A RATIONAL METHODOLOGY FOR PREDICTING EARTHQUAKE LOSSES IN URBAN AREAS

Onder Kustu (I)
David D. Miller (II)
Presenting Author: Onder Kustu

SUMMARY

This paper describes a procedure for predicting earthquake-caused losses in urban areas. The procedure is automated by the computer code SIMPLE--SIMulation Program for Loss Estimates. Damage Probability Matrices (DPMs) are used to represent structure damageability. A Monte Carlo based simulation procedure accounts for the variabilities of all the parameters. Both single-event and annualized loss predictions can be made.

INTRODUCTION

The problem considered in this paper, prediction of earthquake losses in urban areas, is a significant part of a larger problem: the management of seismic risk in urban areas. A large portion of the world's population lives under continuous threat of earthquakes. The seismic hazard, earthquakes, cannot be eliminated. However, seismic risk (risk to human lives, property, and socio-economic systems) can be managed if studied and understood properly, and in most cases mitigated. The methodology described here is a step forward, towards the development of a practical tool to help researchers, planners, risk managers, and other decision makers understand and reduce seismic risks in urban areas.

The general procedure for predicting earthquake losses to urban areas reqires a definition of the seismic environment threatening the area. Various models have been proposed to define seismic environments (Ref. 1, 2, 3, 4); area sources and line sources (faults) with associated rupture and magnitude-recurrence models are commonly used. In a parallel effort, the composition of the urban area, i.e. the structure inventory, needs to be determined. Next, the ground motion that would be generated at a given site by a specified earthquake must be estimated. Peak ground acceleration (PGA) is usually the ground motion parameter selected to estimate site ground motion. Empirical attenuation laws are used to compute the PGA at the site. Soil amplification effects can be accounted for by the use of spectra anchored at the predicted PGA. Damage to individual structures is estimated through damage probability matrices (DPMs) or other forms of damageability models. Different damage or loss types can be predicted; the loss type of interest in this paper is monetary loss, or cost of repair.

A major task in the prediction of damage is the computational procedure. Because most parameters involved are random variables, a deterministic approach has little value; loss predictions have to be made using probabilistic procedures. Computation of predicted losses for a large urban

---

(I) Vice President, EQE INC., San Francisco, California, USA.
(II) Project Engineer, EQE INC., San Francisco, California, USA.

area involves lengthy calculations and requires the procedure to be fully automated, i.e. computerized.

As part of the work summarized in this paper the authors have developed a computer code, named SIMPLE --SIMulation Procedure for Loss Estimates, that automates the Monte Carlo simulation procedure used to make probabilistic loss predictions. Relationships and assumptions differing from those described below can be accomodated by SIMPLE. A detailed description of SIMPLE and the computational procedure is given in Ref. 5.

MODELING THE SEISMIC HAZARD

Modeling the Seismic Environment

The procedure implemented in SIMPLE requires the seismic environment to be defined in one of twc ways. Loss predictions for a single (predefined) seismic event require a description of the event; the input parameters are: event magnitude, hypocentral location, and if there was an associated fault rupture, the rupture length and location.

For an annualized urban loss prediction, all seismic sources which could initiate a damaging event must be modeled. Area and line source models are available in SIMPLE. Area sources are used in regions where there is no known fault system. Line sources are used to explicitly model fault systems. The following input data for each seismic source are required: geometry and location, magnitude-recurrence rates, and for line sources, a rupture length-magnitude relationship.

Definition of Ground Motion Zones

The urban area is divided into ground motion zones (GMZ) to describe the variations in local geology (which effect the site ground motion) and to simplify the computation of losses (i.e., ground motion is estimated for each zone, not for every structure site). GMZs are also used as structure inventory zones. The average size of the GMZs significantly effects the variance of the predicted loss. The proper size of the GMZs is related to the ground motion correlation between two neighboring sites. At present not enough is known about the correlation of ground motion from site to site. For the time being GMZs of approximately 4 to 8 square kilometers seem appropriate. This effect is discussed in detail in Ref. 5.

Predicting Site Ground Motion

Empirically derived attenuation laws are typically used to describe the variation of ground motion with distance from the source. A large number of these relationships have been derived by others from instrumental ground motion data recorded in different regions. In SIMPLE, PGA is predicted for each GMZ using the SAM equations given in Ref. 6. The SAM equations were used because they account for site soil characteristics and the probabilistic nature of ground motion prediction.

Normalized response spectra anchored at the predicted PGA facilitate the computation of structure response. SIMPLE requires a set of response spectra which represent the urban area's soil types. If a representative set is not available, SIMPLE provides three average spectra corresponding to rock, medium soil, and soft soil sites (Ref. 7).

MODELING THE URBAN SYSTEM

If the earthquake losses for an urban area were to be estimated structure by structure, the computational effort and data handling requirements would be enormous. Realistically, conventional structures must be grouped into classes which can be modeled by the average characteristics of their member structures. The total structure population of a city therefore consists of: classes or groups of structures (e.g., wood low-rise residential buildings, reinforced concrete high-rise office buildings) and special or unique structures (e.g., power stations, dams, lifelines).

Each of the structural classes and special structures must be characterized by inventory and damageability models, which in turn must be based on a common classification system. A detailed classification system for building structures that accounts for both structural system characteristics and occupancy is given in Ref 5.

Inventory Model

Predicting earthquake losses in an urban area requires data on all the structures of interest in that area. Enough information is needed to place conventional structures into component inventory groups (CIG) and to define the properties of special structures (a CIG is a set of structures which have been grouped by building class and GMZ).

Typical data which may be required to place a building into a classification include: replacement value, occupancy or use group, age, location, structural system, materials of construction, structure size and configuration, fundamental period of vibration, damageability characteristics, structure component inventory, etc. Some of these data are relevant to the damageability characteristics of structure classes and are discussed in the section on damageability models.

The details of an inventory model depend on the purpose of the prediction and the detail required and available in the damageability models. For example, if only monetary loss is to be predicted, the inventory model for a special structure would simply specify its replacement value. For a CIG, the inventory model would consist of the total number of structures in the CIG and the total replacement value.

Damageability Model

A damageability model defines the structural response-damage relationship for a specific structure or structure class. Various formats have been proposed for damageability models; the authors have selected the Damage Probability Matrix (DPM) format (Ref. 8). DPMs allow flexibility in selecting any ground motion parameter and damage scale, and also allow probabilistic treatment of the problem. DPMs for many structure types are available in the literature (Ref. 5, 9, 10, 11).

The damageability of a given structure is a function of its dynamic response characteristics, material properties, structural system, design and construction quality, and configuration, among other parameters. Damage to a structure is caused by the failure of its components either due to the large inertia forces on these components or due to excessive deformation of the structure, both of which can be estimated through conventional structural analysis. Correlations of local structure response with component damage do exist (Ref. 9, 12) and could be used to estimate damage to the various components of the structure; the total damage would be obtained as the sum of the damages to all components (e.g. beams, columns, walls, ceilings, etc.). However, when many structures are involved, such as in an urban area, this detail is not justified; correlation of a gross structure response parameter, such as spectral response, with overall damage to the structure is appropriate.

The detail and refinement of the DPMs will influence the detail and refinement of the inventory models and required inventory data. The DPMs must therefore be established, at least tentatively, before an inventory model can be finalized. DPMs can be developed from historical experience, theoretical analysis, or expert judgment. The availability of information from these three sources combined defines the accuracy and detail of the model.

COMPUTATION OF LOSSES

Prediction of Earthquake Losses

The predicted earthquake losses are computed by an approximate method using Monte Carlo simulation procedures. The simulation procedure makes direct use of the involved parameters' probabilistic nature to artificially generate many loss samples from repeated experiments. The histogram of these samples approximates the probability distribution of predicted earthquake losses. The Monte Carlo procedure is automated in SIMPLE.

A loss sample, given a specific seismic event, is generated in three steps:

1. Given the seismic event, sample the ground motion probability distribution for each ground motion zone.
2. Given the site ground motion, sample DPMs for each structure or structure class to simulate damage.
3. Given the damage to all structures in the urban area, calculate the urban area earthquake losses; this constitutes one sample of urban area earthquake loss.

Annualized losses are determined in a similar manner except that many earthquakes are simulated over a long period of time using a next-event scheduling procedure based on the model of the seismic environment.

Determination of Loss Statistics

The final step in the damage prediction process is to compute the summary statistics which will constitute the final results. Some examples of desired results are mean values and standard deviations of total loss to the urban area and to a particular structure or inventory area.

Using the mean, standard deviation, and probability density function of the computed losses, total loss predictions can be made at any desired level of confidence. It should be kept in mind that the Monte Carlo simulation procedure is an approximate solution method. The statistics computed here are only estimates of the true values. By increasing the number of damage samples the confidence levels of the estimates improve.

EXAMPLE PROBLEM

To demonstrate the procedure described above a very simple problem was solved using SIMPLE. Figure 1 shows the geometry of a small community of a block of residential buildings and a block of commercial and institutional buildings located within a short distance of an active fault. The seismic characteristics of the fault correspond to the Hayward fault in California, as described in Ref. 14. Both blocks (GMZs) are assumed to have deep cohesionless soils. Table 1 gives an inventory of the buildings in the blocks.

In this example an annualized loss prediction was made for the hypothetical two block community. A 10,000 year period was simulated. Table 2 summarizes the computed loss statistics for a set of component statistics groups. In an actual case this table would be interpreted in various ways, depending on the purpose of the prediction. For example, if the identification of the highest risk structure type was desired, it would be the "UBLK", the unreinforced block buildings. The mean values (or values corresponding to any confidence levels) of annualized losses would be used to decide on insurance needs and to determine insurance premiums. The gross numbers for "ALL CSG" describe the annualized seismic risk to the whole community.

DISCUSSION

The best way to present a methodology, such as the one described here, to its potential users is in the form of a computer program. Hence, the methodology developed through the research has been coded into the program SIMPLE. Some of the basic data necessary for estimating building losses, such as typical building response periods and DPMs, have also been developed as a supplement to the program. This package is the basic tool needed by the potential user. Of course, the user must still do a significant amount of work, especially in developing his inventory model, determining the seismic sources and their properties, and reviewing the assumptions made and procedures used in SIMPLE for applicability to his specific case. Also, DPMs for some structure types are not available and need to be developed. These will have to come from carefully collected data from postearthquake studies.

It is believed that the most significant use for the computer code SIMPLE, or any other code of similar nature, is in "real-time" emergency response planning. It is envisioned that, in the very near future, damage models of cities in seismic areas will be prepared in advance. Using these models, preliminary loss scenarios will be developed, and based on these, preliminary emergency response plans will be prepared. Of course, it will not be possible to have highly accurate scenarios; the emergency actions to be taken following a catastrophic earthquake will have to be based on the preliminary scenario and revised continuously as damage and casualty reports come in. A computerized system using a computer program as a scenario generator is an ideal system for this purpose. Other potential applications of the methodology include land use planning, risk analyses of cities or certain types of structures, and research work, such as studies of certain building code requirements, cost-benefit studies, and various other parametric studies.

ACKNOWLEDGMENTS

The work summarized in this paper was funded by the U.S. Geological Survey and was performed while both authors were employed by URS/ John A. Blume & Associates, Engineers. The authors appreciate the guidance provided to the project by Dr. John A. Blume. Contributions of Dr. Roger E. Scholl, Mr. Joseph P. Nicoletti, and Mr. Kenneth K. Honda are also appreciated.

REFERENCES

1. Cornell, C. A., 1968, Engineering seismic risk analysis: Bulletin of the Seismological Society of America, v. 58, no. 5, p. 1583-1606.

2. _______, 1970, Probabilistic analysis of damage to structures under seismic loads, in Howells, D. A., Haigh, I. P., and Taylor, C., eds : Dynamic waves in civil engineering, London, John Wiley.

3. Mortgat, C. P., and Shah, H. C., 1978, A Bayesian approach to seismic hazard mapping; development of stable design parameters: Report No. 28, Stanford University Department of Civil Engineering, The John A. Blume Earthquake Engineering Center, Stanford, California.

4. _______, 1979, A Bayesian model for seismic hazard mapping: Bulletin of the Seismological Society of America, v. 69, no. 4, p. 1237-1251.

5. Kustu, O., Miller, D. D., and Scholl, R. E., 1983, A computerized method for predicting earthquake losses in urban areas: URS/John A. Blume & Associates, Engineers, San Francisco.

6. Blume, J. A., 1977, The SAM procedure for site-acceleration-magnitude relationships: Sixth World Conference on Earthquake Engineering, New Delhi, Proceedings.

7. Seed, H. B., Ugas, C., and Lysmer, J., 1976, Site-dependent spectra for earthquake-resistant design: Bulletin of the Seismological Society of America, v. 66, no. 1.

8. Whitman, R. V., 1973, Damage probability matrices for prototype buildings: Research Report R73-57, Massachusetts Institute of Technology Department of Civil Engineering, Cambridge.

9. Czarnecki, R. M., 1973, Earthquake damage to tall buildings: Research Report R73-8, Massachusetts Institute of Technology Department of Civil Engineering, Cambridge.

10. Gulliver, R. M., and Sonnenfeld, P., 1980, Estimation of homeless caseload for disaster assistance due to an earthquake: Federal Emergency Management Agency.

11. Scholl, R. E., Kustu, O., Perry, C. L., and Zanetti, J. M., 1982, Seismic damage assessment for high-rise buildings: URS/John A. Blume & Associates, Engineers, San Francisco.

12. Kustu, O., Miller, D. D., and Broken, S. T., 1982, Development of damage functions for high-rise building components, JAB-10145-2, URS/John A. Blume & Associates, Engineers, San Francisco.

13. Kustu, O., Miller, D. D., and Scholl, R. E., 1982, Development of a rational methodology for predicting earthquake losses in urban areas: URS/John A. Blume & Associates, Engineers, San Francisco.

14. Kiremidjian, A. S., and Shah, H. C., 1975, Seismic hazard mapping of California: Report No. 21, Stanford University Civil Engineering Department, The John A. Blume Earthquake Engineering Center, Stanford California.

TABLE 1 - INVENTORY OF BUILDINGS IN THE MOCK-UP CITY

Class	Structural System	Occupancy	CSG	Number of Buildings	Replacement Value of Each Building (thousands of dollars)
Ground Motion Zone RESIDENT					
2-A	1-story wood frame	Permanent and transient residential	HSE1	10	140
3-A	2- to 3-story wood frame	"	HSE2	5	200
10-A	4+-story reinforced masonry	"	APT	1	5,000
Ground Motion Zone COMMERCL					
5-E	1-story unreinforced masonry	Commercial and retail trade, offices, light manufacturing	UBLK	1	1,000
6-E	2- to 3-story unreinforced masonry	"	UBLK	1	2,000
7-E	4+-story unreinforced masonry	"	UBLK	1	3,000
8-E	1-story reinforced masonry	"	RBLK	1	1,000
9-E	2- to 3-story reinforced masonry	"	RBLK	1	2,000
10-E	4+-story reinforced masonry	"	RBLK	1	3,000
21-B	2- to 5-story steel braced frame	Hospitals, schools, clinics, laboratories	HSPT	1	18,000

TABLE 2 - ANNUALIZED LOSS STATISTICS FOR MOCK-UP CITY

Component Statistics Group	Component Inventory Group	Loss Statistics (thousands of dollars)		Mean Damage Factor (%)
		Mean	Standard Deviation	
APT	One 10-A	19.9	254	0.40
HSE1	Ten 2-A	0.309	0.43	0.022
HSE2	Five 3-A	1.108	10.9	0.111
HSPT	One 21-B	44.0	621	0.244
RBLK	8-E, 9-E, 10-E	12.3	147	0.205
UBLK	5-E, 6-E, 7-E	17.1	181	0.285
ALL CSG	All structures	94.7	838	0.253

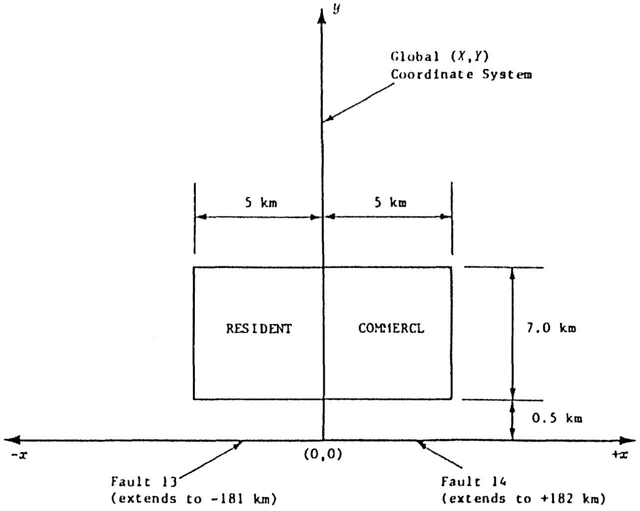

FIGURE 1 - GEOMETRY OF EXAMPLE MOCK-UP CITY