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The cost of seismic structural damage and preventive action

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Abstract

Purpose – This paper first aims to estimate the economic loss due to an earthquake, such as building-related losses, the damage of debris generation and fire, and the social impact. Then, it seeks to evaluate the feasibility of retrofit to prevent buildings from seismic structural damages.

Design/methodology/approach – The HAZUS software is used for the seismic loss estimation using default demographic data, which were obtained from San Francisco Assessor record. The HAZUS estimates the damage using the earthquake of 6.7 magnitude. Based on the HAZUS report incorporated with probabilistic scenarios of earthquakes, Federal Emergency Management Agency (FEMA) guidelines are used to calculate the cost of structural rehabilitation in San Francisco.

Findings – It is recommended that either Options 1 and 3 or Options 2 and 3 provided by FEMA 156 and 157 respectively should be used to calculate the cost of seismic rehabilitation of a structure. The results provide estimated costs of retrofit plans for different types of existing buildings.

Practical implications – The implementation of quantitative and computer methods in the field of natural hazard management is demonstrated. The outcome provides economic guidelines for assessment and prevention (or reduction) of possible seismic loss and building damage.

Originality/value – The study may be a useful reference for retrofit plans for homeowners and business management. The cost estimation also can help government establish or revise some policies properly to provide homeowners with economic incentives (e.g. tax reduction, low interest loan) in retrofitting their homes.

Keywords Earthquakes, Emergency measures, Rehabilitation

Paper type Case study

1. Introduction

Earthquakes are unpredictable, and they are one of the deadliest activities of nature. Earthquakes are a global phenomenon and problem, causing tremendous property damage and life loss around the world each year. Hundreds of millions of people

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throughout the world live with a significant risk of seismic damage to their property, and under the threat of loss of life. In the future, damage will increase, primarily due to two factors: first, constant population growth in urban areas that are prone to earthquakes and second, the vulnerability of the aging building stock. Even buildings that were constructed within the past 20 years are vulnerable to earthquakes. Although we cannot prevent the occurrence of earthquakes, it is possible to mitigate the effects of strong tremors, to reduce loss of life, injuries and damages.

There are geological differences among areas of the San Francisco city. The damage due to a specific earthquake needs to be evaluated separately for each separate area. The California Department of Conservation, a Division of Mines and Geology (DMG), has delineated Seismic Hazard Zones in the city of San Francisco. The purpose is to reduce the threat to public health and safety, and minimize the loss of life and property, by identifying and mitigating seismic hazards. San Francisco itself has suffered from several major earthquakes such as the 1906 San Francisco Earthquake and the 1989 Loma Prieta Earthquake. Based on the research conducted since the 1989 Loma Prieta earthquake, US Geological Survey (USGS) (www.usgs.gov) and other establishments conclude that there is a 70 per cent probability of at least one magnitude 6.7 or greater quake, capable of causing widespread damage, striking the San Francisco Bay region before 2030. However, according to the survey conducted by USGS, the majority of buildings in the regions of high seismicity in the USA do not meet current seismic code requirements, and many of these buildings are vulnerable to damage and collapse in the event of an earthquake. So seismic rehabilitation of existing buildings has received increasing attention, and seismic evaluation and rehabilitation guidelines have become one important subject for the Federal Emergency Management Agency (FEMA) (www.fema.gov) and the State of California, especially because of the need of a unified standard of seismic retrofit.

Before the development of guidelines for retrofitting structures, seismic damage to buildings, and the possible losses directly or indirectly associated with these damages, should be first understood. Then, damage prevention and recovery plans can be constructed, and the cost of rehabilitation can be appropriately estimated. This paper uses San Francisco as a case study in assessment of earthquake generated loss and for cost estimation of seismic retrofit. The latest software program HAZUS-MH MR1 (2005 version) for loss estimation is introduced. It applies the earthquake model that considers the damage and loss to buildings, critical facilities (e.g. hospitals, schools, fire stations, police stations, dams), transportation lifelines (e.g. highways, railways), utility lifelines (e.g. potable water, natural gas) and population, based on scenario or probabilistic earthquakes. In this paper we focus on earthquake-induced structural damages and building-related losses. However, debris generation, fire-following damage, casualties, shelter requirements and indirect economic impact are also discussed. Following that, we calculate the typical cost for seismic rehabilitation of the building using three options provided by FEMA 156 and 157 (www.fema.gov/hazards/earthquakes/nehrp/fema-156.shtm), Typical Costs for Seismic Rehabilitation of Existing Buildings guidelines, to provide the management with a numerical economic guideline. Note that “typical cost” is defined as the mean structural cost of seismic rehabilitation of a building. It does not include the cost of replacing architectural finishes. Option 1 takes into consideration area adjustment, location adjustment and inflation rate. Option 2 takes into account the National Earthquake

Hazards Reduction Program (NEHRP) seismic map area performance objective, besides the factors considered in Option 1. Option 3 is the most statistically rigorous option which considers more factors than the other two, such as the building area and age, number of stories, seismicity of the area, performance objective, occupancy condition… etc. However, using either Options 1 and 3 or Options 2 and 3 to estimate the cost of seismic rehabilitation of structures is recommended. This study demonstrates the implementation of quantitative and computer methods in the field of natural hazard management, and provides a numerical economic example for assessment, prevention, or reduction of possible loss and damage.

2. Methods of earthquake risk analysis

Earthquake risk analysis involves quantitative estimation of damage, casualties and costs within a specified geographic area over a certain period of time, should a hazard of various strength levels occur. There are two types of risk analysis – scenario and probabilistic.

2.1 Scenario earthquake analysis and results

Scenario earthquake stands for the earthquake that is likely to occur. It is generated for a hypothetical scenario set in the future. The parameters needed for this generation are based on information of historic earthquakes and interpretation of the tectonic setting. More precisely, the concept behind it is to estimate how serious a disaster would be today, if a historic earthquake were to repeat itself, or if a similarly large event were to occur in a seismic gap next to a historic rupture. The location could be selected in a segment of a plate boundary that has not ruptured recently, however, in which an earthquake rupture happened nearby not long ago (i.e. a seismic gap). The magnitude can be derived from the length of the gap, or by selecting the mean magnitude of the historic large earthquakes in the vicinity. The scenario-based analysis is limited to a particular location and scale of earthquake.

California Geological Survey (CGS) has estimated economic loss of building damage for various earthquake scenarios. The damage and loss are estimated based on seismic scenarios on known faults in the region. The liquefaction effect, landslide, fire and ground rupture are not considered. Also, the estimate is limited to ground motion induced loss to buildings. The losses due to other elements of the built environment, such as transportation, lifeline and communication facilities, are not reported. Furthermore, CGS estimated only the direct economic losses due to building damage, which consist of capital stock loss and income loss. Indirect economic losses like the losses due to various forms of post-earthquake socioeconomic disruptions (e.g. employment and income, insurance and financial aids, construction, production and import-export of goods and services) are not included.

From the results of the CGS report, among the 34 scenario earthquakes, a repeat of the 1906 San Francisco earthquake would result in the largest economic loss for the ten bay area counties. It would rupture four segments of the San Andreas Fault and cause approximately $54 billion of economic loss due to building damage. There are other scenario earthquakes on the San Andreas Fault, rupturing different combinations of these four segments. Should one occur, it would result in an estimated loss ranging from a few billion dollars to $50 billion. Other earthquakes potentially damaging the San Francisco Bay Area are a magnitude 6.9 event rupturing the entire Hayward Fault causing a $23 billion loss, and a magnitude 7.3 one rupturing the entire Hayward Fault and the Rodgers Creek Fault causing a $34 billion loss. For each scenario, an estimation map can be constructed to show the geographical distribution of estimated economic loss from building damage, so we could plan mitigation programs for each county. Combined with statistical analysis of the housing damage (based on the result of the 1989 Loma Prieta and 1994 Northridge earthquakes), another example of estimation of uninhabitable housing units for selected earthquake scenarios is shown by Association of Bay Area Government's (ABAG) (www.abag.ca.gov) modeling (see ABAG's *Shaken Awake!,* 1996, www.abag.ca.gov/bayarea/eqmaps/shelpop/awaketoc.html).

2.2 Probabilistic earthquake analysis and results

The probabilistic seismic hazard models consider the uncertainty in the scale and location of an earthquake and the resulting ground motions that can affect a particular site. To address the uncertainty element in earthquake behavior, we need to calculate the probabilities for each possible occurrence of this behavior. The calculation involves several issues, for example, defining fault segments and choosing proper statistical models. The aim of this type of analysis is to provide the best probabilistic estimates of future earthquakes and ground motions using the information from past earthquakes, (e.g. the tectonic framework, the attenuation and scaling properties of earthquakes), and thus evaluate the potential seismic effects.

Based on the study of the Working Group on California Earthquake Probabilities in 1999 (http://geopubs.wr.usgs.gov/ open-file/of99-517), there is a 70 per cent (± 10 per cent) probability of a strong earthquake striking the greater San Francisco bay region by magnitude 6.7 or greater earthquake by 2030. In addition, by 2030 there is a 30 per cent chance of one or more magnitude 6.7 or greater earthquakes on the Calaveras, Concord-Green Valley, Mount Diablo Thrust and Greenville Faults (located in the San Francisco bay region's eastern valleys), a 25 per cent chance of one or more magnitude 6.7 or greater earthquakes in the region of Pacific coast in San Mateo, Santa Cruz and Monterey Counties (located between San Gregorio Fault and San Andreas Faults), and an 80 per cent chance of one or more magnitude 6 to 6.6 earthquakes occurring in the San Francisco bay region.

3. Seismic losses in San Francisco – using the HAZUS report

If the probability of an earthquake occurrence in a given region is considerable, it is very important to understand seismic risks that may affect the physical, social and economic components of the region. The latest software package HAZUS-MH (www.fema.gov/hazards/earthquakes/nehrp/fema-255.shtm) MR1 from FEMA is applied here for seismic risk assessment and loss estimation. It uses ground motion and ground failure information to calculate losses. This section summarizes the results from the report generated by HAZUS-MH MR1, based on the earthquake of 6.7 magnitudes.

3.1 Introduction to HAZUS

In response to the need for nationally consistent earthquake risk and loss estimation methodology, FEMA has developed Hazards US (HAZUS), a computer-based analysis, in cooperation with the National Institute of Building Sciences (NIBS). HAZUS works with the latest version of ESRI's geographic information system software (ArcGIS9.0

SP1) to map and display hazard data. Using HAZUS's mathematical model along with information of building inventory, geology and magnitude of potential earthquake, as well as economic data available for the location, the estimation of damage to buildings and related economic loss can be made.

Basically, HAZUS estimates earthquakes via three levels. Level 1 is a rough estimate based on the national data included in HAZUS software. Level 2 involves a more accurate estimate based on professional judgment and geotechnical input that adjusts the HAZUS methodology to the specific condition and community. Level 3 provides the most accurate estimate based on detailed engineering and geotechnical inputs.

FEMA introduced HAZUS-MH (Multi Hazard) in 2004, which can be used to estimate losses from earthquakes, flood and hurricane winds. This new method also provides a link to the models for man-made hazards. HAZUS-MH MR1 is the latest version of HAZUS and is used in this paper to estimate damage to structures and building-related losses based on scenario or probabilistic earthquake analysis. Debris generation, fire-following damage, casualties, shelter requirements and indirect economic impact (employment and income) will be also considered.

3.2 Data collection and findings from the HAZUS report

Since the database management system of HAZUS-MH MR1 has a size limit of 2 GB per database, the size of the region is limited to 2000 census tracts. This study uses the information of building inventory provided by the San Francisco Assessor's office and geotechnical data taken from the USGS. It should be noted that there are limitations using HAZUS:

- The earthquake model has done less well in estimating more detailed results, such as the number of buildings or bridges experiencing different degrees of damage.
- The earthquake model assumes the same soil condition for all locations, though the geographic distribution of damage may be influenced markedly by local soil conditions.
- The results of loss estimation for an individual building must be considered as an average for a group of similar buildings, because it is frequently noted that nominally similar buildings have experienced vastly different damage and losses during an earthquake.
- Based on several initial studies, the losses from small magnitude earthquakes (less than magnitude 6.0) centered within an extensive urban region appear to be overestimated.
- There may be discrepancies in motions predicted within small areas immediately adjacent to faults, because of approximations used in modeling of faults in California.

The geographic size of the region is 45.55 square miles (mi^2) and contains 175 census tracts. There are over 329,000 households in the region and it has a total population of 776,596 people, according to the 2000 Assessor's record. In addition, there are approximately 167,000 buildings in the region, with a total replacement value (or inventory value) of $65,880 million.

To calculate fire-following damage, the following default parameters are used:

- Number of simulations = 4.
- Total simulation time = 120 min.
- Time increment = 5 min.
- Engine speed = 15 mph.
- Wind speed = 10 mph.

To calculate debris, we have used the default percentage of debris generated for each structure type. Calculation of shelter requirements is based on the following parameters:

- The number of displaced households.
- Number of people in the census tract.
- Number of households in the census tract.
- Income breakdown of households in the census tract.
- Ethnicity of households in the census tract.
- Percentage of homeowners and renters in the census tract.
- Age breakdown of households in the census tract.

After the HAZUS report is generated, we summarize the findings as follows:

- In terms of building construction types found in the region, wood frame construction makes up 91 per cent of the building inventory. Approximately 96 per cent of the buildings and 76 per cent of the building value are associated with residential housing. There are about 38,937 buildings that will be at least moderately damaged by the earthquake. This is over 23 per cent of the total number of buildings in the region. There are an estimated 1,218 buildings that will be damaged beyond repair.
- The total building-related economic losses in San Francisco after the earthquake would be $7,284 million, which include direct building losses (the estimated costs to repair or replace the damage caused to the building and its contents) and business interruption losses (associated with inability to operate a business).
- Building type Concrete Shear Wall Low Rise (C2L) and Wood structures have a higher chance of being damaged.
- There will be 34 ignitions that burn about 0.22 mi^2 (0.48 per cent of the region's total area). Fires will displace about 4,084 people and consume about $332 million of building value.
- There will be two million tons of debris generated as a result of building damage, which will require 80,000 truckloads to remove. 13,519 households will be displaced due to the earthquake and out of these, 3,265 people will seek temporary shelter in public shelters.
- Casualties (deaths and various degrees of injuries) from the earthquake will be higher at 2:00 pm because of high commercial, educational and industrial loads.
- The impact on employment and income (indirect economic impact) after the earthquake could last for at least three years.

- South Central District is the densest area in terms of single family residential wooden buildings, but the loss due to earthquake is not significant compared to other districts.
- The probability for building damage is distributed almost equally in the San Francisco region except in the Richmond district located adjacent to Western Addition District. The damage assessment has been conducted considering the design of building using California Building Code 2001.
- The damage to buildings downtown, (the triangle area between Market Street, California Street and Powel Street), is greater than other areas because of considerable non-structural damage and content damage. The monetary value of the total loss estimated from different types of structures in the downtown is shown in Table I.
- Fire demand (the potential for post-earthquake fires) is greater in the South of Market, Western Addition and Buena Vista Planning Districts, and in the triangle area between Market Street, California Street and Powel Street.

4. Cost of structural rehabilitation in San Francisco

We use FEMA guidelines to calculate the cost of rehabilitation in San Francisco based on the HAZUS report for probabilistic earthquakes. FEMA 156 and 157 (the second edition by FEMA in February 1995) provide three options for determination of typical cost of seismic rehabilitation of buildings. The main two types of cost used in FEMA 156 and 157 are direct costs and indirect costs. The cost calculated here focuses on the structural retrofit cost and does not include the cost of replacing architectural finishes. Note that the unit cost is expressed in terms of dollars per square foot ($\$/\text{ft}^2$).

4.1 Types of rehabilitation costs

The direct costs are those incurred by the owner in the actual rehabilitation work. Direct cost is further divided into construction costs and non-construction costs. Construction cost is the cost paid to the contractor and non-construction cost is the cost paid otherwise, in order to finish the project. Construction cost is further subdivided into seismic related construction cost and non-seismic related construction cost.

Seismic related construction cost includes:

- Structural and non-structural rehabilitation costs.
- Demolition and restoration costs, i.e. the cost for architectural work necessitated by the structural work, such as demolition and replacement costs for wall and ceiling finishes, removal and reinstallation of electrical and mechanical

	\$ ('000s)
Concrete	193,312.79
Masonry	169,601.57
Mobile home	213.39
Wood	135,459.84
Steel	86,744.54
Total	585,332.13

Table I. The monetary value of the total loss (in thousands) equipment, and re-roofing as necessary to install the lateral force resisting elements in the building.

- Cost to repair existing elements used as part of the lateral force resisting system.

Non-seismic related construction cost includes:

- Fire and life safety provisions.
- Mechanical, plumbing and electrical renovation.
- Architectural renovation.
- Damage repair costs, i.e. the cost to repair structural damage from previous earthquakes, settlement, or deterioration in elements of the building not affecting the seismic performance of the building.
- Hazardous material removal costs.
- Costs to provide access for the disabled.

As for non-construction costs, they generally include project management costs, architectural and engineering design fees, testing and permitting costs, and relocation costs.

Indirect costs are costs which come about as a result of rehabilitation work and affect the owner, the tenants, the community, or other related groups. Indirect costs include financing, occupant interruption/relocation, increased rents, change in property value and reduction in affordable housing.

4.2 Factors affecting rehabilitation

The main eight factors that affect the cost of rehabilitation are addressed below:

1. *Seismicity*. Costs of rehabilitation are dependent on the areas on the seismic map because it dictates the design forces, which in turn, often influences the scope of structural work.
2. *Performance objective*. The performance objective is defined under three general categories: life safety, damage control and immediate occupancy. The performance objective determines the level of rehabilitation for a building, which in turn influences the cost of the rehabilitation. Life safety allows for unrepairable damage as long as life is not jeopardized and egress routes are not blocked. Damage control is intended to protect some feature or function of the building beyond life safety, such as protecting building contents or preventing the release of toxic materials. Immediate occupancy is characterized by minimal post-earthquake disruption with some non-structural repairs and cleanup.
3. *Structural system*. Different structural systems lead to different costs.
4. *Occupancy class*. Some estimates have attributed a cost impact to the occupancy type of a building. For example, assembly buildings with large open spaces often require special or more unusual rehabilitation solutions. Industrial buildings tend to have higher story heights, forcing more out-of-plane bracing, but they have fewer openings in the existing masonry walls, potentially allowing for less in-plane strengthening. They may also have lower architectural refinishing costs because they lack interior finishes. In general, the occupancy classifications includes:

- assembly-theaters, churches, or other assembly buildings;
- commercial/office – all buildings used for the transaction of business, the rendering of professional services, or other services that involve limited stocks of goods or merchandise;
- factory/industrial/warehouse-factories, assembling plants, industrial laboratories, storage, etc.;
- institutional/educational-schools, hospitals, prisons, etc.;
- mall/retail-retail stores or shopping malls;
- parking-parking garages or structures; and
- residential-houses, hotels, and apartments.

(5) *Building area*.

(6) *Number of stories*. The number of stories can have a significant cost impact in most estimates. In taller buildings, overturning and shear forces may require a proportionately greater cost to improve the foundation compared to shorter buildings.

(7) *Building age characteristics*. Age can be an important cost factor because older buildings often require more new lateral elements and the existing structural system may suffer deterioration. Also, the presence of ornamentation or other significant architectural or historic fabric will influence the design options available to the engineer.

(8) *Occupancy condition*. Cost of seismic rehabilitation depends on occupants in place, occupants temporarily removed or vacant buildings.

4.3 Determination of typical cost for seismic rehabilitation of buildings

FEMA 156 and 157 provide three options for estimation of seismic rehabilitation depending on building inventory information available. Option 1 uses the information of building group (see Appendix 1, Tables AI-AIII), building area, year of construction and the number of buildings in inventory. Option 2 requires the information needed for Option 1 plus the NEHRP seismic map area and the performance objective(s) (Appendix 2, Table AIV). In addition to the information needed for Option 2, Option 3 needs the number of stories, occupancy class and occupancy condition.

For Option 1, the typical structural cost is estimated using the equation:

$$C = C_1 C_2 C_L C_T$$

where:

C = typical structural cost to seismically rehabilitate a building (\$/ft^2).

C_1 = building group mean cost.

C_2 = area adjustment factor.

C_L = location adjustment factor (1.12 for San Francisco).

C_T = time adjustment factor.

The data of C_1 and C_2 is shown in Appendix 1. Therefore, for the year 2004:

C = 1.3888 C_1C_2 (2 per cent inflation rate).

C = 1.7248 C_1C_2 (4 per cent inflation rate).

C = 2.1280 C_1C_2 (6 per cent inflation rate).

C = 2.6096 C_1C_2 (8 per cent inflation rate).

For example, based on inflation rate 4 per cent, the typical structural cost of the medium size steel moment frame building in San Francisco in 2004 is $C = 1.7248 \times 18.86 \times 1.14\$/\mathrm{ft}^2$. ($C_1 = 18.86$ for steel moment frame and $C_2 = 1.14$ for medium size group 5 buildings according to Appendix 1). Table II lists the typical costs for different types of buildings. The inflation rate is taken as 4 per cent.

For Option 2, the typical structural cost is estimated using the equation:

$$C = C_1C_2C_3C_LC_T$$

where C_3 is the seismicity/performance objective adjustment factor (see Appendix 2) and other variables follow the same definitions in Option 1. The expected seismic activity of the building site must be quantified in terms of the NEHRP seismic area. The performance level depends on the occupancy category which should be decided by the user. For example, the typical structural cost of the medium size steel moment frame building in San Francisco (very high seismicity) for immediate occupancy structures in 2004, based on inflation rate 4 per cent, is $C = 1.7248 \times 18.86 \times 1.14 \times 2.08 = 77.126\$/\mathrm{ft}^2$. Note that for this case, we have $C_1 = 18.86$ and $C_2 = 1.14$ as mentioned in the example of Option 1, and $C_3 = 2.08$ for immediate occupancy (see Appendix 2). Tables III-V give the typical costs for the performance objectives of life safety, damage control and immediate occupancy, respectively, for different types of buildings using an inflation rate of 4 per cent.

For Option 3, the typical structural cost is estimated using the equation:

$$C = Cc \cdot (\mathrm{area})^{X1} \cdot (\mathrm{no.ofstories})^{X3} \cdot (\mathrm{age})^{X2} \cdot X4 \cdot X5 \cdot X6$$

where:

Cc = Statistically based constant.

$X2$ = Statistically based variable, whose value depends on the building group.

$X3$ = Statistically based variable, whose value depends on the building group.

$X4$ = Statistically based variable, whose value depends on the building seismicity and performance objective and the building group.

$X5$ = Statistically based variable, whose value depends on the building occupancy class and the building group.

$X6$ = Statistically based variable, whose value depends on the occupancy condition during seismic rehabilitation and the building group.

The values of Cc and the regression parameters $X1$ through $X6$ are given in Appendix 3 (Tables AV-AVIII). Again, Tables VI-VIII summarize the typical costs for the

Table II. Typical structural costs using Option 1 (4 per cent inflation rate)

Building group	Building types	Typ.Struct. Cost \$/ft^2 Building size small 5,000 ft^2	Typ.Struct. Cost \$/ft^2 Building size medium 25,000 ft^2	Typ.Struct. Cost \$/ft^2 Building size large 75,000 ft^2	Typ.Struct. Cost \$/ft^2 Bld. size v.large 100,000 ft^2
1	Unreinforced masonry	26.64	26.37	25.05	21.10
2	Wood light frame wood (commercial or industrial)	20.56	21.62	27.13	34.76
3	Pre-cast concrete tilt-up walls reinforced masonry with metal or wood diaphragm	27.33	25.87	22.25	13.78
4	Concrete moment frame concrete frame with infill walls	37.64	36.60	34.88	29.01
5	Steel moment frame	37.73	37.08	35.46	27.00
6	Steel braced frame steel light frame	14.71	13.97	11.22	6.36
7	Steel frame with infill walls	43.07	42.65	41.00	36.03
8	Concrete shear wall pre-cast concrete frame with concrete shear walls reinforced masonry with precast concrete diaphragm	33.14	32.24	30.45	24.78

Table III.
Typical structural costs using Option 2 for life safety (4 per cent inflation rate)

Bld. Group	Building types	Typ.Struct. Cost $/ft^2 Building size small 5,000 ft^2	Typ.Struct. Cost $/ft^2 Building size medium 25,000 ft^2	Typ.Struct. Cost $/ft^2 Building size large 75,000 ft^2	Typ.Struct. Cost $/ft^2 Bld. size v.large 100,000 ft^2
1	Unreinforced masonry	31.44	31.12	29.56	24.9
2	Wood light frame wood (commercial or industrial)	24.26	25.51	32.01	41.01
3	Pre-cast concrete tilt-up walls reinforced masonry with metal or wood diaphragm	32.25	30.53	26.25	16.26
4	Concrete moment frame concrete frame with infill walls	44.42	43.18	41.16	34.23
5	Steel moment frame	44.52	43.75	41.84	31.86
6	Steel braced frame steel light frame	17.36	16.48	13.24	7.5
7	Steel frame with infill walls	50.82	50.33	48.38	42.52
8	Concrete shear wall pre-cast concrete frame with concrete shear walls reinforced masonry with precast concrete diaphragm	39.10	38.04	35.93	29.24

Table IV. Typical structural costs using Option 2 for damage control (4 per cent inflation rate)

Bld. Group	Building types	Typ.Struct. Cost \$/ft^2 Building size small 5,000 ft^2	Typ.Struct. Cost \$/ft^2 Building size medium 25,000 ft^2	Typ.Struct. Cost \$/ft^2 Building size large 75,000 ft^2	Typ.Struct. Cost \$/ft^2 Bld. size v.large 100,000 ft^2
1	Unreinforced masonry	38.09	37.71	35.83	30.17
2	Wood light frame wood (commercial or industrial)	29.40	30.92	38.80	49.71
3	Pre-cast concrete tilt-up walls reinforced masonry with metal or wood diaphragm	39.08	37.00	31.81	19.71
4	Concrete moment frame concrete frame with infill walls	53.82	52.34	49.87	41.48
5	Steel moment frame	53.96	53.03	50.70	38.61
6	Steel braced frame steel light frame	21.04	19.97	16.05	9.09
7	Steel frame with infill walls	61.59	61.00	58.63	51.52
8	Concrete shear wall pre-cast concrete frame with concrete shear walls reinforced masonry with pre-cast concrete diaphragm	47.39	46.11	43.55	35.44

Table V.
Typical structural costs using Option 2 for immediate occupancy (4 per cent inflation rate)

Bld. group	Building types	Typ.Struct. Cost $/ft^2 Building size small 5,000 ft^2	Typ.Struct. Cost $/ft^2 Building size medium 25,000 ft^2	Typ.Struct. Cost $/ft^2 Building size large 75,000 ft^2	Typ.Struct. Cost $/ft^2 Bld. size v.large 100,000 ft^2
1	Unreinforced masonry	55.40	54.85	52.11	43.88
2	Wood light frame wood (commercial or industrial)	42.77	44.97	56.44	72.31
3	Pre-cast concrete tilt-up walls reinforced masonry with metal or wood diaphragm	56.84	53.82	46.27	28.67
4	Concrete moment frame concrete frame with infill walls	78.29	76.13	72.54	60.33
5	Steel moment frame	78.49	77.13	73.75	56.16
6	Steel braced frame steel light frame	30.61	29.05	23.34	13.23
7	Steel frame with infill walls	89.58	88.72	85.28	74.94
8	Concrete shear wall pre-cast concrete frame with concrete shear walls reinforced masonry with pre-cast concrete diaphragm	68.93	67.07	63.34	51.54

Table VI. Typical structural cost of seismic rehabilitation using Option 3 for immediate occupancy

Building types	Number of storeys	Typ.Struct. Cost \$/ft^2 Building size small 5,000 ft^2 with different ages				Typ.Struct. Cost \$/ft^2 Building size medium 25,000 ft^2 with different ages				Typ.Struct. Cost \$/ft^2 Building size large 75,000 ft^2 with different ages				Typ.Struct. Cost \$/ft^2 Bld. size v.large 100,000 ft^2 with different ages			
		10	25	50	75	10	25	50	75	10	25	50	75	10	25	50	75
Unreinforced masonry	2	35.5	36.2	36.7	37.0	24.5	25.0	25.3	25.5	19.1	19.4	19.7	19.8	17.8	18.2	18.4	18.6
Wood light frame wood (commercial or industrial)	2	1.4	2.2	3.2	3.9	1.3	2.1	3.1	3.8	1.3	2.1	3.0	3.7	1.3	2.1	3.0	3.7
Pre-cast concrete tilt up-walls reinforced masonry with metal or wood diaphragm	2	57.2	99.1	150.2	191.6	37.6	65.2	98.8	126.1	28.3	49.0	74.3	94.7	26.2	45.5	68.9	87.9
Concrete moment frame concrete frame with infill walls	5	44.1	52.0	58.9	63.4	34.6	40.8	46.3	49.8	29.4	34.6	39.2	42.2	28.1	33.2	37.6	40.4
Steel moment frame	5	84.4	100.5	114.6	123.8	52.1	62.0	70.7	76.4	37.5	44.6	50.9	54.9	34.4	40.9	46.7	50.4
Steel braced frame steel light frame	5	11.5	7.3	5.2	4.2	9.7	6.1	4.3	3.5	8.6	5.4	3.8	3.1	8.3	5.2	3.7	3.0
Steel frame with infill walls	5	15.1	21.8	28.7	33.8	9.9	14.3	18.9	22.2	7.5	10.8	14.2	16.7	6.9	10.0	13.2	15.5
Concrete shear wall pre-cast concrete frame with concrete shear walls reinforced masonry with precast concrete diaphragm	5	63.8	72.5	79.9	84.6	40.7	46.2	50.9	53.9	29.9	34.0	37.4	39.6	27.6	31.4	34.5	36.6

Table VII. Typical structural cost of seismic rehabilitation using Option 3 for damage control

Building types	Number of storeys	Typ.Struct. Cost $/ft^2 Building size small 5,000 ft^2 with different ages				Typ.Struct. Cost $/ft^2 Building size medium 25,000 ft^2 with different ages				Typ.Struct. Cost $/ft^2 Building size large 75,000 ft^2 with different ages				Typ.Struct. Cost $/ft^2 Bld. size v.large 100,000 ft^2 with different ages			
		10	25	50	75	10	25	50	75	10	25	50	75	10	25	50	75
Unreinforced masonry	2	39.1	39.8	40.4	40.7	27.0	27.5	27.9	28.1	21.0	21.4	21.7	21.8	19.6	20.0	20.3	20.4
Wood light frame wood (commercial or industrial)	2	3.1	5.1	7.3	9.0	3.0	4.9	7.0	8.7	3.0	4.8	6.9	8.5	3.0	4.8	6.8	8.4
Pre-cast concrete tilt up walls reinforced masonry with metal or wood diaphragm	2	26.9	46.6	70.6	90.0	17.7	30.6	46.4	59.2	13.3	23.0	34.9	44.5	12.3	21.4	32.4	41.3
Concrete moment frame concrete frame with infill walls	5	21.4	25.3	28.6	30.8	16.8	19.8	22.5	24.2	14.3	16.8	19.1	20.5	13.7	16.1	18.3	19.6
Steel moment frame	5	76.2	90.7	103.5	111.7	47.0	56.0	63.8	69.0	33.8	40.2	45.9	49.6	31.0	36.9	42.1	45.5
Steel braced frame steel light frame	5	2.1	1.3	0.9	0.8	1.8	1.1	0.8	0.6	1.6	1.0	0.7	0.6	1.5	1.0	0.7	0.6
Steel frame with infill walls	5	13.7	19.8	26.1	30.7	9.0	13.0	17.2	20.2	6.8	9.8	12.9	15.2	6.3	9.1	12.0	14.1
Concrete shear wall pre-cast concrete frame with concrete shear walls reinforced masonry with pre-cast concrete diaphragm	5	54.3	61.8	68.1	72.1	34.6	39.4	43.4	45.9	25.5	28.9	31.9	33.8	23.5	26.7	29.4	31.1

Table VIII. Typical structural cost of seismic rehabilitation using Option 3 for life safety

Building types	Number of storeys	Typ.Struct. Cost \$/ft^2 Building size small 5,000 ft^2 with different ages				Typ.Struct. Cost \$/ft^2 Building size medium 25,000 ft^2 with different ages				Typ.Struct. Cost \$/ft^2 Building size large 75,000 ft^2 with different ages				Typ.Struct. Cost \$/ft^2 Bld. size v.large 100,000 ft^2 with different ages			
		10	25	50	75	10	25	50	75	10	25	50	75	10	25	50	75
Unreinforced masonry	2	9.7	9.9	10.0	10.1	6.7	6.8	6.9	7.0	5.2	5.3	5.4	5.4	4.9	5.0	5.0	5.1
Wood light frame wood (commercial or industrial)	2	1.6	2.6	3.8	4.6	1.6	2.5	3.6	4.5	1.5	2.5	3.6	4.4	1.5	2.5	3.5	4.4
Pre-cast concrete tilt up walls reinforced masonry with metal or wood diaphragm	2	18.6	32.3	48.9	62.4	12.3	21.2	32.2	41.0	9.2	16.0	24.2	30.8	8.5	14.8	22.4	28.6
Concrete moment frame concrete frame with infill walls	5	21.6	25.5	28.9	31.1	17.0	20.0	22.7	24.4	14.4	17.0	19.2	20.7	13.8	16.3	18.4	19.8
Steel moment frame	5	71.5	85.1	97.1	104.9	44.1	52.5	59.9	64.7	31.7	37.8	43.1	46.5	29.1	34.6	39.5	42.7
Steel braced frame steel light frame	5	4.4	2.8	2.0	1.6	3.7	2.3	1.6	1.3	3.3	2.1	1.5	1.2	3.2	2.0	1.4	1.2
Steel frame with infill walls	5	17.0	24.6	32.4	38.2	11.2	16.2	21.3	25.1	8.4	12.2	16.0	18.9	7.8	11.3	14.9	17.5
Concrete shear wall pre-cast concrete frame with concrete shear walls reinforced masonry with precast concrete diaphragm	5	34.4	39.1	43.1	45.7	21.9	24.9	27.5	29.1	16.1	18.3	20.2	21.4	14.9	16.9	18.6	19.7

performance objectives of life safety, damage control and immediate occupancy, respectively, for different types of buildings using inflation rate 4 per cent.

Option 3 is the most statistically rigorous option to produce the most accurate estimate of the typical structural cost of the building, since all the relevant parameters are included in the analysis. This procedure captures the behavior of the cost data as a function of several factors, such as the building age and area, seismicity, performance objective… etc. If Option 1 or Option 2 is used, the cost derived from the options needs to be adjusted for buildings of different ages, number of stories, occupancy condition etc.

5. Conclusion

This study first uses the probabilistic estimates of magnitude 6.7 earthquakes with the return period of 100 years to calculate damage in San Francisco via the HAZUS model, according to the 2000 Assessor's record. The numerical result measures the loss and damage to structures, and the immediate economic impact of an earthquake on the society. Seismic rehabilitation of existing buildings may be a direct solution to reducing and/or preventing seismic damage, and loss there from.

In order to develop a rehabilitation guideline and evaluate its economic feasibility, the necessary cost should be calculated. We estimate the cost of seismic rehabilitation for different types of buildings and structures using three options describe in FEMA 156 and 157. It is recommended that either Option 1 and 3 or Option 2 and 3 should be used to calculate the cost of seismic rehabilitation of a structure. The results shown in Tables II-VIII may be a useful reference for retrofit plans for homeowners and business management. For example, the cost of repair for a single family wooden two-story structure (assumed to be of small size and about 75 years old) would be just 20.56 $\$/\text{ft}^2$ using Option 1, 24.26 $\$/\text{ft}^2$ for life safety using Option 2, and 4.6 $\$/\text{ft}^2$ for life safety using Option 3. This implies that when there is a 75-year-old two-story residential wooden building of 1,000 ft^2, the cost of seismic repair will be only from \$4,600 to \$24,260 maximum to achieve the objective of life safety, quite reasonable if this can save someone's life or prevent the building from being totally damaged. Thus, homeowners in San Francisco may want to retrofit their homes very soon because of the possibility of seismic events in the near future. Moreover, the cost estimations above can help government establish or revise some policies properly to provide homeowners with economic incentives (e.g. tax reduction, low interest loan) in retrofitting their homes so that the impact of the earthquake on residential buildings can be significantly reduced in the future. We do not have any control over the occurrence of the earthquake, but we can certainly make our housing stock safer and prevent our society from considerable seismic losses by retrofitting those structures.

Further reading

Fema 255, 256, available at: www.fema.gov/hazards/earthquakes/nehrp/fema-255.shtm

Seismic Hazard Evaluation of City & County of San Francisco, California (n.d.), Department of Conservation, Division of Mines & Geology (DMG), available at: www.consrv.ca.gov/dmg

USGS (2003), *Earthquake Probabilities in the San Francisco Bay Region: 2002-2031*, US Geological Survey, OFR 03-214, Reston, VA.

Appendix 1

Building group	Model	Building types
1	URM	Unreinforced masonry
2	W1 W2	Wood light frame Wood (commercial or industrial)
3	PC1 RM1	Pre-cast concrete tilt-up walls Reinforced masonry with metal or wood diaphragm
4	C1 C3	Concrete moment frame Concrete frame with infill walls
5	S1	Steel moment frame
6	S2 S3	Steel braced frame Steel light frame
7	S5	Steel frame with infill walls
8	C2 PC2 RM2 S4	Concrete shear wall Pre-cast concrete frame with concrete shear walls Reinforced masonry with pre-cast concrete diaphragm

Table AI. Building model types and building group types used in FEMA 156 & 157

Building group	Building type	Group mean cost
1	URM	15.29
2	W1, W2	12.29
3	PC1, RM1	14.02
4	C1, C3	20.02
5	S1	18.86
6	S2, S3	7.23
7	S5	24.01
8	C2, PC2, RM2, S4	17.31

Table AII. Group mean cost (C_1)

	Building group							
Area (sq.ft)	1	2	3	4	5	6	7	8
Small	1.01	0.97	1.13	1.09	1.16	1.18	1.04	1.11
Medium	1	1.02	1.07	1.06	1.14	1.12	1.03	1.08
Large	0.95	1.28	0.92	1.01	1.09	0.9	0.99	1.02
Very large	0.8	1.64	0.57	0.84	0.83	0.51	0.87	0.83

Note: Where building sizes used are defined as follows: Small = Less than 10,000 ft^2; Medium = 10,000 to 49,999 ft^2; Large = 50,000 to 99,999 ft^2; Very large = 100,000 ft^2 or greater

Table AIII. Area adjustment factor (C_2)

Appendix 2

Table AIV.
Seismicity/performance objective adjustment factor

Seismicity	Performance objective Life safety	Damage control	Immediate occupancy
Low	0.61	0.71	1.21
Moderate	0.7	0.85	1.4
High	0.89	1.09	1.69
Very High	1.18	1.43	2.08

Appendix 3

Table AV.
Values of regression variables

		Building group							
Coeff.	Category[a]	1	2	3	4	5	6	7	8
Cc	–	151.9	1.2	13.5	36.9	182.5	137.6	59.2	86.5
X1	–	−0.23	−0.02	−0.26	−0.15	−0.30	−0.11	−0.26	−0.28
X2	–	0.02	0.52	0.60	0.18	0.19	−0.50	0.40	0.14
X3	–	0.28	−0.28	1.06	0.43	0.21	−0.71	0.40	0.53
X4	1	0.28	0.48	0.51	0.48	0.53	0.58	0.47	0.61
	2	2.65	0.61	0.41	2.55	0.46	0.73	1.20	0.64
	3	1.16	0.72	1.25	0.72	1.07	1.27	0.97	0.43
	4	0.57	1.31	0.70	1.03	1.22	0.90	1.74	1.02
	5	0.69	0.40	0.35	0.52	0.76	0.83	0.67	0.44
	6	0.57	0.67	1.03	0.52	0.14	0.30	0.32	2.27
	7	0.76	1.17	0.96	1.01	1.23	0.42	0.81	1.42
	8	2.30	2.53	1.01	1.02	1.30	0.43	1.40	1.61
	9	1.48	1.12	1.20	1.17	1.25	1.35	1.10	1.86
	10	1.28	1.31	1.16	0.62	2.71	3.21	1.25	1.38
	11	1.60	1.24	3.23	1.28	1.89	2.12	1.57	0.46
	12	2.09	1.10	2.15	2.10	1.44	2.36	1.54	1.89
X5	P	4.27	1.09	1.09	0.26	1.19	1.48	1.15	0.45
	M	0.76	0.43	0.59	4.50	0.45	0.56	0.85	0.36
	R	0.48	0.90	2.19	0.75	2.72	1.11	0.32	1.09
	F	0.98	0.91	0.99	1.03	0.39	0.54	0.96	2.21
	I	0.97	1.35	1.00	0.82	1.29	0.47	1.17	0.96
	C	0.82	0.94	1.47	1.01	0.81	0.73	2.48	1.25
	A	0.83	2.22	0.53	1.33	0.91	4.77	1.33	2.16
X6	IP	0.69	1.78	1.00	0.77	1.11	0.63	0.93	0.69
	TR	1.12	1.13	0.96	1.44	1.28	1.94	1.08	1.21
	V	1.30	0.50	1.04	0.90	0.70	0.81	0.99	1.20

Note: [a] see Tables AVI-AVIII

Seismicity	Performance objective Life safety	Damage control	Immediate occupancy
Low	1	5	9
Moderate	2	6	10
High	3	7	11
Very high	4	8	12

Table AVI. Category for constant *X4*

Class	Description
A	Assembly
C	Commercial/office
F	Factory/industrial
I	Institutional/educational
M	Mall/retail
P	Parking
R	Residential

Table AVII. Occupancy class

Class	Description
IP	Occupants-in-place
TR	Occupants temporarily removed
V	Building vacant

Table AVIII. Occupancy condition

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