Seismic Hazard and Risk Assessment : Some Case Studies

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1. Introduction

Evaluation of seismic risk depends, in general, on the identification and characterization of: (1) the nature and geographical extent of the hazard; (2) the inventory (description, geographical distribution and value) of the property and/or people exposed to the hazard; and (3) the degree of damage or amount of life loss that is likely to be associated with a certain level or intensity of hazard (the vulnerability). In practice all of these parameters are difficult to assess and consequently the accuracy of risk assessment is a considerable problem. This paper examines several methods of hazard estimation, inventory development and risk assessment. Examples of hazard and risk assessment in three urban areas of the United States that have the potential for serious losses are discussed.

2. Methods of risk assessment

Risk can be estimated using either deterministic or probabilistic techniques or by hypothesizing the occurrence of a single earthquake or an ensemble of earthquakes. The steps in a typical deterministic risk calculation are shown in Figure 1. In Figure 1, the estimated ground motion and vulnerability (loss function) is represented in terms of Modified Mercalli intensity. If the distribution of ground motion and surface faulting can be approximated from existing isoseismal maps and the vulnerability estimated from existing studies of earthquake damage, the economic losses associated with a single earthquake or an ensemble of earthquakes can be estimated. A typical probabilistic hazard calculation is shown in Figure 2. In Figure 2, the seismicity is grouped geographically into "sources" (Figure 2A). The earthquakes may be considered either point sources or faults. The statistics of historical earthquake occurrence for each "source" are evaluated (Figure 2B). Using suitable attenuation functions, the cumulative probability distribution of ground motion for all sites of interest is determined (Figure 2C) and the probability of occurrence of a certain level of ground motion (intensity) is calculated (Figure 2D). $F_{\max,i}(I)$ is the extreme probability. The model shown assumes that earthquakes occur in time

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Figure 1 : Typical deterministic loss calculation. The model is based on the description of earthquake size in terms of maximum intensity (I_0), ground motion attenuation (I) and fault rupture length (L) as a function of magnitude (M).

according to a Poisson model. The risk (or loss) can be calculated using the same type of model and substituting loss as a function of distance for intensity attenuation in Figure 2B. A more complete discussion of probabilistic hazard evaluation may be found in Algermissen and others [1982].

3. Building classification

The building classification discussed here is one developed by K. V. Steinbrugge for loss studies (Steinbrugge and others [1969], Algermissen and others [1978]). A brief summary of the classes is given in Table 1 and representative vulnerability curves are

Figure 2 : Elements of typical probabilistic hazard calculation :

- (A) Typical Source areas and grid of points at which the hazard is to be computed.
- (B) Statistical analysis of seismicity data and typical attenuation curves.
- (C) Cumulative conditional probability distribution of intensity.
- (D) The extreme probability $F_{\text{max},t}(I)$ for various intensities and exposure times (T).

shown in Figure 3. Percent loss shown as the ordinate in Figure 3 is defined here to mean the average percentage of the total actual cash value required to fully repair in kind any building of a particular class experiencing ground motion represented by a particular degree of the Modified Mercalli (MM) Intensity Scale. The measure of the intensity of ground shaking used in this study is the (MM) intensity scale (Wood and Neumann [1931]).

*Table 1 : Notation used to identify building classes
and brief description of building classes*

Building Class	Brief description of building subclasses
1A-1	Wood frame and stuccoed frame dwellings regardless of area and height
1A-2	Wood frame and stuccoed frame buildings, other than dwellings, which do not exceed 3 stories in height and do not exceed 3,000 square feet in ground floor area
1A-3	Wood frame and stuccoed frame structures which do not exceed 3 stories in height regardless of area
1B	Wood frame and stuccoed frame buildings not qualifying under class 1A
2A	One story all metal ; floor area less than 20,000 ft ²
2B	All metal buildings not under 2A
3A	Steel frame, superior damage control features
3B	Steel frame, ordinary damage control features
3C	Steel frame, intermediate damage control features (between 3A and 3B)
3D	Steel frame, floors and roofs not concrete
4A	Reinforced concrete, superior damage control features
4B	Reinforced concrete, ordinary damage control features
4C	Reinforced concrete, intermediate damage control features (between 4A and 4B)
4D	Reinforced concrete, precast reinforced concrete, lift slab
4E	Reinforced concrete, floors and roofs not concrete
5A	Mixed construction, small buildings and dwellings
5B	Mixed construction, superior damage control features
5C	Mixed construction, ordinary damage control features
5D	Mixed construction, intermediate damage control features
5E	Mixed construction, unreinforced masonry
6	Buildings specifically designed to be earthquake resistant

There are a number of other parameters that have been used to express ground motion that are more quantitative in nature such as peak ground acceleration and velocity, spectral amplitude, etc. The advantages and disadvantages of using intensity will be discussed later.

It is important to note that the building classification used here for risk studies is based on the type of construction. Building classifications based on occupancy are unsuitable for estimation of economic loss because of the wide variation in vulnerability of the various construction types.

Figure 3 : Modified Mercalli intensity-loss relationship (by class of construction) used in this study. Brief descriptions of the various classes may be found in table 1.

4. Risk assessment – Salt Lake City, Utah

4.1. Seismic setting

Salt Lake City is an important regional center with a metropolitan area population (1980) of 163,000 and a regional population of about 620,000. The area considered in this

Figure 4 : Salt Lake City urban area. Only the area labelled "Salt Lake City" is considered in this paper. The large numbered blocks are indexes to census tracks.

study is shown in Figure 4. It lies along a trend of nearly north-south earthquake activity known as the Intermountain Seismic Zone (Figure 5). The city is on the boundary between the Rocky Mountains and the Basin and Range physiographic provinces. The boundary between the provinces is also marked by the Wasatch fault zone (Figure 6) which, from geological investigations, is thought to have been the loci of a number of large earthquakes during the past 10,000 years (Holocene time). Large earthquakes have not, however,

Figure 5 : Seismicity of the western United States showing the Intermountain Seismic Zone. Stars indicate maximum MM intensities of IX or greater ; triangles, VII-VIII ; squares, V-VI.

occurred on the fault since the settlement of the area in the 1850's. Segments of the Wasatch fault pass through Salt Lake City. The most important large (magnitude $M_s = 6.0-6.5$) earthquakes during historical time have occurred since 1934 about 130-150 km northwest of Salt Lake City near the north shore of the Great Salt Lake.

Assessment of seismic hazard for Salt Lake City is complicated because : (1) the city lies astride a zone of known historical seismicity and Holocene faulting but has not experienced any severe earthquake damage ; and, (2) segments of the geologically active Wasatch fault pass through the city although historical seismicity on the fault is low.

Figure 6: Location map showing physiographic provinces and the Wasatch fault.

4.2. Hazard estimates

Several hazard assessments of the city have been made. Figure 7 shows a regional probabilistic ground acceleration map completed in 1976 (Algermissen and Perkins [1976]) as part of a national seismic hazard mapping effort. A 50 year exposure time, 90 percent extreme probability map of expected Modified Mercalli intensity has been prepared using the same seismic source zones, earthquake occurrence rates, etc. as in the 1976 acceleration map. This probabilistic intensity map is shown in Figure 8. The national hazard map prepared in 1976 was extensively revised in 1982 with the completion of

Figure 7 : Maximum acceleration in rock in a 50 year period, 90 percent extreme probability (Algermissen and Perkins [1976]).

probabilistic acceleration and velocity maps for exposure times of 10, 50 and 250 years and an extreme probability of 90 percent (Algermissen and others [1982]). The 1982, 50 year acceleration map (Figure 9), shows higher (.28g as compared with .21g) accelerations in the Salt Lake City area than the comparable 1976 acceleration map because of the increased appreciation of prehistoric earthquake activity on the Wasatch fault that has been inferred from Holocene faulting.

In addition to the regional studies of expected ground motion in the Salt Lake City area, a comprehensive investigation of local site amplification has been underway since 1975 (Hays and others [1978]). Figure 10 shows the average relative ground response in

Figure 8 : Maximum MM intensity in average ground in 50 years, 90 percent extreme probability.

the 0.1–0.2 second period range in the Salt Lake City area. The contours of ground response are relative to the response on hard rock (Station 7, Figure 10). The relative responses were obtained by recording ground motions simultaneously at a number of

Figure 9: Maximum acceleration (percent of the acceleration of gravity) in rock in a 50 year period, 90 percent extreme probability (Algermissen and others [1982]).

stations. These ground motions were produced by small earthquakes and mine blasts in the vicinity of the city. Spectral ratios (the ratio of ground amplitudes recorded on sites through the city to those recorded on hard rock) were then computed and averaged in the period ranges of interest and the results contoured.

4.3. Inventory

A program supervised by K. V. Steinbrugge for the U.S. Geological Survey was begun in 1974 to develop a detailed inventory of building by class of construction in Salt Lake City. For one to four family dwellings and for population distribution, the best source of

Figure 10: Ground response based on instrumental field program. Area outlined by dashed line is study area (Hays and others [1978]).

data was found to be the United States Census data. The Census provides information on the numbers and geographical distribution of dwellings according to census tract. Census tracts are a convenient unit since the number of one to four family dwellings in each tract seldom exceeds 2000 units in the Salt Lake area. The most accurate cost estimates for housing was obtained from boards of realtors or realtor associations which compile

Figure 11 : Isoseismal map of Salt Lake City for hypothesized $M_s = 7.5$ earthquake on the Wasatch fault. Subdivided area within the city are census tracts.

frequent (usually monthly) summaries of actual dwelling sales. Aerial photos and appropriate sampling techniques were used to develop the construction characteristics of dwellings since there is a great difference in vulnerability between wood frame and other types of housing construction. Studies (Steinbrugge and others, 1969) have shown that the number of brick, concrete block and related types of construction used for dwellings in, for example, California is small (less than a few percent). It was found that brick, concrete block and related construction types made up about 60 percent of dwellings in the Salt Lake City area. A detailed inventory of buildings by classes of construction other than dwellings was undertaken by the H. C. Hugh Company of Salt Lake City for the U.S. Geological Survey. The development of the inventory was supervised by K. V. Steinbrugge. Air photos and drive-by inspection of buildings in each census tract were conducted. Construction type was noted and the dimensions of the buildings were obtained either from the air photos or from actual measurements. Replacement cost per unit area for the various classes of construction was estimated by a professional building inspector in Salt Lake City with long experience in the region. It is believed that the

inventory obtained in Salt Lake City is extremely accurate for the purposes of an earthquake loss study and that the errors in the estimation of ground motion are likely to be much larger than the inventory errors in this particular study.

4.4. Risk assessment

Losses associated with ground shaking were estimated assuming three different hazard models: (1) a deterministic model with the assumption of a magnitude $M_s = 7.5$ earthquake on the Wasatch fault. The distribution of intensity for this model is shown in Figure 11 and was derived from the data in the Figure 10; (2) a probabilistic model with the assumption that the largest average MM intensity in Salt Lake City in a 50 year period with only a 10 percent chance of exceedance is VII (see Figure 8); and, (3) a probabilistic model similar to that proposed in (2) above except that the average MM intensity in a 50 year period is taken as VIII.

Table 2 : Losses : Selected hazard models – Salt Lake City

Building Class	Value *		$M_s = 7.5$, Wasatch Fault Deterministic Model		Maximum Intensity VII, 50 years, 90 % extreme probability		Maximum Intensity VIII, 50 years, 90 % extreme probability	
	\$	%	\$	% of total loss	\$	% of total loss	\$	% of total loss
Dwellings ; 1-4 family (Class 1A)	\$1348.5	23	\$262.0	21	\$211.3	29	\$340.8	28
Other wood frame (Class 1B)	96.5	2	5.2	1	3.1	1	4.6	0
All Steel (Class 2)	182.7	3	14.1	1	1.1	0	6.3	1
Steel frame (Class 3)	490.5	9	39.2	3	15.4	2	34.0	3
Concrete frame (Class 4)	1280.0	22	139.8	11	74.4	10	164.3	13
Mixed Const. (Class 5)	2388.2	41	766.7	63	419.4	58	662.7	55
Totals	\$5786.4	100	\$1227.0	100	\$724.7	100	\$1212.7	100

* All values and losses are in millions of 1980 dollars (estimated).

Table 2 summarizes the simulated losses for the three models. A number of interesting results are apparent: The losses to dwellings as a percent of total loss for all hazard models considered are much higher than for similar shocks in California where most of the dwellings are wood frame (Algermissen and Steinbrugge [1978]). Note that the total losses estimated for the three models differ by a factor of less than two. This result occurs principally because Utah is an area of relatively high seismicity and the 50 year maximum ground motion approaches the ground motion expected of a large earthquake. For areas with low seismicity and a historical or geological record of only rare occurrences of large shocks, the differences in losses obtained from the deterministic model for a large shock and probabilistic models for nominal periods of interest would be very different.

Table 2 also shows the large contribution to losses of the class of construction called "mixed construction" (class 5) which includes poorly constructed masonry buildings, adobe, etc.

5. Risk assessment – Los Angeles and San Francisco, California

5.1. Seismic setting and hazard estimates

The high seismicity of the west coast of the United States is well known and need not be discussed here. Steinbrugge and others [1981] have published a revision of earlier, less complete risk studies of the Los Angeles and San Francisco areas. The revision is based on deterministic models simulating the effects of a large earthquake on the San Andreas fault passing through San Francisco (Figure 12) and on the Hayward fault east of San Francisco Bay, on the Newport-Inglewood fault (Figure 13) passing through Los Angeles and on the San Andreas fault east of Los Angeles.

5.2. Inventory and risk assessment

The areas considered for risk assessment around San Francisco consisted of the city and the eight surrounding counties: Alameda, Contra Costa, Marin, Napa, San Mateo, Santa Clara, Solano and Sonoma. The area considered for risk assessment around Los Angeles consisted of Los Angeles, San Bernardino, Kern, Riverside, Ventura and Orange counties. Data on dwellings was obtained in the same manner as described in the Salt Lake City study – i.e. from census data and summaries of real estate transactions. For buildings other than dwellings a novel approach was used. Quoting from Steinbrugge and others [1981]: "The initial data were fire insurance property values by county for northern California and an assumed 8.3 magnitude earthquake on the San Andreas fault. These values included dwellings, commercial buildings, manufacturing plants, warehouses, offices, and all other fire-insured properties. These property values were increased to include non-insured private property as well as increased to include under-insured property. Adjustments were made on a judgement basis to include the value of Federal, State of California, and local government-owned buildings. Intensities from the NOAA reports isoseismal maps were converted into loss factors, or the percent loss based on an impersonal definition basis. These percentages were multiplied by the property values to obtain the total impersonal loss by county in the study area, then summed to obtain the total aggregate loss. In this process, values were adjusted to compensate for inflation to 1980.

Figure 12 : Isoseismal map for a $M_s = 8.3$ magnitude earthquake on the San Andreas fault in northern California.

Building contents for the aforementioned San Andreas earthquake were analyzed in a similar manner to derive the total contents aggregate loss.

Loss computation methodology for a major earthquake on the Hayward fault followed the same computational patterns as those for the San Andreas fault.

Southern California provided a different problem in that basic insurance data had not been developed. However, a first-order estimate can be made by extrapolations based on

Figure 13: Isoseismal map for a $M_s = 7.5$ earthquake in the Newport-Inglewood fault in Los Angeles, California.

population differences and estimated differences in the geographic distribution of the buildings by class of construction.”

The results of the risk assessments are shown in Table 3.

6. Discussion

The difficulties in using ground intensity as a measure of shaking are well known. The correlation of intensity with more quantitative measures of ground motion are complex and not well understood. Unfortunately, on a world-wide and even on a regional basis, ground acceleration and velocity information are sparse. Intensity is the only quantity widely available throughout the world that can be used as a measure of ground

Table 3 : Losses : San Francisco and Los Angeles, California areas^a

Location	Total Losses ^d		^b Dwelling Loss ^d
	Buildings	Contents	
San Francisco metropolitan area			
San Andreas fault : $M = 8.3$	\$25,300	\$13,400	\$4,100
Hayward fault : $M = 7.5$	28,700	15,200	3,100
Los Angeles metropolitan area			
Newport-Inglewood fault : $M = 7.5$	40,700	21,500	^c 8,100
San Andreas fault : $M = 8.3$	16,300	8,600	^c 4,800

^a See Steinbrugge and others [1981] for details and exclusions.

^b One to four family dwellings, excluding loss to contents.

^c Only Los Angeles and Orange counties.

^d All losses in millions of dollars.

motion for studies of this type. Intensity also has the advantage that it incorporates local variations in ground response, provided that the intensity data are carefully gathered and interpreted.

The risk assessments of Salt Lake City, Utah, are believed to represent state-of-the-art methods because of the care taken in developing the inventory and the extensive recent seismological and geophysical investigations in this area. The development of building values in the San Francisco and Los Angeles area from fire insurance data represents a novel approach to the inventory problem. An interesting and contemplated future investigation is to use the fire insurance data technique for inventory development in Salt Lake City and check the risk assessment against the more conventional and probably accurate assessment outlined in this paper. Should the fire insurance data technique prove reliable it would greatly simplify risk assessment not only in the United States but throughout the world.

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