Urban Earthquake Disaster Risk Assessment and Management

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ABSTRACT: *In the upcoming years, efforts in the field of earthquake disaster risk assessment and management should focus on three main issues: (1) urban risk, (2) a holistic, multidisciplinary approach, and (3) the implementation and dissemination of current knowledge. This paper introduces a series of three complementary projects—in risk assessment, risk management, and risk forecasting, and describes how, individually and collectively, they embody a new philosophy built on these three main issues. The first study attempts to assess the relative overall earthquake disaster risk of cities worldwide, and the relative contributions of various factors to that risk. The second seeks to compare the cost-effectiveness and feasibility of different risk mitigation strategies for a city. The third aims to forecast how a city's risk, and therefore the most appropriate mitigation strategies, will change over time.*

Keywords: Earthquake; Risk assessment; Disaster risk index; Risk forecasting; Urban management

1. INTRODUCTION

An assessment of the current nature of earthquake disaster risk, and of the major obstacles to mitigation has led to the development of a new approach to earthquake risk assessment and management. The approach focuses on three main issues: (1) urban risk, (2) a holistic, multidisciplinary approach, and (3) the implementation and dissemination of current knowledge. A series of three projects currently underway at Stanford University was developed based on this new approach. Individually, the projects emphasize the three principal ideas. They focus on issues particular to urban regions. They adopt a holistic, multidisciplinary approach by defining their goals in broad terms, and by addressing issues and employing analysis techniques from a wide variety of disciplines and perspectives. Focused on the implementation of research results, the projects are designed and developed based on the needs of the potential users. They integrate numerous focused studies from many fields, extracting the bottom-line information that decision-makers need, and presenting it in an easily understandable form.

Collectively, the three studies confront the challenge of the earthquake threat through efforts in risk assessment, risk management, and risk forecasting. The first project attempts to assess a city's overall level of risk, and describe the factors that contribute to it. The second seeks to compare the effectiveness and feasibility of different risk mitigation strategies for a city. The third adds a time dimension, forecasting how the risk will change in the coming years. Risk assessment serves to articulate the problem of earthquake disaster risk and its causes. Risk management designs strategies to "solve" the problem as effectively and efficiently as possible. Risk forecasting suggests how the nature of the problem, and therefore the solutions, will continue to change.

Following an elaboration of the three cornerstone ideas of the new approach, each of the three complementary projects is presented in turn. Each project summary describes the goals and basic strategy of the study, and demonstrates how it reflects the new approach.

2. A NEW APPROACH TO EARTHQUAKE DISASTER RISK ASSESSMENT AND MANAGEMENT

The proposed new approach to earthquake disaster risk assessment and management highlights three ideas: (1) urban risk, (2) a holistic, multidisciplinary approach, and (3) the implementation and dissemination of current knowledge. Efforts should focus on urban regions for at least two reasons. First, by the year 2005, 50% of the world's population will be gathered in urban areas, and by 2025, more than 60% will be (UN 1995), so by addressing only cities, most of the world's population is still considered. Second, earthquakes primarily affect people and human-made structures, both of which are concentrated in urban areas. Furthermore, the unprecedented size, complexity, and interconnectedness of today's megacities have created situations unlike any that existed in the past. Smaller cities may expect to experience events similar to those that occurred historically. There have been few large earthquakes that directly impacted a megacity, however, so the potential implications of the new nature of cities on earthquake risk are unclear. An improved understanding of earthquake risk assessment and management will be especially important for major urban conglomerations.

A holistic, multidisciplinary approach is vital. The artificial distinctions among earth science, engineering, and social science work have developed as a reflection of common professional and disciplinary divisions. In reality, earthquake disasters and disaster mitigation do not fit neatly within the scope of a single discipline. Earthquakes can affect everyone directly or indirectly, and almost everyone can affect the degree of impact to some extent. Earthquake disasters are an inherently multidisciplinary topic, so attempts to consider them solely from the perspective of one field necessarily neglect important issues.

Earthquake professionals as a group must both explore in detail the components of earthquake disasters, and examine the big picture to understand how the components come together to create a disaster. The all-encompassing goal of understanding earthquake disasters and helping to effectively and efficiently mitigate their negative impact on society is overwhelming in its broadness. To get a handle on the problem, it should be divided into smaller, more focused tasks, and groups from each discipline should undertake the tasks that relate to their area of expertise. Geologists study the characteristics of faults and the geologic setting of a region. Structural engineers explore the vulnerability of the built environment. Emergency planners investigate the needs of a response effort. Each group delves deeply into the details of their task to fully understand the issues. Nevertheless, as pieces of the problem are apportioned to various experts, the big picture should never drift out of sight either for those experts or for the profession as a whole. The ultimate goal should always guide the decisions of which projects to take on and what avenues of research to pursue. Projects should include both those focused on a specific issue, such as the performance of welds in steel frame buildings, and those that bring together all the specific projects to understand earthquake disasters in a holistic way. Past efforts have not given adequate attention to the latter type of work.

Earthquake professionals have made and continue to make significant progress towards their ultimate goal of understanding earthquakes and their effects on society. To achieve their full mission however, the current knowledge must be applied. Appropriate mitigation strategies must be developed based on the best understanding of the problem, and they must be implemented everywhere they are needed. In some regions of the world, mitigation strategies have been enacted and have proven effective already. In many other regions, the most basic aspects of the earthquake problem have not been examined, and the most basic mitigation efforts have not been made. While the quest for better understanding of earthquakes and more sophisticated techniques for assessment and mitigation is of course important, surely the task of implementing currently available knowledge is equally so. It could be argued that an ounce of effort could not be more beneficial than if it was used to help implement current knowledge in a highly vulnerable seismic region.

3. RISK ASSESSMENT: EARTHQUAKE DISASTER RISK INDEX

The risk assessment study aims to develop a multidisciplinary urban Earthquake Disaster Risk Index (EDRI). The composite index will allow direct comparison of the relative overall earthquake disaster risk of different cities throughout the world, and will describe the relative contributions of various factors to that overall risk. The concept of the EDRI is similar to that of the Consumer Price Index (CPI) or the Human Development Index (HDI). Instead of measuring the relative level of prices in different years, or the relative levels of development in different countries, the EDRI will rate the relative levels of earthquake disaster risk in different cities. It will establish a yardstick with which to measure an unobservable concept, in this case, earthquake disaster risk. The CPI is just one reasonable representation of the general level of prices in a country. Its meaning and usefulness are largely the result of being accepted as a measurement scale and being tracked over many years in many countries. The CPI has thus enabled general price level comparisons over time and among countries. The EDRI has the potential to serve an analogous role in the field of disaster mitigation.

The procedure to develop the Earthquake Disaster Risk Index consists of five basic steps:

1. **Factor identification and conceptual framework development**
   A systematic investigation identifies all the factors—geological, engineering, social, economic, political, or cultural—that contribute to a city's earthquake disaster risk, and a conceptual framework is created to organize these factors and facilitate understanding of how they relate to each other and to the overall disaster risk.
2. **Indicator selection**
   One or more simple, measurable indicators (e.g., population, per capita gross domestic product,

number of hospitals) are selected to represent each of the broad, conceptual factors in the framework. Operationalizing the factors, and thus the concept of earthquake disaster risk that they collectively define, enables the performance of objective, quantitative analysis.

3. **Mathematical combination**
   A mathematical model is developed to combine the indicators into the composite EDRI that best represents the concept of earthquake disaster risk.
4. **Data gathering and evaluation**
   Data is gathered for each indicator and each of the world's major cities. The values of the main contributing factors and of the EDRI are evaluated for each city using the mathematical model developed in Step 3.
5. **Post-processing: sensitivity analysis, interpretation, and presentation**
   A sensitivity analysis is performed to determine the robustness of the results, given the many uncertainties involved in the analysis. The numerical findings are interpreted to assess their reasonableness and their implications. Finally, the results are presented using a variety of graphical forms (e.g., charts, maps) to make them as easily accessible as possible.

The following description of a sample analysis that was conducted recently illustrates the EDRI development process as it proceeds through these five steps.

3.1. Sample Analysis

Carrying out the first step of the procedure resulted in the framework shown in Figure 1. It shows the five main factors that contribute to earthquake disaster risk: Hazard, Exposure, Vulnerability, External Context, and Emergency Response and Recovery Capability. Each of these five main factors is disaggregated into the more specific factors that comprise it. For simplicity, the framework does not portray interactions among the factors.

Hazard represents the geological phenomena that serve as initiating events of earthquake disaster, the demand to which a city will be subjected. The factor describes, for both ground shaking and collateral hazards (i.e., liquefaction, landslide, tsunami, and fire), the frequency of each possible severity level as it is distributed throughout the city.

Exposure describes the size of a city; a list of everything that is subject to the physical demands imposed by the hazard. Exposure includes the quantity and distribution of people and physical objects, and the number and type of activities they support. It can be addressed with respect to the following different components of a city: its physical infrastructure, population, economy, and social-political system.

Vulnerability describes how easily and how severely a city's physical infrastructure, population, economy, and social-political system can be affected by an earthquake. Vulnerability refers to the potential for the physical infrastructure to be damaged or destroyed; for individuals to be injured, killed, or left homeless, or to have their daily lives disrupted; and for the economic and social-political systems to be disrupted.

In today's global community, major cities are increasingly interconnected. No city is an island. Neither the factors that contribute to a city's risk, nor the consequences of an earthquake disaster are confined within a city's borders. External Context is included to describe how damage to a city affects people and activities outside the city. It incorporates the reality that, depending on a city's prominence with respect to economics, transportation, politics, and culture, damage to certain cities may have more far-reaching effects than damage to others.

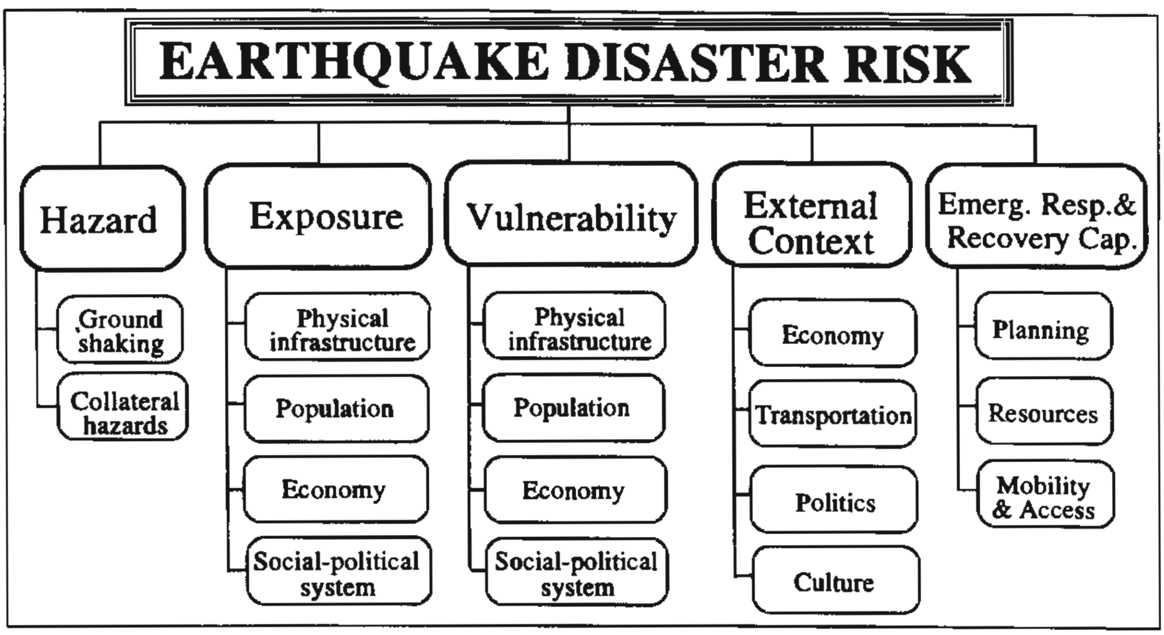


Figure 1. Conceptual framework of earthquake disaster risk.

Emergency Response and Recovery Capability describes how effectively and efficiently a city can recover from short- and long-term impact through formal, organized activities that are performed either after the earthquake, or before the earthquake, but with the primary purpose of improving post-earthquake activities (e.g., planning). It is assumed that any other actions taken before the earthquake (e.g., retrofitting) are significant only if they changed the current snapshot of the city, in which case they are accounted for in other factors. Emergency Response and Recovery Capability relates to pre-earthquake organizational and operational planning; financial, equipment, facilities, and trained manpower resources available after an earthquake; and mobility and access after an earthquake.

In the second step of the EDRI development, simple, measurable indicators are selected to represent the factors in the conceptual framework. Table 1 presents a few examples of the type of indicators that may be used and the factors they intend to represent.

x_{ij} is the scaled value for indicator i and city j ; and $\bar{x}_i$ and s_i are the mean and standard deviation of the sample of cities for indicator i. Six other scaling methods were considered before the one defined by Eq. 1 was selected. The choice was based on three main reasons. First, the method is strictly a mathematical operation, requiring no subjective assessment. All subjectivity is isolated in the determination of the weights, easily visible to the user. Second, since the selected scaling technique relies on the entire sample of cities (i.e., its mean and standard deviation), the results are relatively insensitive to the quality of data for any one or two particular cities. Third, the scaled indicator values derived from this method will all be positive, making the results easily interpretable. Weights are determined using experts' subjective assessments.

Data is gathered for each indicator and city in step four. Each raw data value is scaled, and the five main factor values and the EDRI are evaluated for each city. In the final step, the results are analyzed to determine their

Table 1. Selected examples of indicators used in the sample analysis.

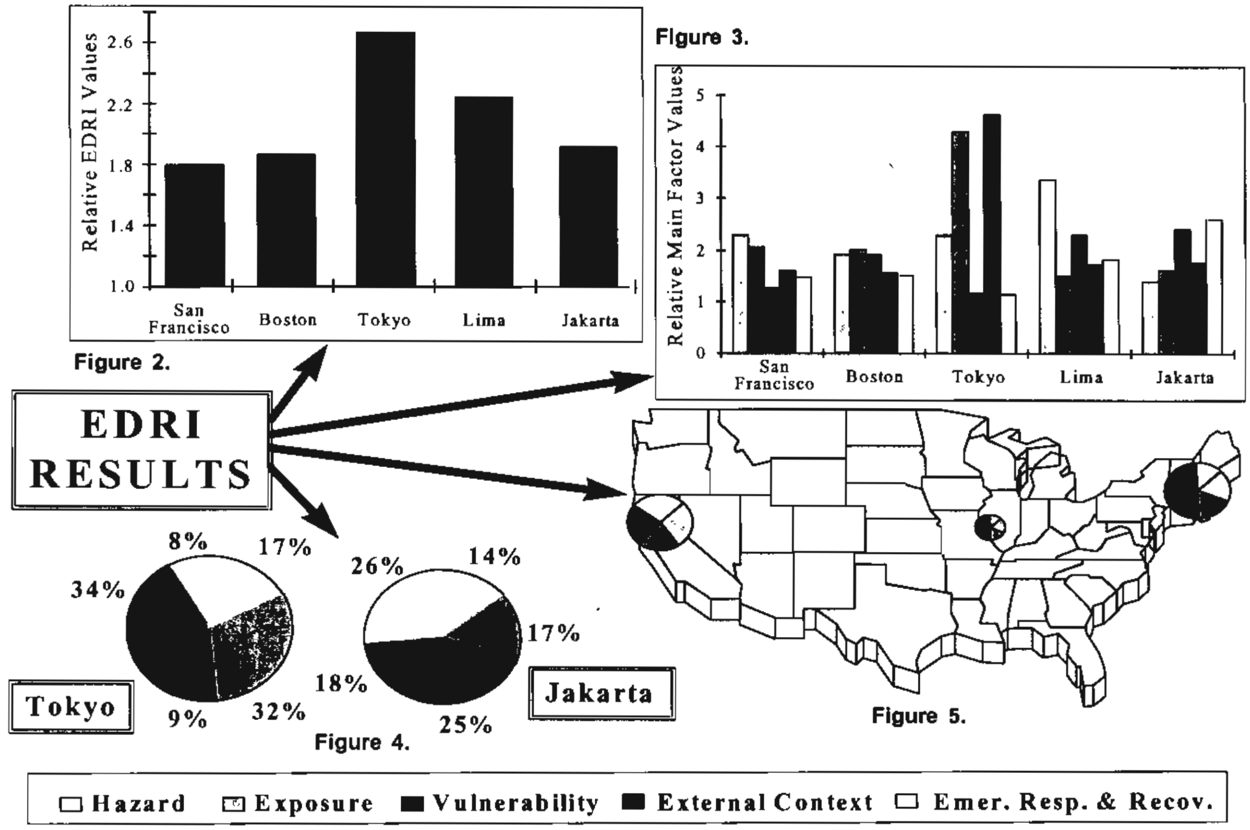
Factors	Indicators
Hazard	Intensity (MMI) with a fifty-year return period Intensity (MMI) with a five-hundred-year return period Percentage of urbanized area of city with soft soil
Exposure	Population Number of housing units Per capita Gross Domestic Product in constant 1990 U.S. dollars
Vulnerability	Seismic building code benchmark years Time history of population growth
External Context	Total value of economic exchange between country & rest of world Population of the largest region of which the city is a political capital
Emergency Response & Recovery Capability	Number of hospitals per 100,000 residents Housing vacancy rate Population density

Once the indicators have been selected, a method for their mathematical combination is devised in step three. In the sample analysis, the EDRI is computed as a linear combination, i.e., EDRI= $\sum_i w_i x_i$ where x_i are the values of indicators that represent the contributing factors, and w_i are weights that convey the relative importance of each to the overall risk. This approach requires first scaling each of the indicators into commensurable units, and determining the weight corresponding to each indicator. The indicators are scaled using Eq. 1:

$$x_{ij} = \left[x_{ij'} - \left(\bar{x}_i - 2s_i\right)\right] / s_i \qquad (1)$$

where $x_{ij'}$ is the raw data value for indicator i and city j;

sensitivity to the indicator selection, combination scheme, weights, data uncertainty, and selection of sample cities. The numerical findings are interpreted to assess their reasonableness and implications. Finally, the results are presented in a series of simple figures. Figure 2 illustrates the relative overall EDRI values of different cities. To learn *why* one city has a higher risk than another, the user can examine the disaggregated results. In Figure 3, the user can focus on one of the five main factors and see how it varies among cities. Figure 4 shows, for a single city, the relative contributions of the five main factors to the overall risk. Finally, the earthquake disaster risk map in Figure 5 consolidates all the information into a concise, visual form. A pie chart is located at each major city. The size of the pie



is proportional to the city's relative overall earthquake disaster risk, and the slices of the pie show the relative contributions of the five main factors to that risk.

3.2. *Reflection on the Main Issues*

The risk assessment project emphasizes the three main issues of the big picture of earthquake risk mentioned above—urban risk, a holistic, multidisciplinary approach, and the dissemination of current knowledge. The project focuses on a city's greater metropolitan area as the unit of study for the reasons presented, and because the impact area of a single earthquake is of the same order as a greater metropolitan area. Impact generally will not be contained within legal city limits; nor will it extend over an entire country. Since many lifeline networks, economic, social, and political functions are defined for or roughly uniform over greater metropolitan areas, that unit of area provides the best common ground for assessing expected physical impact, response capability, and context of the impact.

The study adopts a multidisciplinary, holistic approach by defining the problem in broad terms, and by addressing issues and borrowing analysis techniques from many disciplines. The EDRI attempts to measure a comprehensive concept that is termed *earthquake disaster risk* to distinguish it from the *earthquake risk* assessments of current engineering models. While the term *earthquake risk* often refers to the probability and severity of physical impact (e.g., deaths, injuries, economic loss), the EDRI considers the possibility that a *disaster* will occur. The latter concept extends beyond impact estimates by recognizing the importance of the social, economic, political, and cultural context in which the expected impact will occur. The context determines whether an earthquake will create a disaster situation and how extensively its effect will be felt.

The risk assessment study addresses the need for dissemination of the current state of knowledge of earthquake disasters through its use of a composite index to present earthquake disaster risk, and its worldwide applicability. Presenting the risk as a simple index will make the conclusions and multidisciplinary approach of the research easily accessible to the public, governments, insurance companies, and other potential users. It will allow direct comparison of the overall earthquake disaster risk of urban centers worldwide. Each city may have a range of values for the various factors that contribute to the overall risk. A city may have a high risk with respect to certain factors, and low with respect to others. By synthesizing the vast amount of information on all the pertinent factors, the index will provide a concise summary of urban risk that currently is not available from any other sources. Furthermore, the EDRI is being developed for application to all major cities worldwide, not just those in the developed world, where data, resources, and effort are generally concentrated.

4. RISK MANAGEMENT: STRATEGY EFFECTIVENESS CHARTS

The risk management study is developing a comprehensive Strategy Effectiveness Chart (SEC) that will help to identify the optimal mitigation strategy for a specified urban region. The SEC is unique among past risk management studies in that it compares mitigation strategies not in terms of a reduction in *expected loss*, but in terms of improvement in overall *performance*. While *expected loss* incorporates only the values of potential economic and life loss in a region in future earthquakes, *performance* also reflects the capacity to sustain the losses and recover from them. Incorporating capacity involves integrating the economic, human, and lifeline losses with emergency response and recovery issues within the framework of the existing socio-economic conditions of the region. For a particular mitigation strategy, the SEC provides three pieces of information: current performance before mitigation and the components that contribute to it, performance after the strategy has been implemented, and cost of the strategy. Strategies are evaluated on the basis of how they improve performance for whoever provides the resources, within the economic and political constraints that influence the likelihood of implementation. The SEC could be used by a government agency, like the Federal Emergency Management Agency (FEMA), or by individual homeowners as a guide for investing resources towards mitigation.

Since the performance would be different for each sector in a region (i.e., the residential, commercial, lifeline, and government sectors), strategies are evaluated first for each sector individually, then for the region as a whole. This study develops a Performance Index (PI) to measure each sector's performance. A question that frequently arises in mitigation planning is whether it is more efficient to invest in strategies that reduce the loss (e.g., retrofitting), or in strategies that improve recovery efficiency (e.g., improving recovery plans). With this end in mind, the PI is divided into two components, one of which represents disruption, the other of which represents recovery. Disruption, a function of the economic loss, human loss, loss of service of lifelines, is a measure of the expected severity of earthquake-related loss. Recovery performance reflects the expected rescue, relief, and repair efficiency, which in turn depends on the time and costs required to execute the effort. Performance improves as disruption decreases, and as recovery increases. The PI and each of its two components are evaluated on a scale of zero to one hundred. A score of zero for disruption and one hundred for recovery represents an optimal performance, i.e., when an earthquake results in negligible losses, and the response and recovery efficiency is perfect.

The SEC for each sector is developed in three stages. First, loss and recovery data are generated for different earthquake scenarios in the region, based on the current level of mitigation. The data is normalized by the sector exposure to scale the data to unitless values (e.g., percentage of property value, population). Second, the disruption, recovery, and overall PI scores are computed for this pre-mitigation situation using the normalized data and other sector characteristics (e.g., resident income, annual industry revenue). Finally, the PI scores after mitigation are evaluated by changing the scenario input data based on the anticipated effect of each strategy (e.g., reduction in economic loss, improvement in rescue time), and repeating the analysis. The results before and after mitigation are plotted in the SEC for each strategy. A regional SEC may be constructed by aggregating the SECs for all the sectors within that region. These three stages in the development of an SEC are discussed further in the following three subsections.

4.1. Development of Normalized Loss and Recovery Data

In the first stage, the normalized data for scenario loss and recovery are computed in three steps. First, expected loss data for the overall region are generated for a set of earthquake scenarios. Several different scenarios are required to capture the strengths of different strategies because some strategies are effective in a high magnitude, low probability event, while others are effective in moderate, high probability events. The overall PI for the sector is the aggregation of the PI scores for all scenarios, each weighted by its probability of occurrence in the time period considered. Six factors for the scenario data are chosen:

1. Economic loss-structural and non-structural damage, fire loss, business interruption
2. Human loss - deaths, injuries, displaced households
3. Lifeline loss - utilities, communication, transportation
4. Rescue - time and cost
5. Relief - time and cost
6. Repair - time and cost

The scenario data are initially generated for a region as a whole, and thus in the second step, they must be interpreted from the perspectives of each of the four sectors independently. Different types of loss and different emergency response and recovery issues will be important for each sector (Figure 6). Since strategies are being evaluated on a sector-specific basis, this division of the scenario data is required so that the mitigation concerns of each sector can be identified.

Finally, the expected loss and recovery parameters are normalized based on each sector's exposure. This step allows the losses to be assessed as percentages, rather than absolute values. For example, losses of $5000 and $1000 could have comparable meaning if the first corresponds to a property value that is five times that of the second. Sample exposure characteristics considered for each type of data are shown in Table 2.

4.2. Development of the Sector PI Score Before Mitigation

To calculate the PI scores, the normalized expected loss and recovery data from the first step is converted into disruption and recovery scores on the basis of relevant

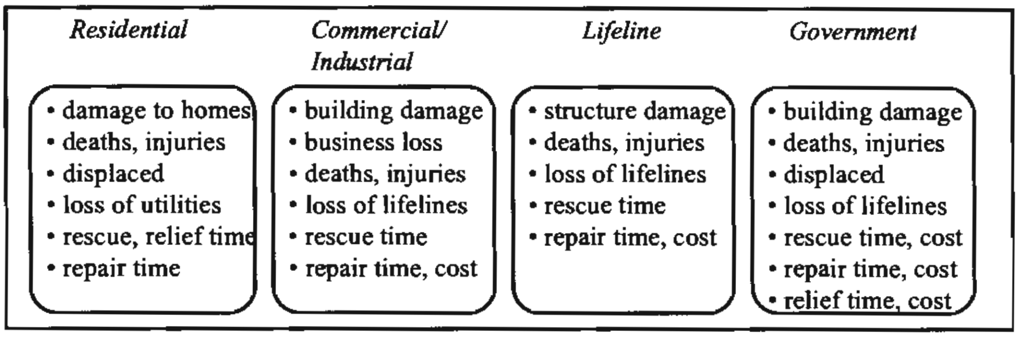


Figure 6. Aspects of the scenario data that are important for each sector.

sector characteristics. For example, a ten percent loss of property value causes a greater disruption for an elderly couple with low income than for a young, single homeowner with a higher income. Each loss factor (economic, human, and lifeline) is converted to an equivalent increase in disruption (from a score of zero), and the recovery factors (rescue, relief, and repair) are converted to reductions in recovery (from a score of hundred). The net disruption and recovery scores obtained by aggregating the individual factors are used to develop the overall PI score for the sector. The characteristics considered for each sector are shown in Figure 7.

Relationships to determine the disruption and recovery scores from the normalized data are developed with the help of expert opinion. Figure 8 depicts a sample curve for the economic loss component. The scenario provides a value for the economic loss as a percentage of the property value exposed. The sample curve would convert it into a performance reduction factor for the residential sector based on the characteristics of that sector. Thus, a loss of ten percent of the property value is equivalent to a disruption score of fourteen.

Table 2. Exposure characteristics used for normalization.

Type of data	Relevant exposure characteristic
Building/content damage	Property value/inventory
Business interruption	Annual revenue
Deaths and injuries	Population
Displacement	Number of households
Loss of lifelines	Households or establishment affected
Recovery costs	Total economic loss

4.3. Development of the Sector PI Score After Mitigation

The implementation of a mitigation strategy is simulated by modifying the input scenario data. To evaluate the change in PI that results from each strategy, the analysis described in the previous section is repeated, and the difference between the results before and after mitigation indicates the strategy's effectiveness. The factors used to evaluate how the input data should be modified to represent the implementation of a particular strategy are listed in Table 3. Both pre-event mitigation (e.g. retrofitting, insurance, education) and post-event emergency response and recovery operations (e.g. rescue and relief) are considered to incorporate a wide range of benefits in the methodology.

Once results for different sets of strategies are computed, they are plotted in the SEC, like the schematic one in Figure 9. Cost (for the entire sector) is shown on the horizontal axis, the disruption and recovery on the left axis, and PI on the right axis. Since disruption reduces PI

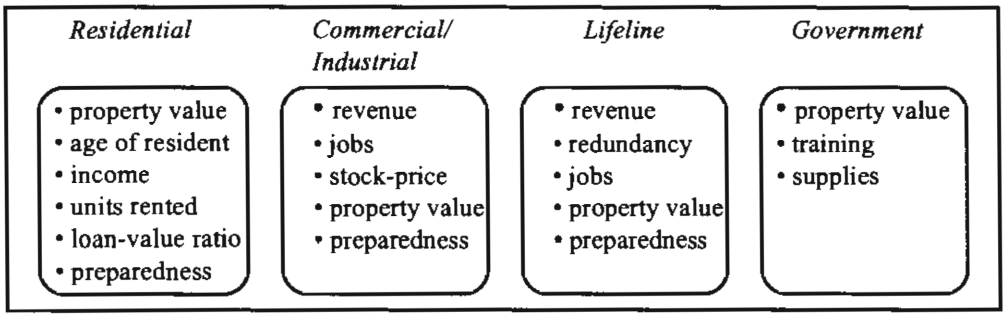


Figure 7. Relevant sector characteristics.

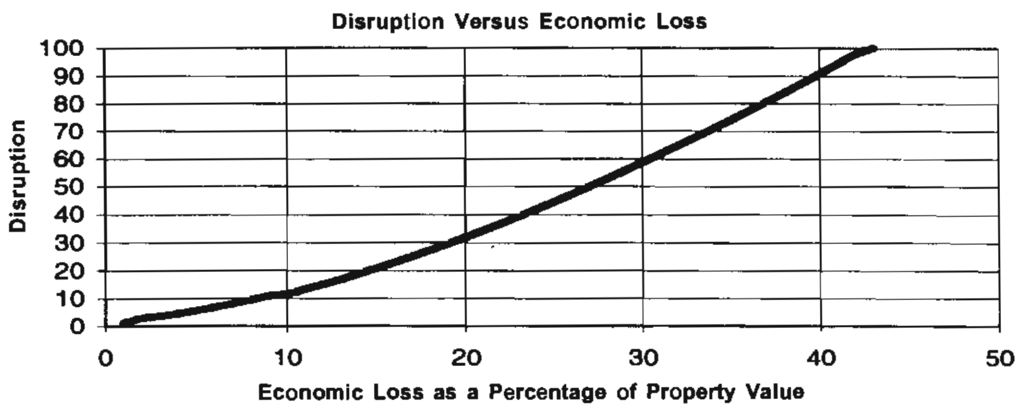


Figure 8. Sample to relate scenario input data to impact performance.

and recovery increases PI, they are shown on negative and positive axes, respectively. The SEC illustrates how each mitigation strategy changes the PI scores from the current situation (zero cost). Charts for the four sectors are combined into a regional SEC, based on their relative contribution to the overall performance of the region. Weights to describe the relative contribution of each sector to the regional SEC are developed using expert opinion.

In Figure 9, each set of three columns correspond to one mitigation strategy. For the current situation, column (a) represents recovery and its components, column (b) represents disruption and its components, and column (c) is the PI. The SEC shows that the sector has an average disruption of thirty-five, recovery of sixty-one, and PI of sixty-two. A sector investment of $1.5 million in strategy S1 increases PI to sixty-eight by reducing the economic loss and improving overall recovery. An additional investment of $3 million in strategy S2 actually reduces performance even though recovery improves, because the strategy is too expensive for the benefits it provides. On the other hand, since there is a large reduction in the human loss, the user might decide that the investment is worthwhile. The SEC provides all the relevant information, and allows each user to weigh that information and make a choice based on his particular priorities.

The choice of the optimal strategy could be made by a number of different ways using the SEC, based on user priorities. First the optimal strategy could be chosen as the one with the highest PI score. Second, the marginal benefits of the strategies could be compared for each

Table 3. Factors affecting change in scenario input data.

Factor	Description
Investment	How much money is invested in the strategy
Coverage	Which components a strategy affects (e.g., bolting of foundations only affects wood-frame buildings)
Influence	To what extent the strategy influences the parameters that it effects (e.g., bolting may reduce loss to the buildings by about 15%)
Implementation	What percentage of the sector is likely to implement the strategy
Time horizon	Time frame for which benefits from the strategies will be evaluated

additional level of investment. Third, the choice could be made based on the change in the scores for one of the six factors contributing to the PI. Finally, given a budget constraint, any of the three above techniques could be used after identifying which strategies lie within the budget.

4.4. Reflection on the Main Issues

This study also defines its goals and scope broadly. The project uses an urban region as a unit of study, and the analysis allows investigation of the full range of possible loss reduction and recovery improvement strategies. The multidisciplinary approach is manifested through the diversity of quantitative and qualitative issues that are incorporated into the model. The perspectives of four different sectors are considered. Performance of each sector is measured on six dimensions: economic loss, human loss, loss of lifeline service, rescue, relief, and repair efficiency. The priorities and resource constraints of each sector and of the region as a whole are included in the Performance Index. All of these features of the project illustrate how it incorporates the broader context of *performance* into its evaluation of the cost-effectiveness of potential mitigation strategies. Structural, economic, social, and political characteristics of the region all come together to provide a comprehensive comparison of mitigation strategies.

By adopting a large decision frame, this study helps determine the relative priorities of the many smaller decisions related to earthquake risk mitigation. For example, before a city spends time and effort determining how best to address the threat of fire following an earthquake (e.g., installing automatic gas shutoff valves versus buying more fire trucks), it should determine how significant the risk of fire is relative to the other risks associated with an earthquake. The holistic perspective of this work not only helps a given sector allocate its resources among the possible mitigation strategies, but also helps allocate a city's funds among the various sectors.

Two aspects of this project demonstrate its consideration of the need for increased implementation. First, the study includes the probability that a strategy will be implemented as one of the characteristics on which the post-mitigation Performance Index is based. The feasibility of implementing a strategy depends on the political and cultural characteristics of the region, and on the priorities and resources of the sectors who will pay for the effort. Second, by analyzing each sector separately, the project can help identify potential incentive mechanisms to encourage each group to enact mitigation measures. Unlike studies that directly estimate the costs and benefits for a region as a whole, this study evaluates performance for a sector alone, thereby illustrating for that particular sector the direct benefits it can expect to receive for its investment, and perhaps spurring it to action.

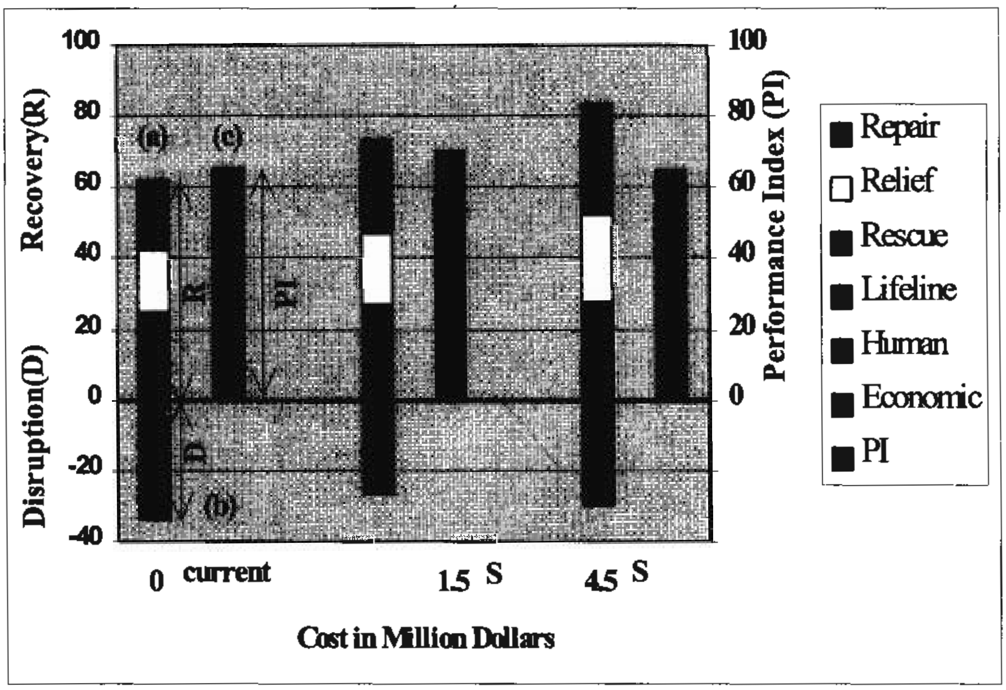


Figure 9. Schematic sector strategy effectiveness chart.

5. RISK FORECASTING: ESTIMATING FUTURE EARTHQUAKE RISK

The third study focuses on developing an integrated framework to describe how earthquake disaster risk varies over time, to estimate the earthquake disaster risk of an urban region at some future time, to assess the long-term effects of earthquake disaster, and to understand the future implications of today's mitigation decisions.

Earthquake disaster risk should be assessed in the social and economic context of the region in which it exists. This context changes with time due to the interdependence of social and economic circumstances and external influences. Changing circumstances affect the location, exposure, vulnerability, and hence, the risk of a region. Therefore, a framework capable of portraying the rapidly changing nature of regional risk is necessary to describe risk as accurately as possible.

5.1. Framework Development Criteria

The criteria for developing a framework to portray the changing nature of earthquake disaster risk can be conveniently divided into challenges and constraints. Challenges denote the requirements that the framework should be capable of fulfilling, while constraints represent restrictions imposed on the framework due to the practical need to restrict the scope of research, and due to limited data availability.

The challenges faced by such a framework are that it should portray risk on a *macro* level to facilitate easier understanding, while at the same time delving into *micro* issues to a reasonable extent to offer explanations about the dynamics of risk. From a researcher's point-of-view, this challenge relates to the need to balance breadth and depth in developing the framework. The framework should clearly portray cause-effect relationships to express the root causes of the various components of risk and explain the time variation. The final challenge is to keep the model simple, and not add complexity without additional understanding.

The constraints due to limitations in scope of research represent the researcher's need to simplify the problem sufficiently to direct focused efforts in tackling it. Limitations in data availability can be a significant practical constraint, depending on the differences between theoretical model requirements and availability of real data. These considerations drive not only the breadth and depth of the framework, but also the approach in developing it.

5.2. Framework Overview

An understanding of the nature of urban dynamics will provide a setting to evaluate the framework. Urban agglomerations, which represent concentrated, high risk areas in terms of population and economy, are inherently complex, "organic" systems in which each sub-system depends on the other in a unique manner, interacting through various socio-economic mechanisms. These different sub-systems (also called sectors) include the demographic sector (describing the compositional statistics of the population), the inter-industry sector (businesses), the capital sector (investment), and the political sector (policy- and decision-making). The sectors are complete entities in themselves, while at the same time being interacting components of a larger system. For example, the demographic sector, which consists of the population and its compositional statistics, interacts with the inter-industry sector through labor supply and demand, which in turn may influence the capital sector, i.e., investment in the region. By defining and quantifying these cause-effect relationships the change in various components of each sector, and hence the change in the overall earthquake disaster risk that they collectively determine can be measured. This systems approach explicitly defines the relationships between sub-systems, and also addresses the way in which the sub-systems make up the "whole".

The variation of the city's risk with time is depicted through dynamic simulation. Each component of a city's behavior is represented by a set of variables that are functions of time. The interactions among the components are characterized through equations that relate those variables. By solving the equations sequentially, starting with the given values at the current time step, the values of the variables at subsequent time steps can be determined, thus simulating future earthquake risk. Mitigation policies will have the effect of changing the values of the variables at the time step corresponding to implementation. Resolving the equations with these changed variables will result in an altered estimate of the future risk, thereby enabling a comparison of the future risk with and without the policy. Such a comparison will suggest the policy's implications on the future risk.

5.3. Procedure to Develop a Dynamic Earthquake Disaster Risk Framework

Based on the above criteria and considering the nature of the dynamics of risk as explained in the preceding sections, the following general procedure has been developed to create a dynamic earthquake disaster risk framework. The first step consists of identifying the major sub-systems of the urban area as mentioned before and investigating the factors indicative of the state of each sub-system. Thus, collectively these factors encompass engineering and socio-economic as well as political components of a region's risk. At this stage, two things must be kept in mind in choosing these indicators: Does the indicator change with time?, and Does it significantly affect the region's risk? Note that the particular aspect of the sub-system itself (to be represented in the model), may be qualitative, but in that case, quantitative, measurable indicators must be devised to represent it. The indicators which have been chosen, are similar to the indicators used in constructing the EDRI.

The second step includes building an econometric model of the region using a systems approach. The model utilizes cause-effect relationships to combine interactions within and between the different sub-systems, measuring changes in the various indicators at a certain time step. The econometric model accounts for changes in the indicators over time. A suitable indicator of the hazard faced by a region is included in the framework.

As the final step, the content and format of the output of the model are designed so that they portray the information most helpful to potential users in the most easily and directly applicable way possible. A standardized measure of the region's risk is defined as a function of the indicator values. The measure of risk is similar to the EDRI, so effectively, the framework tracks an index similar to the EDRI, over time. The uncertainty in the data concerning different variables as well as uncertainty in their interdependence relationships is propagated into uncertainty regarding risk. Thus, a chart showing this risk over time also depicts the upper and lower bounds for a region's risk at a particular instance of time. One can also refer to the average risk faced by the region over time and provide suitable standard deviations on this measure.

Different plots (showing the range of risk for a particular case) are obtained for no mitigation, mitigation strategy X, mitigation strategy Y, etc. (see Figure 10). Comparison between the risk with and without the mitigation strategies helps the decision-maker clearly see the implications of the strategies at different instances of time, thus enabling him to see the long-term effects of the strategies. As stated earlier, the measure of risk can be easily converted to monetary values for direct application of the charts towards cost-benefit analysis of different mitigation strategies.

5.4. Reflection on the Main Issues

Currently, earthquake mitigation efforts are primarily reactive. Each time an earthquake occurs, the event is analyzed to determine the degree and nature of the impact, to uncover any unanticipated problems, and to evaluate which previous mitigation efforts helped and which did not. Such postmortem analyses provide invaluable information to help guide the development of mitigation efforts in preparation of the next event. Nevertheless, with this reactive approach, earthquake professionals remain a step behind the game. With each new earthquake there will be new, unforeseen problems. By forecasting the changing degree and nature of earthquake risk, this third study attempts to anticipate more fully the effects of future earthquakes, so that they can be addressed, perhaps even before they are witnessed.

The implementation focus of the risk forecasting work is noticeable through its goal to develop a tool that will aid decision-makers in understanding future implications of their decisions. The plots showing variation of risk with time can be used very effectively to convince (even unwilling) decision-makers to invest in solid, long term mitigation strategies and help people see through strategies implemented just for short term political gains.

The bounds of this project extend even further than those of the first two projects. Not only does the analysis span geological, structural, economical, social, and political dimensions, but it ventures into the time dimension as well. The study must rely on previously-developed analysis techniques and principles from a variety of fields to achieve its sweeping objectives.

6. CONCLUSION

Together, the three projects presented above, attempt to assess, manage and forecast risk in a broader context. They add multidisciplinary dimensions to traditional solutions, and in doing so, provide a clearer view of the big picture. The projects could be applied in conjunction with each other to enable the decision-maker to better assess the circumstances and make better, informed decisions. For example, local governments could evaluate the EDRI for a city and find out the relative risk as compared to other cities and how much each factor contributes to that risk. They could then formulate mitigation strategies and adopt efficient ones by evaluating their effectiveness using the SEC. Finally, they could plan for the future by simulating and forecasting the region's risk with and without mitigation strategies using the RTC.

During the past several decades, earth scientists, engineers, and social scientists have developed a core of knowledge about the causes and characteristics of earthquakes and their varied effects on humans and the

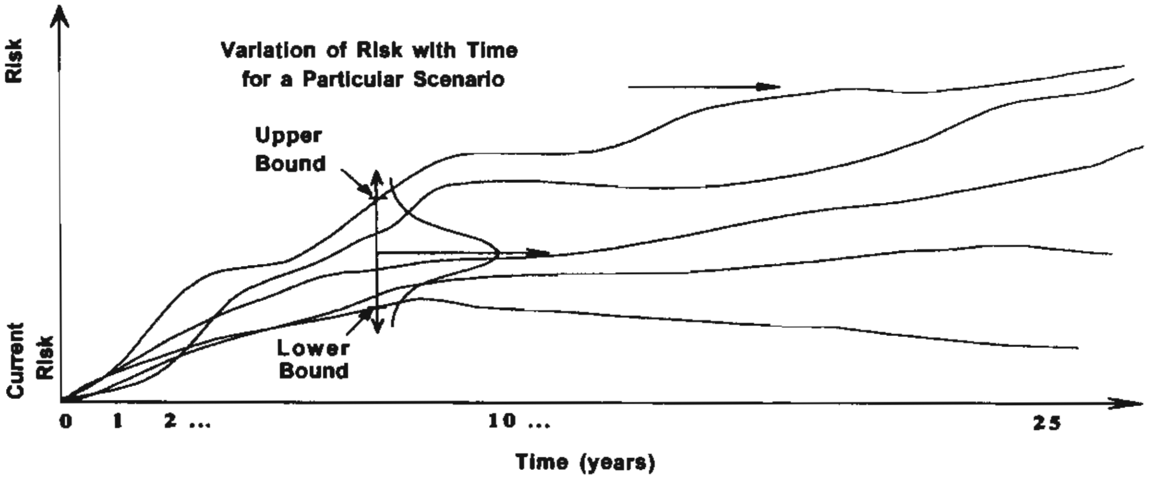


Figure 10. Schematic output results of the dynamic earthquake disaster risk framework.

built environment. With this foundation as a starting point, earthquake professionals now must focus their work on implementing and disseminating the current level of understanding, and on undertaking new research to develop a holistic, multidisciplinary understanding of urban risk. It is the authors' hope that the three projects introduced in this paper can serve as a modest start to a new, concerted effort by the earthquake community; an effort to address deliberately and fervently the three principal issues that have been identified as the most pressing.

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