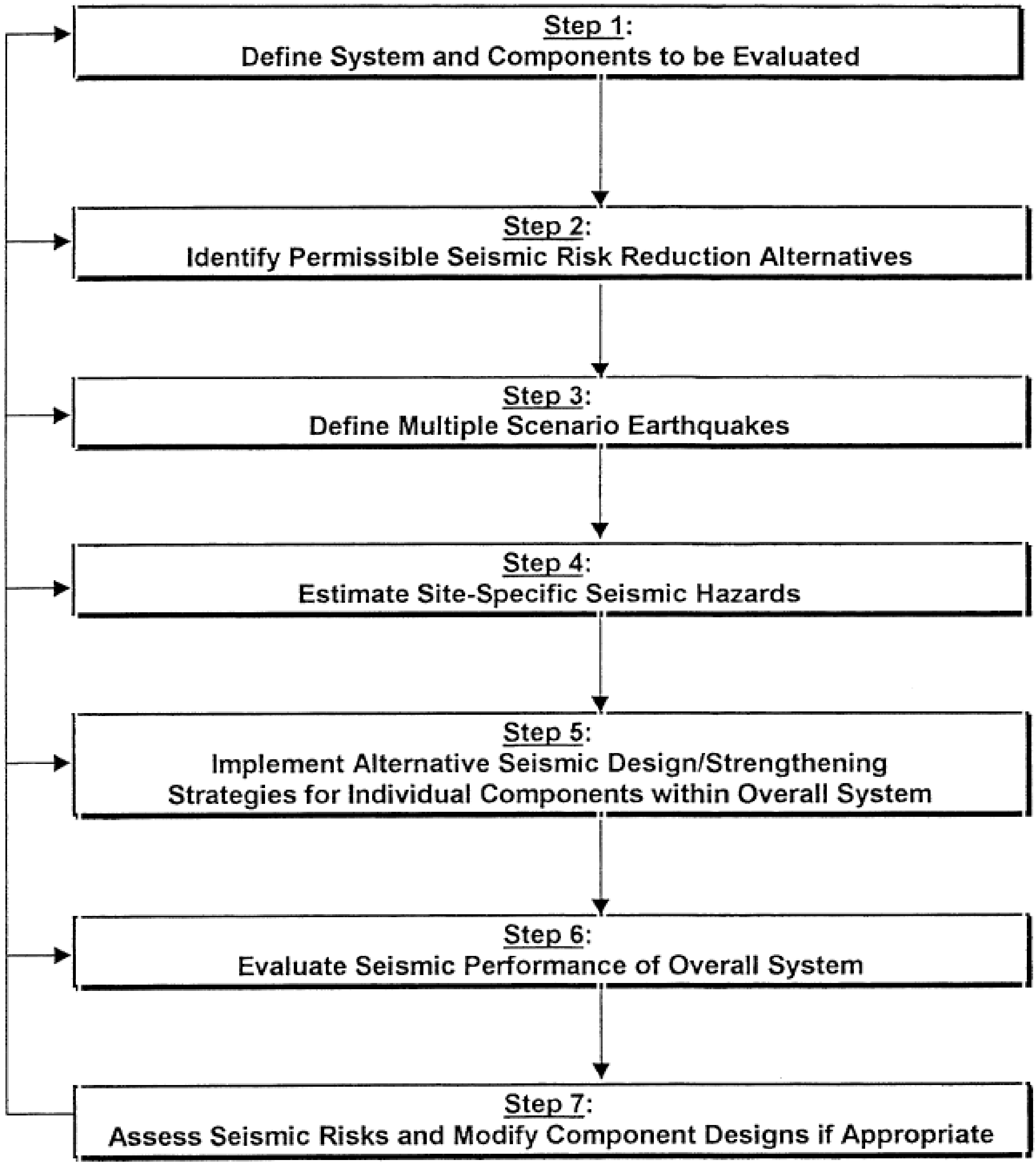


Figure 6-7
Acceptable Risk Procedure

Pier structure including pile foundation	$18.1 M
Utilities	$11.5 M
Fendering	$ 3.1 M
Dredging	$12.3 M
Demolition previous structure	$ 2.6 M
Contingency etc.	$ 5.4 M

As can be seen the actual structural costs are only 34 percent of the total project costs. Changing the pile design may influence the structure cost 15 percent but would only influence the total cost by about 5 percent.

Since the potential for harm to the environment from a large oil spill is high, the following section will address the element of risk as well as economics. The Port of Los Angeles commissioned a study of the design of the Pier 300 wharf Taylor and Werner, (1993). This study gives a valuable insight on the economics of the decision process and also allows for the inclusion of risk. The following section builds and expands on that work.

Expanded Economic Analysis To Include Risk

The preceding section presented procedures to utilize economic analysis as an aid in decision making and selection of the best alternative design. This section expands the general economic analysis procedure to include risk. The operation of a marine oil terminal is an economic process requiring prudent decision making based on business conditions and competition. However, it goes beyond simple economics because it considers potential risks to the surrounding environment due to earthquake damage to the terminal.

Overview of Procedure

This section describes an "acceptable seismic risk" evaluation procedure that can be used to provide information to enable regulatory agencies, owners, and other marine oil terminal stakeholders to make rational decisions for reducing seismic risks at such terminals. This procedure is based on the premise that it is not possible to achieve zero seismic risk; that is, no matter what degree of seismic design or strengthening is implemented, there will always be some finite residual risk of unacceptable seismic performance (which may be measured in terms of release of hazardous materials, repair costs, loss of operations, etc.). The acceptable risk procedure uses state-of-the-practice geoscience, engineering, systems, and economic analysis methods to establish that level of residual risk that is "acceptable" – i.e., for which the costs required to further reduce these residual risks are so high as to be no longer acceptable. These costs may not only be economic, but may also entail other types of costs as well (e.g., the social, political, and legal costs that may be associated with a given degree of earthquake damage).

Steps

This section outlines the seven steps (see Figure 6-7) that comprise the acceptable risk evaluation procedure. The procedure may be applied to ports, marine oil terminals, or any other system that may be at risk during an earthquake. As applied to different system types, the acceptable risk procedure evaluates costs and risks associated with alternative seismic risk reduction strategies.

The risks to be considered in a given application may differ according to the system type and objectives of the decision-makers. For example, decision-makers at a large commercial container port (e.g., port owners and tenants) may focus their evaluation on the reduction of risk from economic losses due to excessive earthquake damage and loss of operations. Decision makers at government regulatory agencies charged with developing performance requirements at facilities with hazardous materials (e.g., marine oil terminals) may focus on reducing risks from unacceptable release of these materials during an earthquake.

Step 1: Define System and Components to be Evaluated Under Step 1, the overall system to be considered in this evaluation is defined and described. This description should include the system's location, overall configuration, scheduled modifications, operational requirements, volumes and types of cargoes handled, and its components and their operational interfaces. The description of each component in the system should include: (a) its location(s) within the system; (b) function; (c) importance to system operations; (d) replacement costs; (e) structural elements (materials of construction, mass, e.g. location, stiffness, support conditions, etc.); (f) equipment essential to system and component operations; and (g) any prior seismic design or strengthening.

In addition, a set of operational goals should be established either for new construction or existing construction. For existing construction, the shortfalls of the present construction should be identified.

Step 2: Identify Permissible Seismic Risk Reduction Alternatives Step 2 of the procedure identifies those seismic risk reduction alternatives that are in the decision-maker's jurisdiction to implement. In general, these alternatives may include:

Engineering – These alternatives most commonly consist of seismic design of new facilities, seismic retrofit of existing facilities, and improvement of potentially liquefiable soils. Engineering evaluation may also result in other measures to reduce risks such as alternative site location, occupancy reduction of less safe buildings, and use of temporary shoring.

System Enhancement – The objective of these alternatives is to assure that systemic goals of the port or marine oil terminal are achieved such as maintaining cargo handling, transport, and storage operations, implementation of emergency response and recovery operations, etc. System enhancement alternatives include the development of multiple redundant operational paths and nodes for maintaining system operations and emergency power, communication, and fire fighting capability.

Financial Reserving – These alternatives include the retaining of funds for emergency response and recovery contingencies.

Disaster Recovery and Restoration – These alternatives include the development of post-earthquake emergency response procedures for port or marine oil terminal personnel, stockpiling of materials and equipment, and coordination with the government, police department, fire fighting agencies, hazardous material cleanup agencies, medical agencies, and utilities.

Risk/Liability Transfer – These alternatives include the use of insurance or other liability transfer mechanisms to limit post-disaster liabilities and assure that adequate recovery funds exist.

The acceptable risk procedure as described in the remainder of this section and in the example application below specifically addresses only one of these alternatives – engineering. However, it should be recognized that engineering is only one of several risk reduction alternatives that may be implemented. A comprehensive seismic risk reduction plan should encompass many or all of the various alternatives listed above.

Step 3: Define Multiple Scenario Earthquakes This acceptable risk approach applies a multi-scenario method within the framework of a Monte Carlo approach, in order to assess system costs and risks. *Scenarios* are defined as a suite of earthquakes that collectively represent the seismicity, geology, and tectonics of surrounding region. Each scenario earthquake is defined in terms of its moment magnitude and location (i.e., the location of the earthquake's epicenter, focus, center of energy release, or fault rupture zones). Only scenario earthquakes with a potential for damaging the system are considered (e.g., earthquakes with moment magnitude 5.0 and that lead to ground shaking at the site that exceeds some designated damage threshold level). The example described in the following section summarizes a state-of-the-art procedure for establishing scenario earthquakes in California.

There are many ways to develop a suite of scenario earthquakes, and to incorporate the multitude of uncertainties inherent in estimating potential future earthquakes and their locations. A Monte Carlo approach to the development of scenarios permits the incorporation of various uncertainties into the process of defining scenarios. Scenarios may be modeled in terms of one or more *simulations*. Each simulation represents the application of a random process to the independent parameters. As a consequence, to the extent that the random parameters can be modeled in terms of uncertainty distributions, a Monte Carlo approach can incorporate uncertainties in the process for selecting scenarios and the various simulations generated from these scenarios. In addition, this application of scenarios and simulations can readily incorporate spatially extended systems, such as those combining analysis of the port or marine oil terminal facility and the inland transportation systems that serve it.

To assess costs and risks over time that may be associated with alternative seismic risk reduction decisions, the scenario earthquakes may be represented in a form for use in a walk-through analysis. This form would consist of a table whose first column contains a year number (1,2, 3,…..up to possibly thousands of years), and whose subsequent columns list the magnitude and location of each earthquake determined to have occurred in the region during that year. The number of potentially damaging earthquakes during each year would range from zero (during many of the years) to some maximum number, probably about 4 for California as a whole, with a smaller expected number for a facility within a specific region of the state.

Step 4: Estimate Site-Specific Seismic Hazards Under Step 4, geoscience and engineering procedures are used to estimate the seismic hazards throughout the system due to each scenario earthquake from Step 3. Strong ground motion estimates are developed for each scenario earthquake from Step 3 both as a means to estimate strong ground motion hazards and to estimate those secondary hazards such as liquefaction, slope instability, and tsunamis that may result from strong ground motions. Local fault displacement hazards are also estimated for those earthquake scenarios associated with fault systems traversing the port system in question.

Step 5: Implement Alternative Seismic Design/Strengthening Strategies for Individual Components within Overall System Under Step 5, preliminary seismic designs are carried out for all new components, for strengthening of all existing components, for ground improvement, etc. A series of alternative designs may be carried out for each component (e.g., designing each component to alternative design criteria, considering alternative seismic detailing of structural elements, alternative levels of ground improvement, alternative equipment designs and/or support systems, etc.). These designs should be taken far enough so that initial construction costs can be evaluated under this step, and overall system seismic performance can be evaluated under Step 6.

Step 6: Evaluate Seismic Performance of Overall System Step 6 provides a model of the overall system as a function of damage to each of its components. The overall system model will include (a) physical interaction effects among diverse components within the system (e.g., how damage to one component affects performance of another component); (b) direct revenue losses to the port as a consequence of damages to components and the system; and (c) impacts on other stakeholders (e.g., shippers, those living and working in close proximity to the port) of primary and secondary damage to the port.

Step 7: Assess Seismic Risks and Modify Component Designs if Appropriate Step 7 contains the following substeps that are described below.

Substep 7-1: Develop Risk and Decision Calculations for Risk Reduction Alternatives

Substep 7-1 evaluates the risk reduction alternatives from Step 2 in terms of the loss and risk estimates developed under Steps 3 through 6. These alternatives can be compared in terms of significant performance criteria. For commercial container port facilities that handle container cargo with minimal environmental risk, the performance criteria will often focus on minimizing economic risks – i.e., the potential risks of significant repair costs, business interruption losses, and higher order economic impacts due to earthquake damage (see above). For marine oil terminals that transport and store environmentally sensitive materials, these criteria will focus on minimizing environmental risks (e.g., oil spills) as well as economic risks. As discussed above, seismic risk analysis of marine oil terminals can compare the likelihood of diverse extents of oil spills to the life-cycle costs of various design and/or seismic retrofit alternatives.

An important element of this substep is the estimation of economic risks in accordance with the following considerations:

General. Regardless of whether commercial ports or marine oil terminals are considered, the evaluation of economic risks associated with alternative seismic risk reduction decisions will be an important element of the risk analysis. These economic criteria used in the analysis emphasize both the mean and the variance of the life-cycle costs. Life cycle costs consider both the initial outlays (e,g., initial construction costs) and the present value of the downstream costs of alternative decisions (e.g., as noted above, the repair costs, business interruption losses, and higher order economic impacts due to earthquake damage).

Mean Value of Life-Cycle Costs. Emphasizing the mean value of the life-cycle costs is best represented by a least-cost analysis. Such analysis can indicate which of the various seismic risk reduction alternatives lead to the lowest value of the life cycle costs. From an investment perspective, this is analogous to obtaining the best possible "yield" from an "investment" in seismic risk reduction. That is, if one ignores the variance of life-cycle costs, the optimal seismic risk reduction alternative will have the least mean life-cycle cost. To obtain such information, there are several reasons why a least-cost analysis is superior to a benefit-cost analysis. For example, a seismic risk reduction alternative with a ***"favorable"*** benefit-cost ratio may nevertheless not have the ***most favorable*** benefit-cost ratio. Also, some decisions, especially those involving insurance purchase, do not (or in principle should not) have a favorable benefit-cost ratio. Instead, insurance purchases are made in order to reduce the volatility of decisions.

Variance of Life-Cycle Costs. Emphasizing the variance of life-cycle costs incorporates this "insurance" feature of investments. The variance represents the volatility (riskiness) associated with a given seismic risk reduction decision. In traditional capital markets, volatility is typically assessed in terms of the variance on the investment return. This is particularly important to ports, since port investments are not fully diversified, and ports do not have unlimited capital to cover investments that go bad (or are unlucky). Therefore, port investments consider volatility as well as expected value (mean) of the return on investments. These investments are primarily designed to reduce the volatility of port investments generally, and so act in significant ways as substitutes for insurance. (See Bernstein, 1996; Taylor and Werner, 1995, 1998).

Applicability in Acceptable Risk Methodology. Incorporating considerations of volatility into investments is very important for natural and environmental hazards mitigation programs. It is analogous to a prudent investor who not only considers the maximum yield of an investment, but also considers the volatility of the investment. Within the context of the acceptable risk methodology, consideration of the variance of life-cycle costs is a measure of the extent to which life cycle costs due to a given scenario earthquake can deviate from the mean value computed by a least-cost analysis. Therefore this should be an important element of the seismic risk reduction decision process.

Discount Rate Considerations. The application of a discount rate is necessary in economic analyses in order to compare present costs and benefits with downstream costs and benefits. However, selection of a suitable discount rate has raised many issues. Very often, the (real or constant dollar) discount rate selected is the difference between the rate for an extremely secure (non-volatile) investment and inflation. For instance, one may select long-term federal treasury bonds as extremely secure investments, and subtract from the current rate of these long-term financial instruments the rate of inflation. Cost of capital to a port, though, may imply a slightly higher rate, since the cost of borrowing for the port may be higher than the current rate of a very secure investment.

Discount Rate Multiplier. For the application of a discount rate j over an exposure time T in least-cost analysis, one may apply the following multiplier, $R_{j,T}$, to the average annualized loss:

$$R_{j,T} = \frac{1}{(1+j)} + \frac{1}{(1+j)^2} + \frac{1}{(1+j)^3} + \dots\dots\dots + \frac{1}{(1+j)^T}$$

or

$$R_{j,T} = \frac{1-(1+j)^{-T}}{j}$$

Applicability to Non-Economic Risks. The application of discount rates to lives saved, injuries averted, environmental damage, and treasures lost, to mention a few categories, has raised serious questions. Is one life saved today equivalent to five lives saved in twenty years or to twenty-five lives saved in forty years? Other than in calculating the economics of health programs, can one properly discount lives saved?

Substep 7-2: Select Risk Reduction Alternative(s) that Best Fit Performance Criteria.

Under Substep 7-2, the results from Substep 7-1 are used to eliminate various alternatives and select among those alternatives that remain. For example, alternatives may be ruled out if they lead to consequences that are proscribed by regulation, or if there are some clearly superior alternatives in terms of existing performance criteria (e.g., oil spill size probabilities and total life-cycle economic costs).

Substep 7-3: Review Selections of Risk Reduction Alternative(s) with Public.

Substep 7-3 provides justification of the acceptability of the selected risk reduction alternatives through programs that incorporate public review and criticism. Stakeholders in the decision are brought in through this substep. Based on feedback from this process, one or more of the prior steps of the acceptable risk procedure, and the resulting selection of a seismic risk reduction alternative, may be revisited or modified.

Demonstration Application

Background This section describes a demonstration application of the foregoing procedure to a hypothetical container wharf at a major commercial port. In this application, costs and economic risks associated with the use of alternative design acceleration levels are compared. Information of this type provides a port decision-maker with information for making a rational decision regarding an appropriate level of design acceleration to use for his or her wharf facility. This demonstration application is designed to be tractable, in the sense that other investigators should be able to replicate the results (except, perhaps, for the numbers resulting from application of random generators). The text of this section contains example calculations to assist in this replication.

This application is a modification of an analysis previously carried out for the Port of Los Angeles (POLA) and described elsewhere (e.g., Taylor and Werner, 1995 and 1998; Werner, Dickenson, and Taylor, 1997; Werner, Thiessen, and Ferritto, 1998). In view of these modifications, this example does not directly reflect the details and conclusions of the prior work. The main difference between the current example and the previous analysis is that the current example uses a much more complete scenario earthquake representation for the region. This current representation contains over 13,000 scenario earthquakes that cause peak ground accelerations at the site in excess of 0.01 g. As discussed subsequently, this representation was developed by adapting earthquake modeling procedures for California that were developed under the USGS National Hazards Mapping Program (Frankel et al., 1996). In the previous example, only 24 scenario earthquakes were considered that were based on previous work for POLA that was performed by others.

In addition to the scenario earthquake modeling, there were other differences between the current and previous examples. These consist of: (a) consideration of multiple discount rates, rather than a single rate, in the prior example; and (b) a modification of the site coordinates in the current example.

Because the objective of this analysis is solely to demonstrate the economic and risk evaluation procedure discussed above, the analysis contains certain simplifications that should be improved, to the extent possible, when applying the procedure to an actual port. These include:

- The analysis should consider more detailed characterization of faults in that could affect the hazards at the site, as well as local soil conditions and potential for ground failure due to liquefaction, slope instability, and surface fault rupture. The procedures recommended by the other investigators under this CSLC-USN project for marine oil terminals should be helpful for this purpose.

- The modeling of the seismic vulnerability of the wharf structure in this example is very simplified and should be improved. Again, the procedures in other chapters of this report should be helpful in this regard.

- It is preferable that the entire port be treated as a system. That is, instead of concentrating on only one component such as the wharf structure in this example, other components and their operational and physical interfaces should be addressed as well.

- The example addresses only one type of seismic risk reduction alternative – the selection of the level of seismic design acceleration to be considered for the wharf design. It does not consider that range of other seismic risk reduction alternatives that are available.

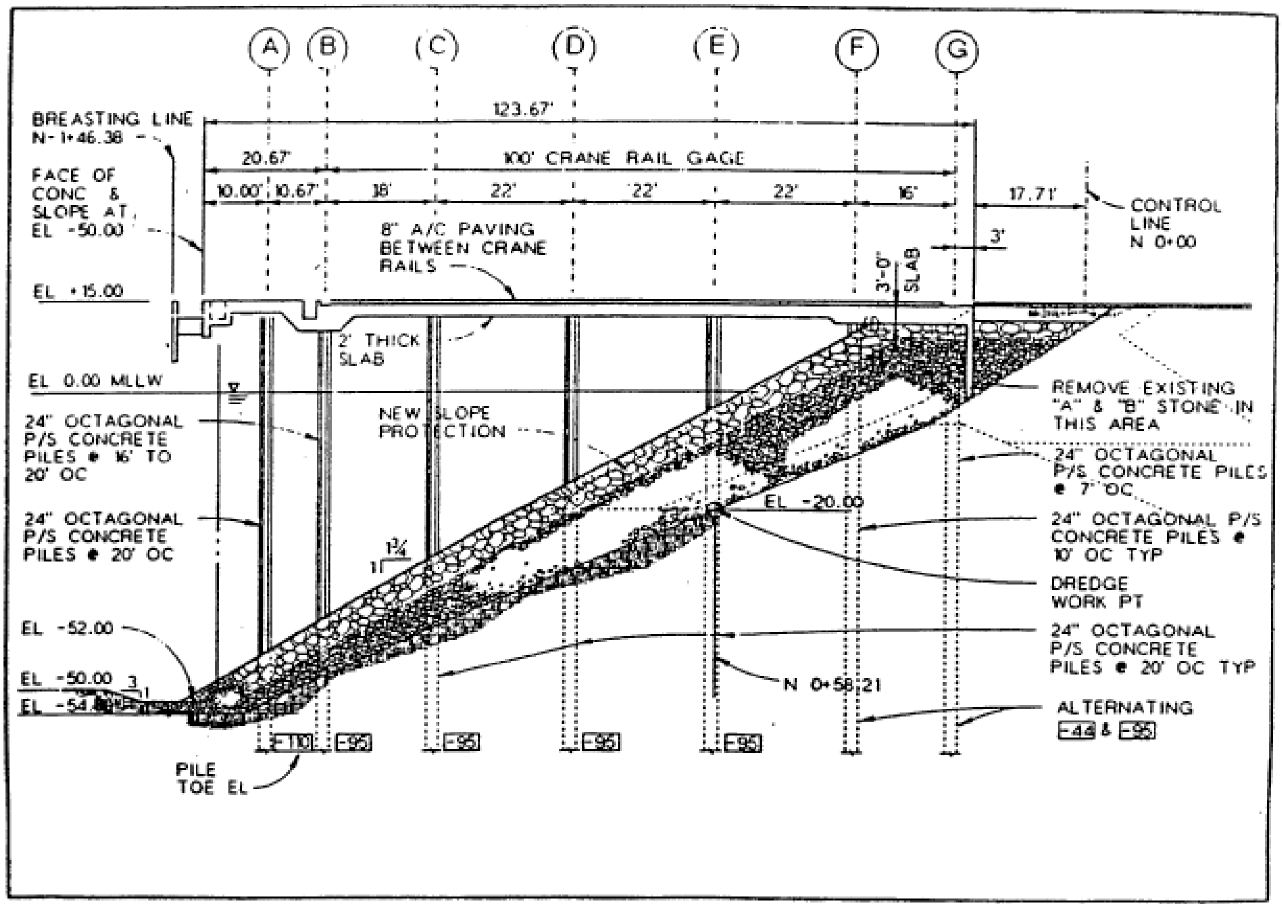


Figure 6-8
Cross Section of Wharf

Analyses of uncertainties and higher order economic losses are still very much in the research and development stage. Sensitivity analyses are desirable to overcome the belief that current models yield precise and accurate (rather than approximate) results.

The example directly considers only ground shaking hazards. Other hazards that could be significant at a port or a marine oil terminal – such as liquefaction, slope instability, and surface fault rupture – should be considered in future applications of this procedure to an actual port or marine oil terminal.

Finally, it is important to emphasize that this example is for a hypothetical commercial container port for which the principal risks are economic losses due to excessive repair costs and loss of operations. Other possible risks from earthquakes, such as environmental risks, risks to life safety, etc. have not been considered. The extension of this risk analysis procedure to also address environmental risks at marine oil terminals is described in a later section.

Step 1: Define System and Components to be Evaluated The hypothetical facility in this demonstration application is the pile/wharf structure, embankment and dike shown in Figure 6-8. This wharf has a total length of 4,000 feet. It consists of a cast-in-place concrete flat-slab deck system supported on 24-inch diameter prestressed concrete piles that extend into the underlying rock embankment. The wharf is located in the Los Angeles – San Pedro area of southern California. Its site has a longitude of –118.28 degrees and a latitude of 33.74 degrees. This is close to but not identical to the site originally analyzed for POLA.

Immediately behind this structure is a zone of fills that is 75 ft. wide and is prone to isolated pockets of liquefaction. This zone is not critical to wharf operations, and prior investigation has shown that soil improvement costs to reduce liquefaction hazards to this area are greater than the economic risks associated with these hazards (i.e., repair costs and losses due to interruption of wharf operations). Therefore, a decision was made not to proceed with improvement of these soils. Accordingly, analysis of costs and risks due to liquefaction of these fills is not included in this demonstration application.

Step 2. Identify Permissible Seismic Risk Reduction Alternatives The seismic risk reduction alternatives considered in this example pertain to the selection of a design acceleration corresponding to the "Level 2 Earthquake" (L2E) motion for the seismic design of a major wharf structure. The L2E motion is defined as the level of earthquake ground shaking for which damage could occur, but impairment of port operations and other economic risks would be maintained at acceptable levels. It is noted that seismic performance requirements for this hypothetical wharf also require that the wharf be designed to resist a lower levels of shaking – termed the "Level 1 Earthquake" (L1E) motion – with no significant damage. In this example, the L1E motion was set equal to a constant multiple (0.533) of the L2E motion. The L2E and L1E ground motions are defined in terms of a peak horizontal ground acceleration (PGA) expressed as a fraction of gravity, g.

This demonstration example also assumes that the designation of the L2E motion for the design of this wharf is not mandated through regulation or code. Level 1 and Level 2 earthquake motions are minimum requirements specified by the criteria guidelines developed herein. This example is a demonstration of the procedure to illustrate the effect of various seismic design levels. **As such it does not follow the criteria recommendations requiring use of a Level 1 and Level 2 earthquake motions and associated response strains.** In this demonstration example, all possible levels of L2E motion are evaluated in terms of their economic risk consequences to the wharf. Therefore, the example shows that definition of design level ground motions in terms of fixed probability levels may be overly conservative in some cases and unconservative in other cases. This will depend on the facility's location, seismic response characteristics, important seismic risks to be considered, and seismic performance requirements relative to these risks, as well as the seismologic and geologic characteristics of the surrounding region.

In this example, the seismic risk reduction alternatives consist of the seven design PGA levels for the L2E motions that are listed in Table 6-3. Based on these seven alternatives, interpolation was used to represent a continuum (from 0.0g to 0.60g) of seismic design alternatives. It is noted that the largest PGA induced at this site by any of the scenario earthquakes in this application is about 0.7g.

Table 6-3
Seismic Design Alternatives Considered For Demonstration Acceptable Risk Analysis Of Hypothetical Wharf

Seismic Design Alternative	PGA Level used to determine Lateral Design Force for Level 2 Earthquake (L2E) Motions
1	0.0 g (no seismic resistance built into wharf design).
2	0.24 g
3	0.30 g
4	0.37 g
5	0.45 g
6	0.50 g
7	0.60 g

Step 3: Define Multiple Scenario Earthquakes In this example, scenario earthquakes are established by *adapting* California data, models, and assumptions used by the United States Geological Survey (USGS) under their probabilistic National Hazard Mapping Project. USGS have worked jointly with their counterparts at the California Division of Mines and Geology

(CDMG) in order to develop data and models for representing California earthquakes. (see Frankel et al., 1996 and Cramer et al., 1996)

In this application, this process is used to develop over 20,000 scenario earthquakes throughout California that are consistent with the USGS and CDMG source models, maximum magnitude designations, activity rates, etc. These scenarios result from a random-walk analysis for a duration of 10,000 years. Ground motion attenuation equations are applied to each earthquake, in order to assess which earthquakes could cause damaging levels of ground shaking at the site being evaluated.

More specific information on the various types of earthquake sources that comprise this model, and the extent of the model that was considered can be provided. One of the significant sources for this example is an active fault that underlies a portion of the wharf.

Step 4: Estimate Site-Specific Seismic Hazards As previously noted, the only seismic hazard that is modeled in this demonstration application is ground shaking. Potential hazards from liquefaction, slope instability, and surface fault rupture are not considered

The USGS National Hazard Mapping program models ground motion attenuation by using the equations developed by Campbell et al. (1994), Boore et al, (1993, 1994a, and 1994b), and Sadigh et al.(1993). Results of these attenuation equations are equally weighted in accordance with a “logic tree” procedure. These investigators since updated their attenuation functions in the January/February, 1997 volume of *Seismological Research Letters*. For this demonstration analysis, ground motions are estimated by applying the Boore et al. (1997) attenuation functions for peak horizontal ground acceleration only, in which the wharf’s site is represented by a NEHRP Type D site classification with an effective shear wave velocity of 250 m/sec. Uncertainties in these attenuation functions are not modeled, although procedures for so doing are available (see Werner et al., 1998). A more thorough evaluation could compare the diverse attenuation functions available and their uncertainties. Likewise, a more extended port study involving spatially dispersed components with diverse soil conditions would consider differences in soil amplification effects on the ground shaking at these diverse sites.

The Boore et al. (1997) relationship has the following form

$$\ln Y = b_1 + b_2(M_w - 6) + b_3(M_w - 6)^2 + b_5 \ln r + b_v \ln(V_S / V_A) \qquad (6\text{-}1)$$

where

$$r = \sqrt{r_{jb}{}^2 + h^2}$$

and

Y is the ground-motion parameter (spectral acceleration at a variety of natural periods or, for this, example, peak horizontal ground acceleration, in units of g)

b_1 is defined separately for strike-slip, reverse-slip, and mechanism-unspecified scenarios

M_w is the moment magnitude,

r_{jb} is the epicentral distance and h is the focal depth (both in km),

V_S is the average shear-wave velocity of the site soil materials in question (=250 m/sec), and b_3, b_5, b_V, and V_A are regression coefficients developed for a variety of periods of potential interest.

In this application, the following parameter values are used to compute peak ground acceleration in accordance with the above equation: b_1 = -0.242 for all types of faults; b_2 =0.527; b_3 = 0.0; b_5 =0.778; h = 5.57 km; V_A = 1,396 m/sec; and b_v =-0.371.

The Boore et al. (1997) attenuation equation is used to compute PGAs at the wharf site for each scenario earthquake considered in the walk through analysis. A probabilistic seismic hazard analysis is then carried out according to the following procedure:

PGA values in increments of 0.01 g are sorted in increasing order. For the ith PGA value, (denoted as $(PGA)_i$, the number of other PGAs with larger values is counted. This is represented as N'_i.

The annual frequency of occurrence of PGA values **in excess of** $(PGA)_i$, denoted as υ'_i, is

$$\upsilon'_i = N'_i / 10{,}000 \qquad \text{(6-2a)}$$

where 10,000 years is the total duration of the walk-through analysis for this example. Note that this frequency differs from the frequency of occurrence of PGA values **equal to** $(PGA)_i$, which is denoted as υ_i. If there are N_i samples of PGA values equal to $(PGA)_i$, then

$$\upsilon_i = N_i / 10{,}000 \qquad \text{(6-2b)}$$

The probability that $(PGA)_i$ is exceeded over an exposure time of T years is computed as

$$P\left(A \geq (PGA)_i\right)_T = 1 - \exp^{-\upsilon'_i T} \qquad \text{(6-3)}$$

Step 5: Implement Alternative Seismic Design/Strengthening Strategies for Individual Components within Overall System

1. **Implementation of Alternative Seismic Design Strategies** A preliminary seismic design of the wharf is carried out for each L2E design acceleration level listed in Table 6-3. Then, initial construction costs for each design were estimated. These are shown in Table 6-4, and are expressed as a multiple of an assumed baseline replacement cost of $65 million, which is the total replacement cost for the wharf when no seismic design is implemented (L2E acceleration = 0.0 g). Therefore, initial seismic outlays are the marginal costs of constructing a wharf designed to the range of non-zero CLE acceleration levels listed in Table 6-3.

2. **Seismic Vulnerability Assessment.** Assessment of the seismic vulnerability of this hypothetical wharf is based on linear and nonlinear pseudostatic analysis methods. This assessment uses only very preliminary information on potential embankment deformations, and does not include effects of soil-structure interaction. In addition, the possible beneficial effects of pinning action of the wharf's pile elements are neglected. A follow-up evaluation would be desirable to incorporate these potentially important effects.

The following discussion outlines considerations for estimating repair costs due to damage to each wharf design alternative that estimated by the seismic vulnerability analysis. The resulting repair cost model that is used for this demonstration analysis is also described. It is noted that this repair cost modeling for this demonstration analysis is based on a number of simplifying assumptions. When analyzing acceptable risks to an actual port, more detailed estimates of repair costs should be developed.

(a) Repair Considerations

The estimation of repair costs and times at an actual wharf should consider the anticipated damage modes, repair strategies, available labor, materials, and equipment for implementing the repairs, and repair strategies to minimize impacts on ongoing operations at undamaged sections of the wharf. These considerations for this particular hypothetical wharf are listed below.

TABLE 6-4
Initial Construction Costs For Various Seismic Design Alternatives

Seismic Design Alternative		Initial Seismic Construction Cost	
Number	L2E Design Acceleration	Total	As Multiple of Baseline Replacement Cost ($65 Million)
1	0.0 g	$ 0.0	0.00
2	0.24g	$ 0.7 M	0.011
3	0.30g	$ 2.2 M	0.034
4	0.37g	$ 3.3 M	0.051
5	0.45g	$ 4.9 M	0.075
6	0.51g	$ 5.2 M	0.08
7	0.60g	$ 10.4 M	0.16

At PGAs above the design L2E acceleration level, it is estimated that the landward row of piles (i.e., the G row in Figure 6-8) will take the brunt of the seismic force, and will suffer the major damage. At these higher accelerations, damage is also anticipated at the F row of piles outboard from the dike. The pile damage is expected to be concentrated at the connection of the pile to the deck. However, at these high acceleration levels, it is estimated that ground deformation could cause additional damage in the form of spalling of the cover to the piles below grade. Although this additional damage is not expected to impair the structural integrity of the piles, the loss of concrete cover could lead to accelerated corrosion of the prestressing strands and the confinement steel.

Possible repair strategies include: (a) excavation below the deck to expose the landward rows of piles; (b) repair of the connection between the piles and the deck, and also any spalling damage along the length of the pile, to prevent corrosion of the prestressing and reinforcing steel.; (c) backfill of the dike with rock to improve the dike's lateral stability; (d) installation of a cutoff wall; and (d) backfilling behind the wharf, preparation of a base for AC paving, and installation of the paving

Repair work is estimated to occur over small lengths of the wharf (50-200 ft) in order to reduce operational constraints on the container wharf. Repair costs will not be very sensitive to this length.

The duration of the repair effort is assumed to be roughly proportional to the number of crews assigned to the repair. In this example, it is assumed that two crews will work simultaneously to repair the wharf at different damage locations.

It is assumed that the main variable in the repair model is the number of damaged piles, which accounts for about 20 percent of the total repair costs. Excavation and backfilling are assumed to require a minimum of one (1) work week (5 work days) per 100 foot section. At lower PGA levels, the time to repair piles does not generally exceed the time to perform the excavation and backfilling.

If the underlying fault at the wharf generates an earthquake with surface rupture, it is assumed that repair costs will sharply increase. These repair costs are assumed to include costs for repair of the pile connections and for replacement of 800 feet of wharf (the spacing between expansion joints). Crane rails may need to be realigned, and to do so may require replacement of the wharf deck merely to provide adequate transition to allow the cranes to traverse across the misaligned section. It is estimated that one berth along the wharf will be out of service for about one year during reconstruction.

(b) Repair Times

Based on the above considerations, repair times are estimated from the following assumptions:

At PGAs below the L1E design acceleration value, only a brief inspection period is required. No subsequent repair time is needed.

At PGAs equal to the L1E design acceleration value, approximately 180 work days (8 calendar months) are required to complete the repairs.

At PGAs slightly above the L2E design acceleration (L1E design acceleration + 0.02 g), approximately 200 work days (8 calendar months) are required to complete the repair. This estimate is assumed to be valid for all scenario earthquakes not involving significant surface fault rupture at the wharf.

If significant fault rupture occurs at the wharf, approximately 260 work days (12 calendar months) are required to complete repairs. This would significantly impact other wharf operations.

(c) Overall Repair Cost Model

The resulting repair cost model for this hypothetical wharf is based on the above assumptions and considerations, together with regional construction rates adjusted to account for expected

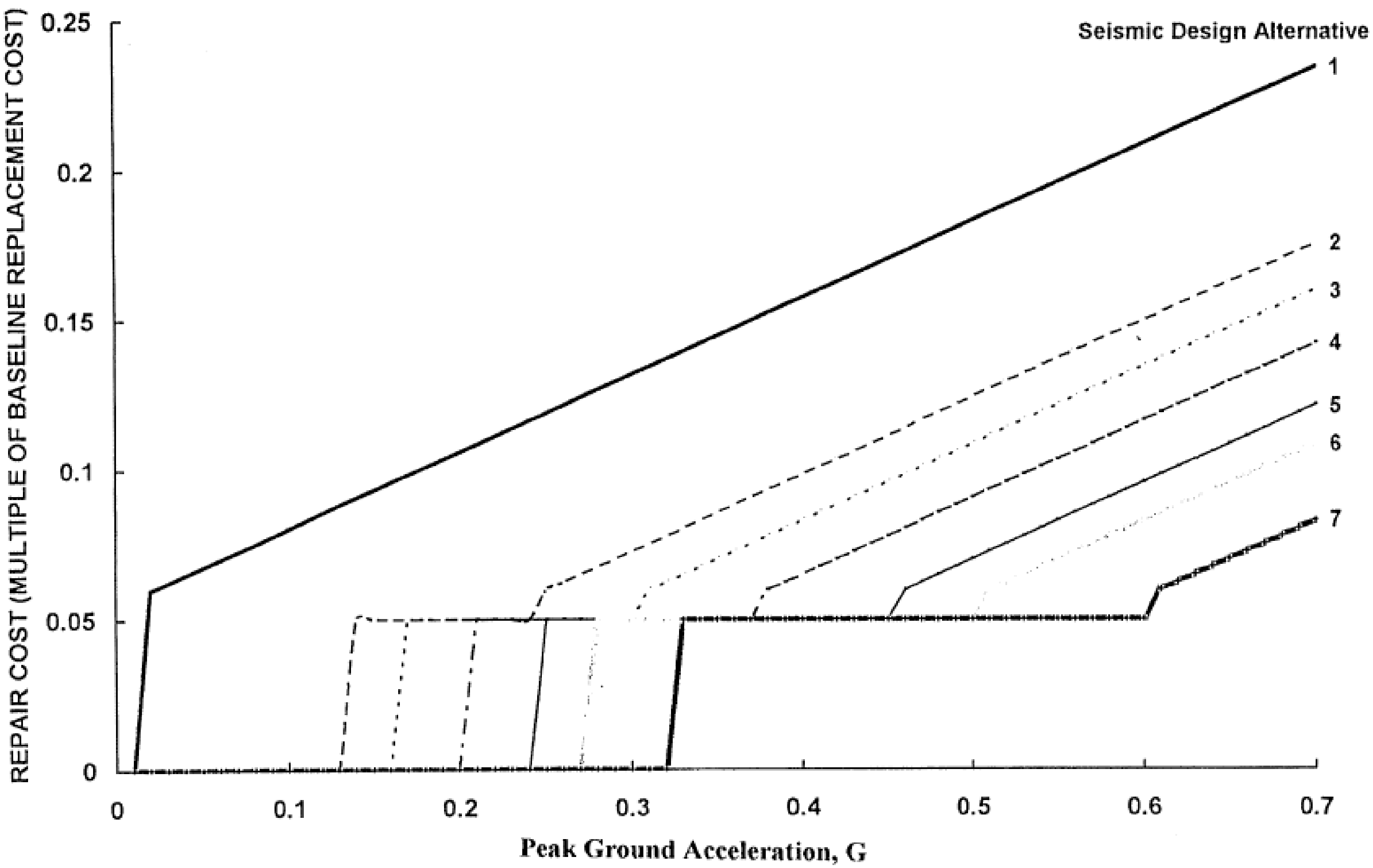


Figure 6-9
Repair Cost Model for Wharf Demonstration Analysis

access difficulties and restrictions. The repair cost model is summarized below, and is shown in Figure 6-9 for each seismic design alternative.

At PGAs below the L1E design acceleration, there are no repair costs.

At PGAs slightly above the L1E design accelerations, damage repair costs are five (5) percent of the baseline replacement cost of $65 million.

At PGAs equal to the L2E design acceleration level, repair costs are six (6) percent of the baseline replacement cost.

For each incremental 0.03 g increase in PGA above the L2E design acceleration level, repair costs increase by about 0.077 times the baseline replacement cost.

Regardless of the dollar losses from ground shaking, serious surface fault rupture (leading to between one and three meters of permanent ground displacement) causes an additional repair/replacement cost of 18 percent of the baseline replacement cost, due to misalignment of the wharf face.

Step 6: Evaluate Seismic Performance of the Overall System Because only a single port component is considered in this example, analysis of secondary and higher order losses is limited to an analysis of possible direct losses of throughputs to the port. The complexity of even this business interruption loss analysis can be very significant (Morrison et al., 1986). For performing this analysis, one may consider such factors as: (a) the excess capacity of the port (the ability of other wharves to handle cargo); (b) the various types of cargo handled at the port (e.g., metal products, automobiles, cement, gypsum, and cement clinkers, ores scrap metal and other dry bulk, break-bulk, forest products, crude oil, refined petroleum products); (c) daily schedules, increased demand over time to the port facilities etc.; and (d) which of various stakeholders bears the secondary and higher order losses (e.g., shippers, the port itself, etc.) (Werner et al., 1998)

In this demonstration analysis, an upper bound estimate of business interruption losses is developed. This estimate is based on the following assumptions: (a) the wharf handles 3,300 TEU of container cargo during each work day; (b) the port will lose $26 for each TEU not handled due to earthquake damage; and (c) the duration of the business interruption loss will be directly proportional to the primary losses (repair costs) incurred due to earthquake damage to the wharf; and (d) this constant of proportionality considers that if the required repair costs following a given earthquake (L_i) equal $0, the duration of the business interruption (D_{BI}) will be zero days, and if the required repair cost equals the total baseline replacement cost ($R_c = \$65{,}000{,}000$), the duration of the business interruption will equal 280 days, i.e.,

$$D_{BI}\,(days) = \frac{280 L_i}{R_c}$$

Therefore, the total number of TEUs not handled at the port due to earthquake damage is 3,300 x $280L_i$, and the losses due to earthquake-induced business interruption, L_{BI} , is

$$L_{BI} = \$26x(\$3{,}330x\frac{280L_i}{R_c}) = \$24{,}024{,}000x\frac{L_i}{R_c}$$

Substituting $R_c = \$65{,}000{,}000$ into the above expression, the cost of business interruption becomes

$$L_{BI} = \$24{,}024{,}000 \; x \; L_i \; / \; \$65{,}000{,}000 = 0.37 \; x \; L_i \qquad (6\text{-}4)$$

The average annualized value of the business interruption cost, $L_{BI,TOT}$ is estimated by substituting the average annualized value of repair costs, $L_{R,TOT}$, for L_i in the above equation, i.e.,

$$L_{BI,TOT} = 0.37 \; x \; L_{R,TOT} \qquad (6\text{-}5)$$

where the computation of $L_{R,TOT}$ is described in Step 7.

It is noted that the above estimate of business interruption losses is an upper bound because the inherent assumptions ignore: (a) the likelihood that the some if not all of the entire wharf will be operable after almost all earthquakes, and so will permit average to peak loads virtually whenever they are available; and (b) double-counting considerations, e.g., the transportation system for the wharf may also be damaged and wharf damage will therefore not necessarily be responsible or solely responsible for business interruption losses incurred.

Step 7. Assess Seismic Risks and Modify Component Designs if Appropriate The seventh step contains three major substeps: (a) development of risk and decision calculations for the design alternatives, in terms of key performance criteria; (b) selection of the decision alternative(s) that best meet these criteria; and (c) review these selections(s) and their rationale with the public. The following calculations of least costs and variances illustrate the application of Substep a.

Step 7 Least Cost Calculations For each of the seven seismic design alternatives considered in this example, calculation of overall mean life-cycle costs involves the following three steps: (a) calculation of the average annualized loss; (b) calculation of the present value of the losses; and (c) adding this present value of the losses to the initial construction costs to derive the overall mean life-cycle costs. These steps are further described below.

(a) Substep 7-1: Calculation of Average Annualized Value of Repair Cost for Each Seismic Design Alternative

To carry out this step, it is necessary to first calculate:

The annual frequency of occurrence of each PGA level. As noted in Step 4, this quantity is computed from Equation 6-2b, and is denoted as υ_i for the ith PGA level $(PGA)_i$

The repair costs associated with each PGA level for each design alternative. The estimation of this cost should consider possible types of repairs needed for each PGA level, in accordance with the results of the seismic vulnerability analysis. The repair cost at the ith PGA level is denoted as λ_i .

From this, the average annualized repair cost for the decision alternative, $L_{R,TOT}$ is computed as

$$L_{R,TOT} = \sum_{i}^{NA} \upsilon_i \lambda_i \tag{6-6}$$

where NA is the total number of incremental PGA values considered in this example.

This formulation uses "frequencies" rather than probabilities, because probabilities can underestimate average annualized losses[1]. To illustrate, assume that the number of accidents by drivers in a neighborhood averages 3 per year, with an average cost of $1,200 per accident. Hence, the average annualized cost is 3 x $1,200, = $3,600 per year. Using probabilities, one may find that in 90 percent of the years at least one traffic accident occurs. Ignoring the probabilities of occurrence of 2, 3, 4, or more accidents in a year, one might erroneously conclude that the average annualized loss is 0.9 x $1200, or $1080. In general, the use of frequencies of occurrence is preferable to probabilities in regions of higher seismicity with more frequent earthquakes and/or strong ground motion levels.

To illustrate how the average annualized value of repair costs is calculated, one might examine design alternative 5 (L2E acceleration = 0.45g). Table 6-5 summarizes these calculations. It begins with a PGA of 0.25g since this is slightly above the L1E acceleration for Design Alternative 5. Below this level, it is assumed that no significant damage occurs. It should further be noted that the frequency of occurrence is not—as might be expected—monotonically decreasing as PGAs increase. This is chiefly a result of the Monte Carlo sampling method employed. Since almost 14,000 earthquake scenarios generate PGAs of 0.01 g or greater for the 10,000 year time frame simulated, the number of simulations is statistically robust. Only for small probabilities should the simulation program consider longer time frames and many more uncertainties; instead, most of the emphasis of the uncertainty evaluation should be on the modeling itself.

(b) Substep 7-2: Calculation of Present Value of Losses

[1] This underestimation will occur unless probabilities of two occurrences, three occurrences, and so on are considered.

As noted above, the discount rate multiplier for a constant dollar value discount rate j (based on annul loss) and a time of exposure of T years, denoted as $R_{j,T}$, is computed from the following equation:

$$R_{j,T} = \frac{1-(1+j)^{-T}}{j} \qquad (6\text{-}7)$$

Using the above equation for a 50-year time of exposure, the discount rate multipliers associated with a range of discount rates are computed, as shown in Table 6-6. This table shows that, as discount rates increase, the impacts of reducing earthquake losses decreases.

Once a discount rate is established and the corresponding discount rate multiplier is computed, the present value of the total loss, including repair costs plus business interruption losses, is computed as:

$$L_{PV} = R_{j,T}(L_{R,TOT} + L_{BI,TOT}) \qquad (6\text{-}8)$$

Table 6-7 illustrates the computation of the total mean life-cycle cost for Design Alternative 5, based on discount rates of 1% and 7%, respectively. This proceeds as follows:

The last line of Table 6-5 has shown that the average annualized repair cost value for Design Alternative 5 (computed using Equation 6-6), as a ratio of the baseline replacement cost for the wharf, is

$$L_{R,TOT} = 0.00075 \qquad (6\text{-}9)$$

Step 6 has shown that, for this hypothetical wharf, the average annualized business interruption loss for Design Alternative 5, L_{BI} , is 37 percent of the average annualized repair cost value, $L_{R,TOT}$. Therefore, the business interruption loss is

$$L_{BI,TOT} = 0.37 L_{R,TOT} = 0.37 * 0.00075 = 0.00028 \qquad (6\text{-}10)$$

From this, the total loss, L'_{TOT}, (including both repair costs and business interruption losses) is

$$L'_{TOT} = L_{R,TOT} + L_{BI,TOT} = 0.00075 + 0.00028 = 0.00103 \qquad (6\text{-}11)$$

Table 6-5
Average Annualized Value of Repair Cost For Design Alternative 5 (Cle = 0.45g)

PGA, g	Frequency of Occurrence, υ_i	Repair Cost at ith PGA Level, λ_i	Annualized Repair Cost at ith PGA level = $\upsilon_i \lambda_i$
0.25	0.0002	0.05	0.00001
0.26	0.0013	0.05	0.00007
0.27	0.0004	0.05	0.00002
0.28	0.0006	0.05	0.00003
0.29	0.0015	0.05	0.00008
0.30	0.0022	0.05	0.00011
0.31	0.0001	0.05	0.00001
0.32	0.0004	0.05	0.00002
0.33	0.0002	0.05	0.00001
0.34	0.0002	0.05	0.00001
0.35	0.0002	0.05	0.00001
0.36	0.0010	0.05	0.00005
0.37	0.0002	0.05	0.00001
0.38	0.0000	0.05	0.00000
0.39	0.0002	0.05	0.00001
0.40	0.0001	0.05	0.00001
0.41	0.0003	0.05	0.00002
0.42	0.0014	0.05	0.00007
0.43	0.0004	0.05	0.00002
0.44	0.0012	0.05	0.00006
0.45	0.0002	0.05	0.00001
0.46	0.0000	0.06	0.00000
0.47	0.0000	0.0626	0.00000
0.48	0.0004	0.0651	0.00003
0.49	0.0000	0.0677	0.00000
0.50	0.0000	0.0702	0.00000
0.51	0.0001	0.0728	0.00001
0.52	0.0000	0.0754	0.00000
0.53	0.0000	0.0779	0.00000
0.54	0.0000	0.0805	0.00000
0.55	0.0002	0.0830	0.00002
0.56	0.0000	0.0856	0.00000
0.57	0.0001	0.0882	0.00001
0.58	0.0000	0.0907	0.00000
0.59	0.0000	0.0933	0.00000
0.60	0.0001	0.0958	0.00001
0.61	0.0000	0.0984	0.00000
0.62	0.0000	0.1010	0.00000
0.63	0.0002	0.1035	0.00002
0.64	0.0001	0.1061	0.00001
0.65	0.0002	0.1086	0.00002
0.66	0.0000	0.1112	0.00000
0.67	0.0000	0.1138	0.00000
0.68	0.0000	0.1163	0.00000
0.69	0.0001	0.1189	0.00001
0.70	0.0000	0.1214	0.00000
Sum (= $L_{R,TOT}$)			0.00075

TABLE 6-6
Discount Rate Multipliers For 50 Year Exposure Time

Discount Rate, j	Discount Rate Multiplier, $R_{j,50}$ (for annual loss)
1%	39.2
2%	31.4
3%	25.7
4%	21.5
5%	18.3
6%	15.8
7%	13.8
8%	12.2
9%	11.0
10%	9.9

Table 6-6 shows that the present value of this total loss is obtained by multiplying it by 39.2 for a real discount rate of 1% and by 13.8 for a real discount rate of 7%. Therefore, the present value of the losses for Design Alternative 5 is

$$L_{PV} = 39.2 * 0.00103 = 0.0404 \quad \text{for a discount rate of 1\%}$$

and

$$L_{PV} = 13.8 * 0.00103 = 0.0142 \quad \text{for a discount rate of 7\%}$$

The values of L_{PV} for all design alternatives are shown in Table 6-7.

(c)Substep7- 3: Determination of Overall Mean Life-Cycle Costs

The mean value of the total life cycle cost, C_{LC}, is the sum of the present value of losses, L_{PV}, plus the initial construction cost, C_C, i.e.,

$$C_{LC} = L_{PV} + C_C \qquad (6\text{-}12)$$

For Design Alternative 5, the initial construction cost is 0.075 times the baseline replacement cost of the wharf. Therefore, C_{LC} is computed as

$$C_{LC} = 0.075 + 0.040 = 0.115 \text{ for a discount rate of 1\%} \quad (6\text{-}13)$$

and

$$C_{LC} = 0.075 + 0.014 = 0.089 \text{ for a discount rate of 7\%} \quad (6\text{-}14)$$

The total life cycle costs for Design Alternative 5 and also for the other design alternatives are shown in Table 6-7.

Table 6-7
Illustrative Calculations of Mean Life Cycle Costs for the Seven Design Alternatives

Cost*	Alt.. 1 (L2E= 0.0g)	Alt. 2 (L2E = 0.24g)	Alt. 3 (L2E = 0.30g)	Alt. 4 (L2E = 0.37g)	Alt. 5 (L2E = 0.45g)	Alt. 6 (L2E = 0.50g)	Alt. 7 (L2E = 0.60g)
Average Annualized Repair Cost	0.0482	0.00205	0.00150	0.00103	0.00075	0.00063	0.00037
Business Interruption Loss	0.0178	0.00076	0.00056	0.00038	0.00028	0.00023	0.00014
Total Average Annual Loss	0.0660	0.0028	0.0021	0.0014	0.0010	0.0009	0.0005
Present Value of Losses (Discount Rate =1%)	2.588	0.110	0.080	0.055	0.040	0.034	0.020
Present Value of Losses (Discount Rate =7%)	0.911	0.039	0.028	0.019	0.014	0.012	0.007
Initial Seismic Construction Cost	0.00	0.011	0.034	0.051	0.075	0.08	0.16
Total Mean Life-Cycle Cost (Discount Rate = 1%)	2.588	0.121	0.114	0.106	0.115	0.114	0.180
Total Mean Life-Cycle Cost (Discount Rate = 7%)	0.911	0.050	0.062	0.070	0.089	0.092	0.167

*Costs given as multiple of baseline replacement cost for wharf configuration with no seismic design (= $65,000,000).

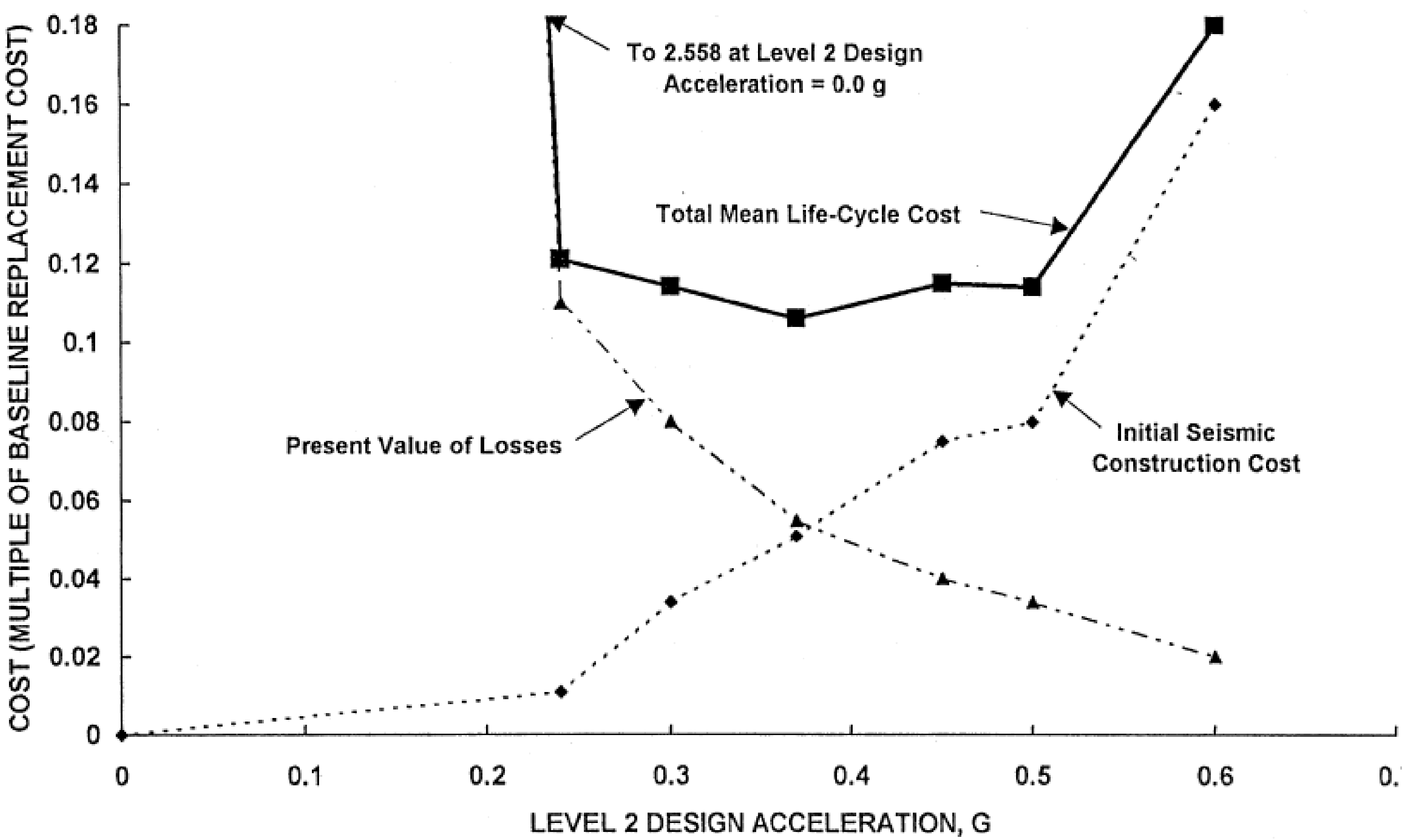


Figure 6-10
Development of Mean Life-Cycle Costs for Wharf Demonstration Analysis:
Discount Rate = 1%

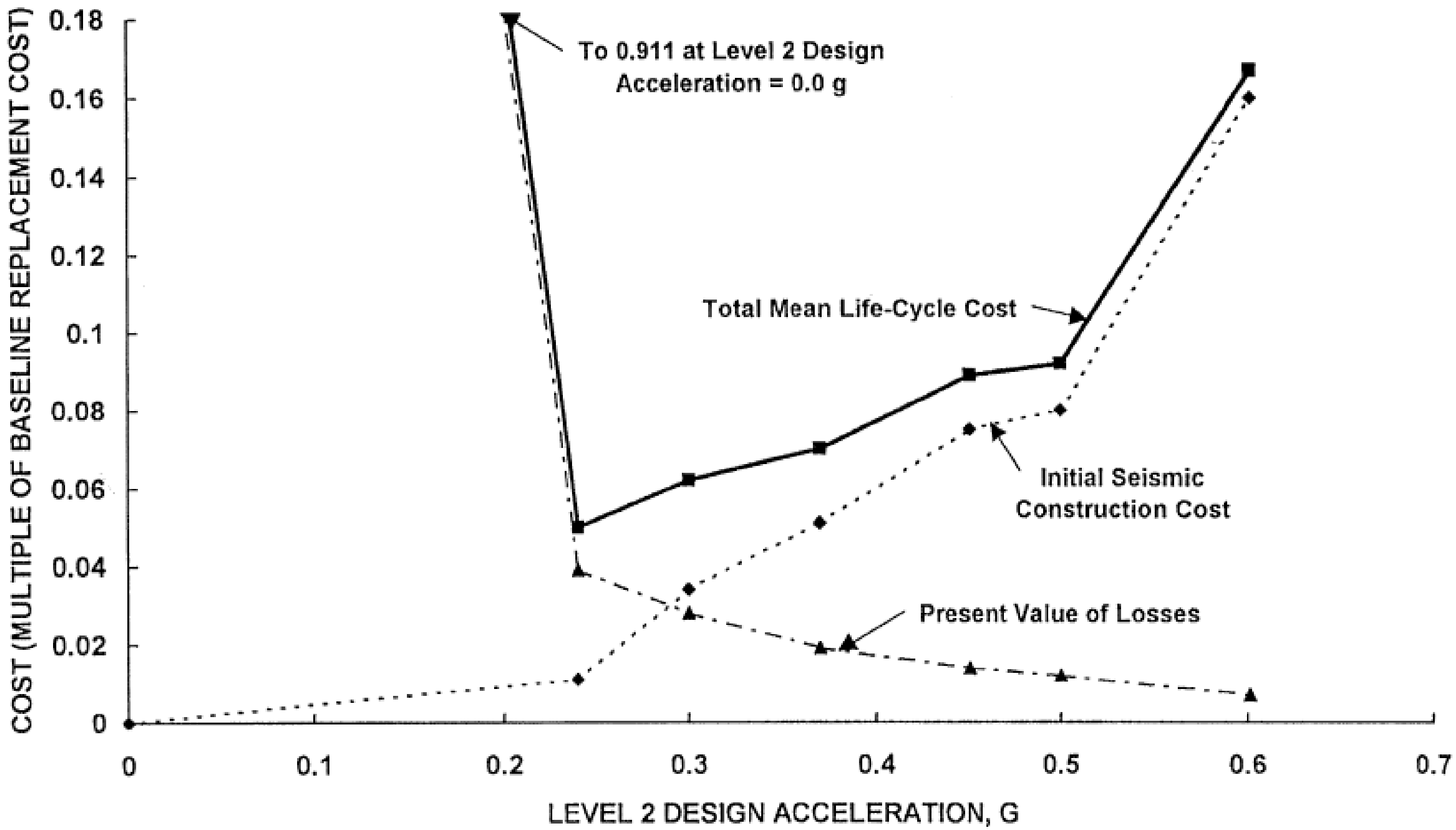


Figure 6-11
Development of Mean Life-Cycle Costs for Wharf Demonstration Analysis: Discount Rate = 7%

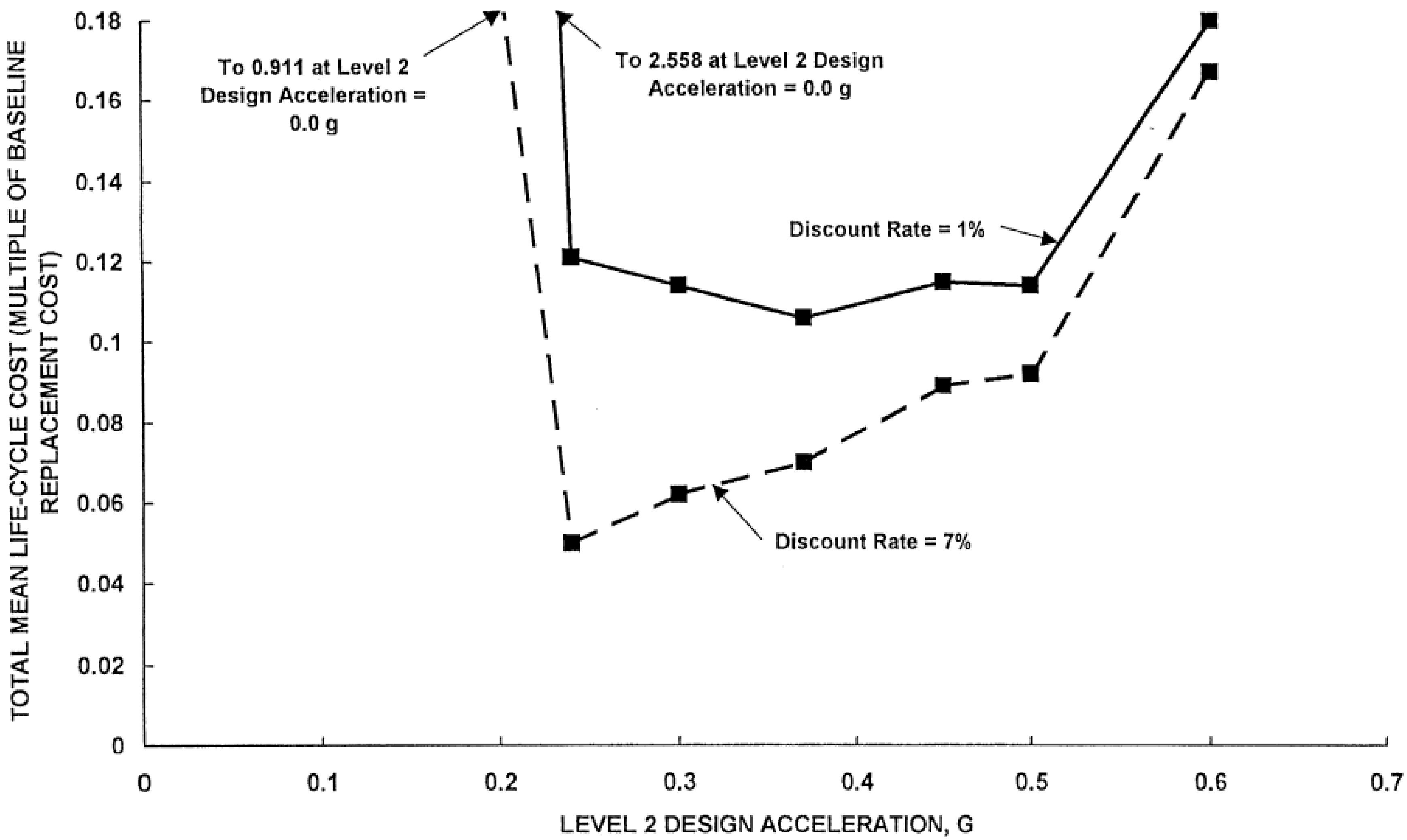


Figure 6-12
Effect of Discount Rate on Mean Life-Cycle Costs for Wharf Demonstration Analysis

Figures 6-10 and 6-11 illustrate the development of total mean life-cycle costs for each design alternative, as the sum of the initial seismic construction cost (i.e., the construction cost over and above the construction cost if no seismic design is implemented) plus the present value of the losses. These results are provided in Figures 6-10 and 6-11 for discount rates of 1 % and 7 % respectively.

Figure 6-12 compares the mean life-cycle costs for discount rates of 1 % and 7 %. This comparison demonstrates the sensitivity of the results to the discount rate selected. For example, Figure 6-12 shows that, if a discount rate of 1 % is selected, Design Alternative 4 has the most favorable mean life-cycle cost whereas, if a discount rate of 7 % is selected, Design Alternative 2 has the most favorable cost. The figure also shows that, for a given design alternative, the mean life-cycle cost decreases as the selected discount rate increases – i.e., higher discount rates will generally reduce the importance of seismic risk reduction activities.

Figures 6-10 to 6-12 also show that Design Alternative 1 (no seismic design) has very large mean life-cycle costs as compared to the other design alternatives. This is due to the large present-value losses estimated for that alternative. Of the remaining alternatives, Design Alternative 6 (L2E design acceleration = 0.6 g) has the next highest mean life-cycle cost, due to its large initial seismic construction cost. The differences in mean life-cycle cost among Design Alternatives 2 through 5 are relatively minor if a discount rate of 1 % is selected, and are more pronounced when a discount rate of 7 % is considered.

Step 7 Variance Calculations Supplementing this least-cost analysis is an analysis of the variance of losses. As stated already, investments do not aim merely at the highest rate of return. To do so would be to ignore the volatility of investments, as represented by the variance or standard deviation of the losses. Therefore, whereas minimizing the least cost represents a maximization of the return of the investment in seismic risk reduction of this hypothetical wharf, reducing the variance and standard deviation of the losses is also prudent, from the standpoint of reducing the riskiness or volatility of the investment. A careful investor would consider both of these aspects when evaluating a potential investment. For example, junk bonds often have high rates of return; however, because of their extreme volatility, they are often not considered to be a good investment. Insurance purchase, hedging, portfolio diversification, and other activities are used in investing in order to reduce the volatility of investments. (Bernstein, 1996).

In this analysis, the variance of initial construction costs has not been estimated. Instead, the analysis confines itself to the calculation of variance and standard deviation of the losses. Also, it is not necessary to calculate the present value of the variance or standard deviation in order to demonstrate the relative volatility and riskiness of the various design alternatives. This is because the present value of variance and standard deviation is simply a linear multiple of the variance and standard deviation.

The variance of the earthquake losses for this example, σ^2, is computed as:

$$\sigma^2 = \sum_{i=1}^{NA} \frac{\upsilon_i}{\upsilon_{TOT}} \left(L'_i - L'_{TOT} \right)^2 \qquad (6\text{-}15)$$

where

NA = total number of PGA increments considered in the analysis

υ_i = annual frequency of occurrence of ith PGA level (Equation 6-2b)

$\upsilon_{TOT} = \sum_{i-1}^{NA} \upsilon_i$ = total annual frequency of occurrence of all PGA levels

L'_i = total loss due to ith PGA level including repair costs and business interruption losses

L'_{TOT} = average annualized value of total loss including repair costs and business interruption

The standard deviation of the earthquake losses is

$$\sigma = \sqrt{\sigma^2} \qquad (6\text{-}16)$$

To illustrate the use of Equation 6-15 and 6-16, consider Design Alternative 5, and a PGA level of 0.01 g, whose parameters are as follows:

L'_{TOT} = average annualized loss including repair costs plus business interruption loss = 0.00103, expressed as a multiple of the baseline wharf replacement cost), as computed using Equation 6-8

υ_i = frequency of occurrence of PGAs with value of 0.01 g = 0.6809

υ_{TOT} = total frequency of occurrence of all PGA values = 1.3929

L'_i = total loss at PGA of 0.01 g = 0.0

Therefore the variance increment for this PGA level is

$$\sigma_i^2 = \frac{\upsilon_i}{\upsilon_{TOT}}\left(L'_i - L'_{TOT}\right)^2 = \frac{0.6809}{1.3929}\left(0 - 0.00103\right)^2 = 5.19x10^{-7}$$

Similar calculations can be carried out for each of the other PGA levels. Then, the variance increments for all of the PGA levels are summed to obtain the total variance (which turns out to be 5.76 x 10^{-5} for Design Alternative 5. The resulting value of the standard deviation of the losses for this alternative is

$$\sigma_i = \sqrt{5.76x10^{-5}} = 7.59x10^{-3}$$

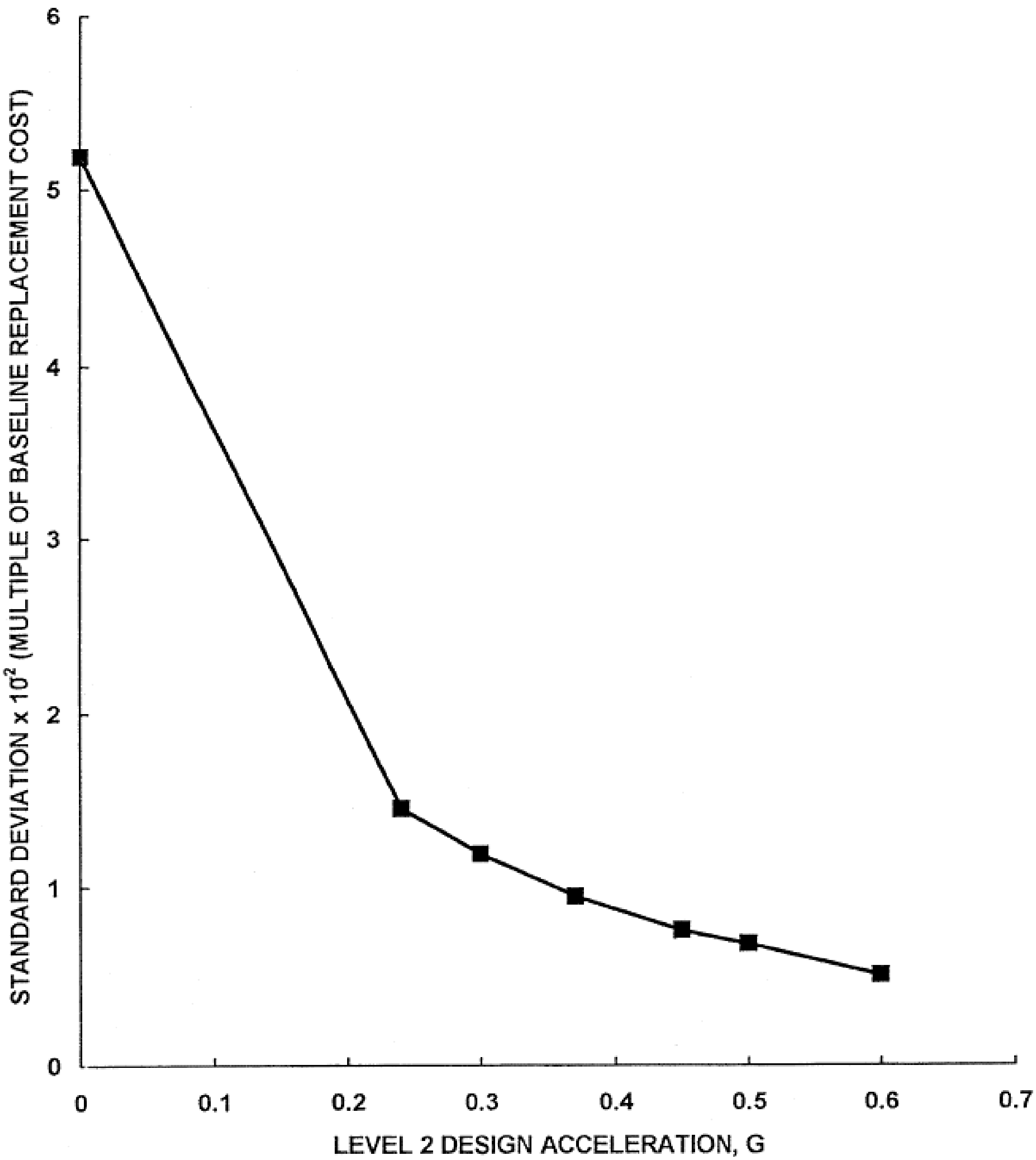


Figure 6-13
Standard Deviation of Losses for Wharf Demonstration Analysis

Table 6-8 and Figure 6-13 summarizes these estimates for standard deviation for all seven alternatives. This table and figure show that the standard deviation decreases as the CLE design acceleration increases. Thus, increasing the CLE design acceleration for this hypothetical wharf reduces the riskiness of the seismic performance of the wharf and the resulting volatility in the investment in the wharf's seismic risk reduction. Table 6-8 and Figure 6-13 also show that Design Alternative 1 (CLE design acceleration = 0.0 g) clearly has the largest standard deviation, demonstrating the extreme riskiness of the no seismic design option for this wharf facility.

Table 6-8
Standard Deviations for the Seven Seismic Design Alternatives

Seismic Design Alternative	Level 2 Design Acceleration	Standard Deviation, σ, x10^{-2} (Multiple of Baseline Replacement Cost)
1	0.0 g	5.190
2	0.24 g	1.455
3	0.30 g	1.192
4	0.37 g	0.950
5	0.45 g	0.759
6	0.50 g	0.685
7	0.60 g	0.507

Conclusion from Demonstration Application

The purpose of this demonstration analysis has been to illustrate the application of the acceptable-risk procedure to a commercial container wharf for which the primary risks of concern are earthquake-induced economic losses. The analysis was based on a random-walk evaluation that involved over 20,000 scenario earthquakes occurring over a 10,000 year time frame.

By necessity, the analysis entailed certain limitations in the treatment of the seismic hazards, in the modeling of the seismic vulnerability of the wharf, and in the estimation of repair costs and business interruption losses. These simplifications may not be fully appropriate when this procedure is applied to an actual port, for use in guiding the subsequent selection of a seismic risk reduction strategy. It is noted that the acceptable risk evaluation approach can accept models with whatever level of sophistication is deemed appropriate by the user. Whatever degree of model sophistication is employed, the user should consider uncertainties in the models and the input data when interpreting the acceptable-risk analysis results for decision-making purposes.

Even though simplified models have been used, this demonstration analysis has clearly illustrated the applicability of the acceptable-risk method as a seismic risk reduction decision-making tool. The analysis results have also shown the following clear trends:

The risk analysis results are sensitive to the discount factor that is selected.

The mean-variance approach that is incorporated into the acceptable risk procedure enables the user to assess alternative seismic risk reduction options from the standpoint of an investor concerned not only with optimizing the yield of his investment in seismic risk reduction (i.e., examining the relative mean life-cycle costs of the various risk reduction alternatives), but also with maintaining tolerable levels of riskiness or volatility of his or her decision (by examining how the standard deviations of the earthquake losses differ among the various alternatives).

For this example, the no seismic-design option was clearly shown to be extremely unfavorable, based on its very high values of mean life-cycle cost and standard deviation of earthquake losses.

This example was intended to illustrate the application of the acceptable risk procedure and not to give specific guidance on cost-effective seismic design acceleration levels.

Application To Marine Oil Terminals

The demonstration application of the acceptable risk procedure that is described in the previous section has shown how the procedure can be used to assess economic risks due to earthquake damage at a commercial container port. This section describes how this same procedure can be used by a regulatory agency (i.e., CSLC) to assess various seismic risk reduction alternatives new or existing marine oil terminals. However, the performance criteria to be considered by the regulatory agency for marine oil terminals will differ from those of port decision-makers for a commercial container port. For a marine oil terminal, the primary risks of concern to the agency will be the environmental risks due to release of oil products into the surrounding waterway during an earthquake. However, cost would still be a factor from the standpoint of the practicality of implementing the regulations once they are in place. Therefore, a suitable balancing of these costs and risks is needed.

To describe the applicability of this procedure to marine oil terminals, this section is organized into two parts. The first part summarizes how the previously described steps of the procedure can accommodate consideration of both economic and environmental risks. The second part outlines a qualitative application of the procedure to evaluate these risks for a marine oil terminal.

Extended Procedure

In this extended procedure, Steps 1 through 5 are identical to those described and illustrated above in the section titled "Expanded Economic Analysis To Include Risk". Steps 6 and 7 are modified as described below.

Step 6: Evaluate Seismic Performance of Overall System Step 6 evaluates the seismic performance of each alternative system configuration established in Step 5, when each configuration is analyzed for each earthquake that occurs during each year of the walk-through established in Step 4. The results of each seismic performance evaluation for each system configuration and each earthquake should indicate: (a) whether the marine oil terminal system has been damaged; and, if so: (b) the present value of total losses due to this damage (sum of initial construction costs from Step 5 plus repair costs, business interruption losses, oil spill costs and any higher order economic losses that can be assessed); and (c) whether this damage has led to a release of hazardous materials, quantification of the size of the release, and whether it exceeds CSLC acceptable spill volumes (in excess of 1,200 barrels).

Note the cost of an oil spill was shown above to be high and to involve not only direct cleanup costs but also costs of damage to the shoreline and environment and third-pary costs. These costs must be included

Step 7: Assess Seismic Risks and Modify Component Designs if Appropriate Step 7 carries out a reliability assessment of each alternative system configurations, based on the walkthrough analysis of scenario earthquakes that has a duration of 10,000 years. The end results of the analysis should provide the following information: (a) the present value of the total economic losses incurred by the system alternative over the 10,000 year duration; and (b) the "reliability" of each alternative – which is an assessment of the design alternative's potential for limiting the release of oil during an earthquake to an acceptable volume mandated by CSLC; and (c) the "risk" associated with each design alternative – which is an assessment of the potential that the design alternative will experience earthquake-induced oil spillage that will exceed CSLC acceptable volumes (i.e., the risk is the converse of the reliability). The focus here is on the risk and size of an earthquake-induced oil spill. Decision-making pertaining to the selection of an appropriate system alternative is based on prudent management of this risk. This reliability and risk assessment process is illustrated below.

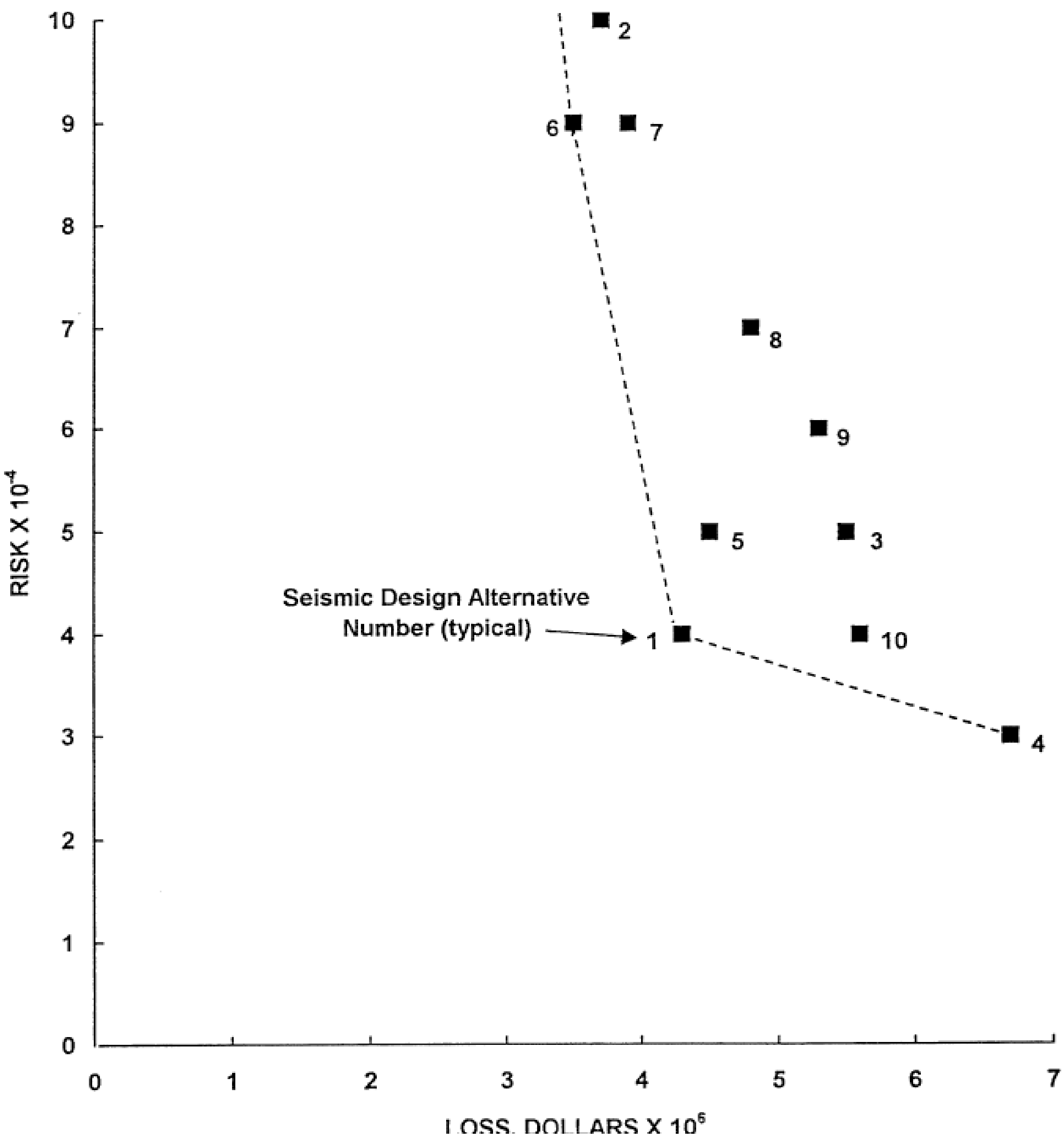


Figure 6-14
Form of Results: Acceptable Risk Analysis of Marine Oil Terminal

Illustrative Application

To illustrate this process for a given marine oil terminal system, suppose that ten different seismic design alternatives have been developed for the various oil terminal components, and that the seismic performance of each alternative has been evaluated for a suitable number of scenario earthquakes. Also, suppose that this evaluation was in the form of a walk-through analysis with a duration of 10,000 years, and that acceptable seismic performance of the terminal system is defined in terms of limiting the volume of oil released during an earthquake to 1,200 barrels.

Finally, let us consider that the application of Steps 6 and 7 to each design alternative provides the following results: (a) the present value of the total mean life-cycle costs due to earthquake damage to the system over the 10,000 year duration; and (b) the "risk" associated with each design alternative, which is number of times during the walk-through when the system failed due to earthquake damage (i.e., more than 1,200 barrels of oil were released), divided by the 10,000 year duration of the walk-through. In addition, the "reliability" of each alternative is computed, which is the number of times during the walk-through when the system did not fail due to earthquake damage (i.e., less than 1,200 barrels of oil were released) divided by the 10,000 year duration of the walk-through. (Note that reliability = 1.0 – risk). Let us also assume that these results are as follows:

Alternative	Cost[2]	Reliability	Risk
1	$4.3M	9,996/10,000	4/10,000
2	$3.7M	9,990/10,000	10/10,000
3	$5.5M	9,995/10,000	5/10,000
4	$6.7M	9,997/10,000	3/10,000
5	$4.5M	9,995/10,000	5/10,000
6	$3.5M	9,991/10,000	9/10,000
7	$3.9M	9,991/10,000	9/10,000
8	$4.8M	9,993/10,000	7/10,000
9	$5.3M	9,994/10,000	6/10,000
10	$5.6M	9,996/10,000	4/10,000

A plot of the costs vs. risk for each alternative (Figure 6-14) shows that System Alternatives 1, 4, and 6 represent the most favorable cost–risk combinations. Alternative 4 is the lowest risk and highest cost option, Alternative 6 is the highest risk and lowest cost option, and Alternative 1 is a middle ground between these two extremes.

These cost vs. risk results provide information that can be used to guide the establishment of an appropriate design alternative for the marine oil terminal. This will depend on the acceptability of alternative levels of cost and risk that may be experienced. Input from various stakeholders and interveners may bean important element of this decision process.

[2] This cost is the total mean life-cycle cost, which is calculated as illustrated above.

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