EARTHQUAKE VULNERABILITY

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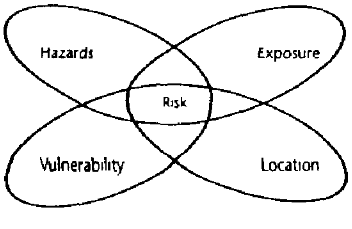
ABSTRACT

Throughout the world, each earthquake-prone community's vulnerability, or susceptibility to damage from earthquake ground shaking, ground failure, surface fault rupture, regional tectonic deformation, tsunamis and aftershocks is growing rapidly as a result of either a lack of public policy, or flaws in public policy. These mistakes have led incrementally over time to inadequate consideration by many communities of the need for planning, siting, design, construction, quality control and use. These oversights have become the root causes of unacceptable risk to individual elements of the built environment and the overall unacceptable risk to the community. The 21st century presents the most opportune moment ever to correct these flaws and to reduce community vulnerability because of advances made during the International Decade for Natural Disaster Reduction (IDNDR). For the first time, more professionals, policy makers and stakeholders are collaborating than ever before, and every earthquake-prone community has access to scientific and technical data needed to anticipate the consequences of earthquakes and to form public policy for reducing community vulnerability. The 1990s have seen an increase in the technical capacity, desire to collaborate, capability to anticipate, and political will to change public policies. Seismic zonation, a policy tool that can be used to link risk assessment and risk management, is now available to every earthquake-prone community. Seismic zonation calls for anticipation (i e. mitigation and preparedness measures) instead of reaction (response and recovery), integration (i.e. linking risk assessment with risk management) instead of fragmentation, and public-private partnerships instead of individual efforts to promote reduction of community vulnerability as a public value. The most effective course of action now is for every earthquake-prone community to call for public policies that: 1) stop increasing the risk as new development are added to the built environment inventory, 2) start decreasing the risk to the existing built environment, and 3) continue planning for the inevitable earthquake.

1.
INTRODUCTION

This paper highlights the results of a collaborative 10-year effort led by the United States Geological Survey and the United Nations Educational Scientific and Cultural Organization to promote seismic zonation [Hays, Mohammadioun, and Mohammadioun, 1998]. More than 300 professionals contributed to the effort which pointed out that the current trend of large unacceptable economic losses experienced recently in Northern California, Southern California, Japan, and other countries is a wake-up call for responsible, innovative actions to reduce community vulnerability (Figure 1). Scientists, engineers, planners, and policy makers in every earthquake-prone community of the world have an important role to play in a cooperative worldwide effort. Earthquakes are an international problem. They occur globally, impacting people, property, and infrastructure without regard to political boundaries, season, time of day, social status, and state-of-preparedness in the stricken community. The problem is exacerbated over time because of the increasing vulnerability of existing community development and new community development expanding into new geographic areas that are susceptible to ground shaking, ground failure, surface faulting, regional tectonic deformation, tsunamis, and the aftershock sequence. Over 1.6 million people died in earthquakes during the 20th century, many more were injured, and direct economic losses from a single, moderate sized earthquake reached a record high of at least US $140 billion in the 17 January 1995 Kobe, Japan earthquake. This trend, expected to continue throughout the world, has ominous social implications.

Figure 1. Schematic illustration showing the principal elements of risk: hazards, location, exposure, and vulnerability. The focus of worldwide collaboration must now be on reduction of community vulnerability, which should be seen as the key to sustainability.



Vulnerability reduction is urgent because, not only are economic losses, mortality, and morbidity increasing with time in every country, but also the

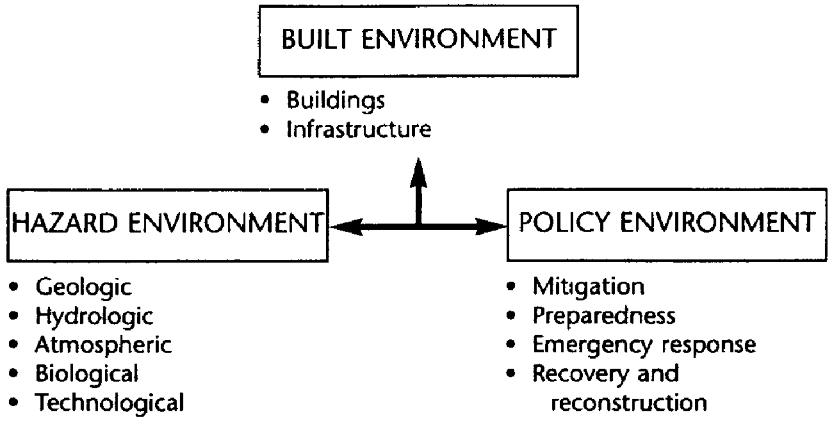


Figure 2. Reduction of community vulnerability calls for integrated strategies that consider all aspects of the community's hazard, built and policy environments.

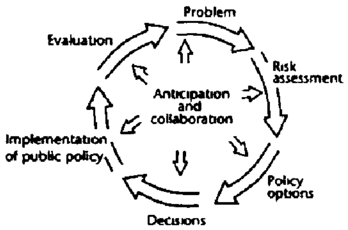


Figure 3. Scientists, engineers, planners and public officials need to collaborate as they improve their ability to anticipate what is likely to happen in the future and their capacity to work together, devising, implementing, and enforcing integrated public policies that will reduce vulnerability in each community at risk to earthquakes.

number of "surprises" is increasing. The expectation is that losses will continue to increase until earthquake-prone communities start reducing their vulnerabilities through integrated strategies for the hazard, built, and policy environments (Figure 2).

Vulnerability reduction calls for scientists, engineers, planners, and public officials to work together to anticipate what is likely to happen in the future (Figure 3), and to devise and implement integrated public policies that are designed to reduce a community's vulnerability. Anticipation of what is likely to happen and collaboration to eliminate flaws in planning, siting, design, construction, quality control and use—the sources of community vulnerability—are the keys to reduction of community vulnerability.

2.

WHAT MAKES A COMMUNITY VULNERABLE TO EARTHQUAKES?

Many factors combine to make a community vulnerable to the physical effects of earthquakes. They range from the manner in which engineered and non-engineered buildings and infrastructure performing the essential functions of supply, disposal, transportation, and communication are combined to inform the community on the temporal and spatial characteristics of the earthquake hazards. To the furthest extent possible, all must be identified and incorporated in a model of the community's hazard and built environment when assessing the overall urban vulnerability and risk (Figure 4).

A community's vulnerability to the earthquake hazards of ground shaking, ground failure, surface fault rupture, regional tectonic deformation, tsunamis, and aftershocks is the result of either no public policy, or flaws in public policies related to: a) planning, b) siting, c) design, d) construction, e) quality control, and use of individual elements of the built environment (i.e. single family dwellings, commercial buildings, schools, hospitals, government buildings, highway structures, bridges, underground pipelines, dams, power plants, airports, ports, railways).

Comprehensive studies following damaging earthquakes to determine what happened before, during, and after the earthquake and to explain why it happened have isolated the principal factors that increase the vulnerability of a community. They include:

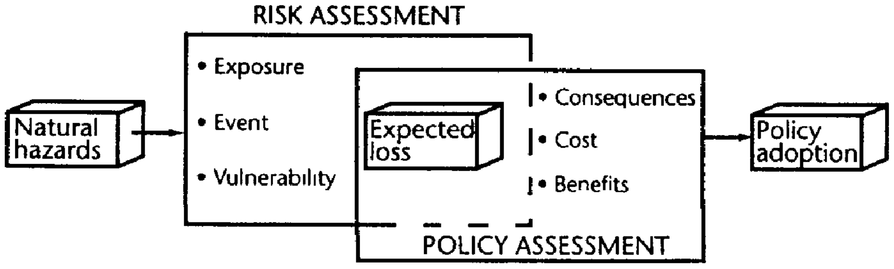


Figure 4. Elements of a model for a comprehensive risk assessment of a community.

1. Older, non-engineered residential and commercial buildings typically constructed with un-reinforced masonry or other construction materials having little or no resistance to the lateral forces of ground shaking.
2. Older infrastructure constructed at one time to conform with a seismic code or standard that is now considered to be outdated, and inadequate as a result of changes in the state-of-the art or state-of-practice.
3 Non-engineered residential and commercial buildings that are vulnerable to fire following an earthquake.
4. New buildings and/or infrastructure that have been sited, designed, and constructed without adequate consideration of the proximity to the fault.
5. Communities sited at the water's edge or in low-lying or coastal areas that are susceptible to tsunami.
6. Buildings or lifeline systems sited on or encased within poor soils that either enhance ground shaking, or fail through permanent displacements (e.g. liquefaction, lateral spreading, falls, topples, slides, and flows of soil and rock).
7. Buildings with irregular plan, and elevation and vertical and/or horizontal discontinuities in mass, strength, and stiffness.
8. Schools and hospitals—a community's "safe haven" facilities — that have been designed and constructed with materials with low resistance to lateral forces and irregular plan and elevation and vertical and horizontal discontinuities in mass, strength, and stiffness.
9. Communities with their communication facilities and disaster response control centres concentrated in the most hazardous areas instead of being widely distributed geographically to spread the risk.
10. Outdated bridges and viaducts.
11. Underground utilities providing the essential community services of supply and disposal for electricity, gas, water, and sewage that are likely to fail or be rendered unusable by ground failure.
12. Ports and harbours that are in locations susceptible to regional tectonic deformation, lateral spreads, and liquefaction.

3.
WHAT DO THE "SURPRISES" THROUGHOUT THE WORLD INDICATE?

The number of "surprises" after earthquake disasters throughout the world indicate that, at present, many communities: 1) do not know that they are vulnerable; 2) do not understand why they are vulnerable; or 3) are ineffective in reducing their vulnerability. In fact, most communities are just beginning to be willing to acknowledge that they are vulnerable because of inadequate public policies to ensure comprehensive planning, siting, design, construction, and use of the built environment. The numerous so-called "surprises" that the media has highlighted in most countries during the past two decades have included the following situations:

1. Discovering after the earthquake disaster that an active fault system was located directly beneath the community or very close to the community.
2. Experiencing unanticipated damage and loss of function to essential buildings (e.g hospitals, schools, government buildings), and lifelines (e.g. elevated highway systems, ports), especially when the scientific and technical consensus before the earthquake is that these structures have adequate earthquake resistance.
3. Discovering that portions of the community are susceptible to fire following the earthquake.
4. Experiencing thousands to tens of thousands of deaths and injuries, and thousands to hundreds of thousands left without homes and jobs.
5. Unexpected loss of community revenue, tax base, economic loss, and insured payments in the billions of dollars.
6. Discovering that the community lacks the capability for speedy emergency response and effective recovery and reconstruction.
7 Discovering after the earthquake disaster that the causes of the surprises were within the power of the community's policy makers and stakeholders (earth scientists, engineers, planners, insurers, businesses, and others) to correct before the disaster occurred.

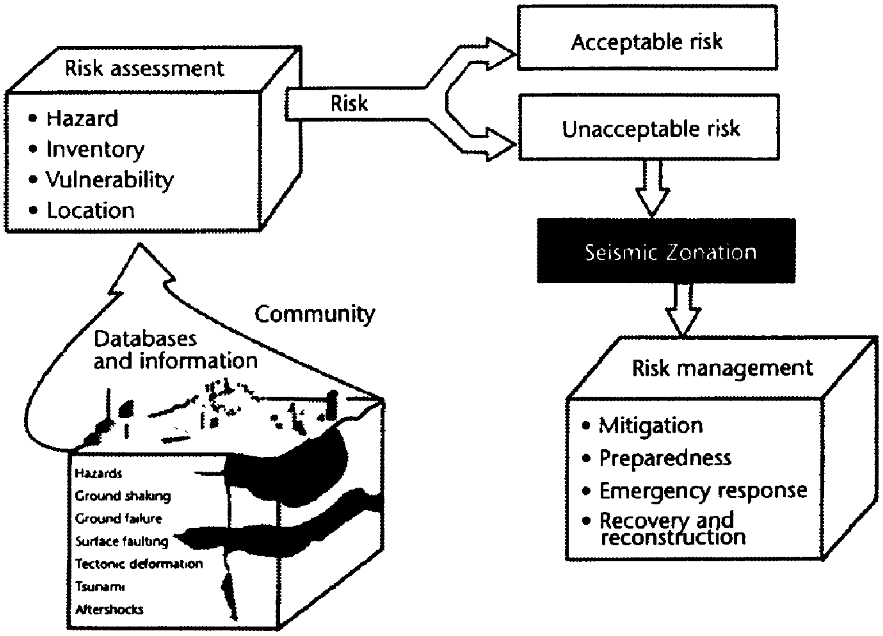


Figure 5. Schematic illustration of seismic zonation as a policy tool to link earthquake risk assessment and earthquake risk management before new community development is approved. This concept has been a legal mandate in California since 1990.

4.

WHY IS SEISMIC ZONATION—A POLICY TOOL FOR INTEGRATED RISK ASSESSMENT AND RISK MANAGEMENT—URGENTLY NEEDED AND A HOPE FOR THE FUTURE?

Integrated risk assessment and risk assessment—seismic zonation—is needed if earthquake-prone communities are going to anticipate what is likely to happen and collaborate to eliminate or reduce actual and perceived vulnerabilities at the source and potential losses (see Figures 3, 4, and 5).

Each community needs to devise strategies that will: 1) stop increasing the risk as new development is added to the community's inventory of buildings and lifeline systems comprising the built environment; 2) start decreasing the risk to existing buildings and lifeline systems; and 3) continue planning for the inevitable earthquake. The need for integration of risk assessment and risk management is urgent because the number of vulnerable structures and the economic value at risk are increasing rapidly in every community throughout the world Because of the advances made during the 1990s, and the increased availability of basic scientific and technical information, databases, hazards maps, codes and standards, and analytical tools, seismic zonation is now feasible anywhere, Moreover, it is becoming increasingly feasible technically and politically to link seismic zonation and performance codes and standards.

The two keys to linking, in the near future, seismic zonation with performance codes and standards are: 1) access to basic scientific and technical information, databases, hazards maps, codes and standards, and analytical tools; and 2) capacity to perform the assessments required to characterize a community's hazard and built environments for a risk assessment. Databases and case histories are now readily available to every earthquake-prone country, either from professionals within the country or through collaboration with professionals in other countries. The following are examples:

1. Location of the active and inactive faults
2. Geometry of the faults
3. The regional tectonic setting
4. The spatial and temporal characteristics of the seismicity
5. Rate of decay of seismic energy with distance from the point of fault rupture
6. Effects of geologic structure, tectonic setting, databases, and magnitude
7. Data on site response
8. Data on ground failure potential
9. Data on surface fault rupture potential
10. Data on flooding potential
11. Maps of the ground shaking hazard
12. Maps of ground failure hazard
13. Maps of potential surface fault rupture

14 Maps of potential regional tectonic deformation
15. Maps of potential tsunami flood wave run-up
16. Locations of the community's engineered and non-engineered buildings in relation to soil deposits and their earthquake resistance in terms of the criteria of a modern building code
17. Locations/routes of the community's lifeline systems in relation the soil deposits and the criteria of modern lifeline standards
18. Vulnerability/fragility relations for the community's buildings and lifelines

5. WHAT ARE THE GAPS IN KNOWLEDGE

Gaps in knowledge exist. The most critical gaps in knowledge that need to be filled by ongoing "works in progress" in order to improve seismic zonation as a policy tool to link risk assessments and risk management include the following:

1. The physics of the fault rupture
2. Near-source phenomena
3. Identifying tsunami sources
4. Basin effects
5. Attenuation laws for plate margin and intra-plate regions
6. Effects of soil non-linearity on site response
7. Optimum soil profile characterizations for generalized site response characterization
8. Prediction of lateral displacements associated with liquefaction-induced lateral spreading
9. Prediction of non-liquefaction related settlements and lateral displacements (e.g. in soft clay soils)
10. Tsunami modelling
11. Synthetic seismograms for specific source-path-site-structure configurations
12. Vulnerability/fragility relations for buildings of various types, materials, and functions
    1. Vulnerability/fragility relations for lifeline systems of various types, materials, and functions
    2. Implications of uncertainty in the characterizations of a community's hazard and built environments for the enactment and implementation of public policies for risk assessment and risk management

6. WHAT ARE THE PRINCIPAL OPTIONS FOR REDUCING COMMUNITY VULNERABILITY?

At present. community policy makers and community stakeholders have many options available for reducing community vulnerability, each having a wide range of potential benefit and costs. The ultimate realization of a specific benefit cost depends on the capability of the community to enact and enforce specific mitigation measures and regulations. The options and estimated ranges of benefit or cost are summarized below:

1 Insurance, with a potential benefit or cost ranging from one to one million, which spreads the risk and enhances recovery and, because of recent paradigm shifts within the insurance sector, offers hope for new mitigation incentives and initiatives.
2. Non-structural mitigation, with a potential benefit or cost ranging from one to one thousand, which protects equipment and contents, while ensuring continued use of buildings and facilities.
3. Building codes, with a potential benefit or cost ranging from one to one thousand, which prevent collapse of buildings; protects life and reduces injuries.
4. Demolition, with a potential benefit or cost ranging from one to one thousand, which eliminates collapse- hazard buildings and highway structures and reduces potential for loss of life and injuries.
5. Standards and guidelines for lifelines, with a potential benefit or cost ranging from one to one thousand, which protect community infrastructure.
6. Performance-based design, with a potential benefit or cost ranging from one to a hundred, which prevent loss of function and loss of use, especially in essential and critical facilities.
7 Training and exercises, with a potential benefit or cost ranging from one to a hundred, which expand the capability and self-reliance of professionals.
8 Retrofit, strengthening, upgrading, and repair, with a potential benefit or cost ranging from one to a hundred, which prevent collapse, eliminate vulnerabilities

caused by asymmetries, irregularities, and vertical and horizontal discontinuities in mass, stiffness, and strength in elevation and plan and reduce damage.

9. Base isolation, with a potential benefit or cost ranging from one to a hundred, which ensures continued functioning of essential and critical structures and facilities.
10. Soil remediation, with a potential benefit or cost ranging from one to a hundred, which prevents liquefaction, lateral spreading and landslides.
11. Public-private partnerships, with a potential benefit or cost ranging from one to ten, which spread responsibility.
12. Earthquake disaster scenarios, with a potential benefit or cost ranging from one to ten, which facilitate advance planning for the expected and the unexpected (i.e. "the surprises").
13. Siting criteria and land-use, with a potential benefit or cost ranging from one to ten, which avoid surface fault rupture, soil failure and soil-structure resonance.
14. Relocation and rerouting, with a potential benefit or cost ranging from one to ten, which reduce the likelihood of damage to communities, buildings, and important lifelines.
15. Protective works, with a potential benefit or cost ranging from one to ten, which prevent release of hazardous materials.
16. Changes in use and density of use, with a potential benefit/cost ranging from one to ten, which reduce the likelihood of loss of function; loss of life and injuries.

7. CONCLUSIONS

The time is right for all earthquake-prone communities to collaborate in order to increase their capacity to anticipate the consequences of earthquakes, devise and enact mitigation measures to eliminate or reduce community-specific vulnerabilities at the source, and to decrease the likelihood of an earthquake disaster. Reduction of community vulnerability, an increasingly urgent goal for every nation during the 21st century, is feasible and closer to realization now because of the scientific, technical, and political advances made during the 1990s under the auspices of the IDNDR.

The key action for the 21st century is for community professionals and community policy makers and stakeholders to anticipate the need and to collaborate in solving their problems. Seismic zonation, a policy tool to integrate risk assessment and risk management before permitting new construction, is now an option that all earthquake-prone communities can consider. The next step, a policy tool for linking seismic zonation with performance codes and standards is also feasible now and is perhaps the best way to move the state-of-the-art and the state-of-practice forward.

REFERENCE

Hays, W.W., B. Mohammadioun and J. Mohammadioun, 1998: *Seismic zonation: a framework for linking earthquake risk assessment and earthquake risk management*, Ouest Editions, Nantes, France, 147 p.