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Methods for regional damage estimation

Anne S. Kiremidjian
Stanford University, Calif., USA

ABSTRACT: Estimation of damage and loss to a region is of primary importance for disaster planning, mitigation and rehabilitation purposes. In this paper, a unified approach to regional damage assessment is presented. The primary earthquake hazards are identified as severe ground shaking, liquefaction, landslides and differential fault displacement. For each hazard an analytical formulation is developed to enable computation of the probability of exceeding the hazard level over a future time period. Formulations for mean annual damage and the expected damage over time for individual structure are developed for each hazard. Regional damage distributions are obtained through integration of damage to structures in census blocks in that region. For this purpose relational database management systems are utilized to consolidate building inventories and geographic information systems are used to integrate the hazard, inventory and damage information. The model is illustrated through an application to the City of Palo Alto, California.

1. INTRODUCTION

The need for regional earthquake damage and loss estimation is continuously reemphasized with each new major earthquake. Recent earthquakes have demonstrated that the direct losses from damage to major metropolitan areas can run into billions of dollars. The indirect, short-term losses can add another 15% to 25% to the direct losses. For example, the direct dollar loss from the October 17, 1989 Loma Prieta California earthquakes were estimated to be 5.9 billion dollars (ABAG, 1991) and the short-term indirect losses amounted to another 15% of the total direct loss. The long-term effect on the economy of a community is difficult to assess but they are usually a significant portion of the overall loss.

Current methods for estimating direct dollar losses employ either a deterministic or a probabilistic approach. In the deterministic approach, the maximum credible event for all seismic sources in a region is estimated and losses are assessed for that event. In the probabilistic approach the likelihood of all significant events is considered and the loss from all events over a future time is estimated. In both approaches numerous simplifying assumptions are made to overcome difficulties with handling large sizes of data or the lack of sufficient data. While both approaches have their advantages and disadvantages, in this paper we consider the probabilistic approach for loss evaluation. For this purpose the primary causes of damage are identified and analytical formulations for damage and losses are developed for each type of cause. The formulations are simple and computationally very efficient because they need to be applied repeatedly over a large region. Use is made of the data base management systems ORACLE^{TM} to facilitate manipulation of the large data bases needed for the analysis and the geographic information system ARC/INFO^{TM} to aid in the spatial integration and representation of the results. The regional loss estimation method discussed in this paper is limited to damage to buildings and does not include damage and loss from other structures such as bridges, industrial plants, or lifeline systems.

2. BUILDING DAMAGE AND LOSS EVALUATION METHOD

To develop a regional seismic loss evaluation model, it is necessary to identify the causes of earthquake damage and the types of damage. The analytical formulations for damage depend on the questions that are of interest for disaster mitigation, rehabilitation, emergency planning and insurance purposes. We pose some of these questions and attempt to develop equations to solve them. Some of the formulations are presented in conceptual form, while others are more specific.

2.1 *Causes of Earthquake Damage*

Severe ground shaking, liquefaction, landslides, differential fault displacements and subsidence are the primary causes of damage and loss from major earthquakes. In addition, considerable losses can result from secondary effects, such as conflagrations, inundations and explosions. The focus in this paper is on the direct causes of loss.

Modeling of the direct causes includes three main components: (a) characterization of the frequency, magnitude and location of seismic of events; (b) propagation of the seismic waves from the source to the site; and (c) assessment of the local site effects. Several models are currently available for evaluating the hazard from ground shaking. However, only a few probabilistic methods for liquefaction, landslide and differential fault displacement have been develop. An attempt is made in this paper to identify appropriate formulations for all primary effects and cast them in a unified approach for regional loss evaluation.

The most commonly used site hazard methods are based on a Poisson process for earthquake occurrences, a magnitude frequency relationship and empirical ground motion attenuation function. Some models also incorporate the rupture length for each magnitude. In these models, earthquakes are assumed to occur independently in time and space. Methods that consider the spatial and temporal dependence of earthquakes are currently being developed for use in damage evaluation (Lutz and Kiremidjian, 1992). In this paper, the site hazard models based on Poisson sequence of events are adopted.

For a Poisson sequence of earthquakes, the rate of event occurrences is given by λ and the probability that there will be n events in time (0,t) is

$$P\{N = n, (0,t)\} = \frac{e^{-\lambda t}(\lambda t)^n}{n!} \qquad (1)$$

where $n = 0,1,2,...$ and $\lambda > 0$. We define the set of site hazard parameters to be

$$Z = \{ Y, S, U, L\}$$

where

Y = ground shaking at the ground surface
S = liquefaction parameter
U = differential fault displacement
L = landslide parameter

The result of the site hazard analysis is the probability of exceeding various levels of a site parameter over a future time period, expressed as

$$P\{Z \geq z, (0,t)\} = P\{\text{site hazard Z will exceed level z at least once in time } (0,t)\}$$
$$= G_Z(z) \qquad (2)$$

To obtain the analytical form for this probability it is necessary to define the site hazard parameters and their relationship to the earthquake magnitude. In general, it is hypothesized that a functional relationship can be developed between each site hazard parameter Z, the magnitude of an earthquake M, the distance from the fault to the site R and an error term ε. More specifically

$$Z = g(M, R, \varepsilon) \qquad (3)$$

The hazard from ground shaking, Y, is most frequently expressed as peak acceleration, response spectral acceleration or response spectral velocity. Site-specific ground motions can also be simulated using geophysical models for fault rupture and wave propagation. These models, however, require data on the faulting mechanism and the wave propagation path. In addition, they are computationally time consuming and are, therefore, inappropriate for use when ground motions are to be estimated only at few sites. Thus they and are not considered in this paper.

Numerous empirical attenuation functions for the various ground motion parameters have been developed for seismic regions in the world (e.g., Joyner and Boore, 1989; Campbell 1981). These will be used in the ground shaking hazard analysis. Most of these equations predict the ground motion at the bedrock level. Thus, an additional step in the analysis is required to amplify the ground motion from the bedrock level to the ground surface depending on the the properties of the local soil conditions. A simple approach for amplification of ground motion is proposed by Borcherdt (1992), Sugito (1986) and Kiremidjian et al. (1992). In these papers, the amplification is considered to be a function of the geologic characteristics of the local soil, the shear wave velocities, the depth to bedrock and the bedrock motion. The advantage of these amplification functions is that they are simple and depend only on few site parameters, thus making them easy to apply over a large region. Other models, (e.g., Schnabel et al, 1972) require information on the variation of local soil properties with depth and are difficult to implement over a large region. The difficulties arise primarily because soil property data are not available for dense grid points over a large area and because the computation time required to determine the amplification capability at all grid points in the region can be excessive.

Liquefaction potential and the extent of the resulting lateral spreading are more difficult to measure and quantify than ground shaking. Youd (1991) has summarized the various methods used in liquefaction hazard mapping. These models can be classified into two categories: (a) models based on a simplified estimate of the cyclic stress ratio, ground motion amplitude and duration of motion; and (b) empirical relationships between earthquake magnitude, distance from the fault and the liquefaction severity. Of the various models discussed, the approach proposed by Youd and Perkins (1987) is be best suited for the purposes of regional damage and loss estimation. In their approach the liquefaction parameter is defined as the liquefaction severity index, S. The parameter S is measured in mm divided by 25 (or inches) and is bounded between 0 and 100. Youd and Perkins (1987) also provide a table of liquefaction characteristics for the various levels of S. This table is used subsequently to correlate the liquefaction severity index to the degree of damage t

Earthquake induced landslides depend on the severity of ground shaking and on the characteristics of the sloping site. Hansen and Franks (1991) summarize the local site factors that affect landslides as being the geology and ground-water conditions, topography, shear strength of the materials, and the preexisting slope-stability. In general, landslide severity is considerably more difficult to quantify than liquefaction severity. No functional relationships have been developed to date that relate the landslide severity to the magnitude and distance of an earthquake in a manner similar to ground shaking and liquefaction. However, correlations have been made between earthquake magnitude and total area affected by landslides (e.g., Li, 1978; 1979) and site ground motion and landslide severity (e.g., Wiezorek et al, 1985). For the purposes of this paper, the method proposed by Wiezorek et al. (1985) is adopted. In their approach landslide severity L is expressed in terms of landslide movement in centimeters. Thus, it is proposed that a ground motion attenuation function be used first to forecast the ground shaking hazard at a site and then apply the empirical relationship between ground acceleration and landslide movement. A landslide susceptibility map should be used with this approach.

The method for differential ground displacement considered in this paper was developed by Kiremidjian (1984). Two quantities to be forecasted in this model include: the amount of differential fault displacement and the length of fault over which displacement extents. For this purpose, relationships between magnitude versus fault displacement and magnitude versus fault rupture length are used. The differential displacement is the average surface displacement and the rupture length is the surface rupture length. Relationships for horizontal and vertical displacements and rupture length are available for various regions in the world (e.g., Wells and Coppersmith, 1991, Bonilla et al., 1984).

The probability of exceeding a hazard Z is expressed as follows:

$$G_Z(z) = \int_Z \int_R \int_M \lambda\, f_{Z\mid M,R}(z \mid M, R)\; f_{R\mid M}(r \mid M)\, f_M(m)\, dz\, dr\, dm \quad (4)$$

where $f_{Z|R,M}(z \mid R,M)$ = probability density of site hazard parameter Z given the magnitude of the earthquake and the distance form the fault to the site; $f_{R \mid M}(r \mid M)$ = probability density of the distance R given the magnitude of the earthquake; and $f_M(m)$ = probability density of earthquake magnitudes. In equation 4 the parameter Z represents the ground motion Y or the liquefaction severity S.

For the case of landslides, the probability of observing landslide of size l or larger in time (0,t) is given by

$$G_L(l) = -\int_l^{L_{max}} f_{L\mid Y}(l \mid Y)\, dG_Y(y) \quad (5)$$

where $f_{L|Y}(l \mid Y)$ is the probability density of a landslide of size l given the ground shaking Y. This probability density function will vary depending on the landslide susceptibility level. Thus, different functions will be used if the landslide potential is high than if the landslide potential is low.

For differential fault displacement U, the probability density $f_{Y|R,M}(y \mid R,M)$ is replaced by $f_{U|M,W}(u \mid M,W)$ where W is the rupture length of the fault and $f_{R|M}(r|M)$ is replaced by $f_{W|M}(w|M)$. In this case the probability density $f_{W|M}(W|M)$ represents the probability density of the rupture length W given the magnitude of the earthquake is M. Thus the probability of exceeding a rupture u in time (0,t) is

$$G_U(u) = \int_U \int_W \int_M \lambda\, f_{U\mid M,W}(u \mid M, W)\; f_{W\mid M}(w \mid M)\, f_M(m)\, du\, dw\, dm \quad (6)$$

At a particular site, the hazard will be a combination of one or more causes. However, it is likely that ground shaking and at most one of the other primary hazards will be present at one site. Thus at most two hazards will be considered simultaneously.

2.2 *Types of Damage and Loss*

Earthquake damage to buildings is divided into structural and non-structural damage. Direct losses relate to the building's physical characteristics and its use. Thus, losses are identified as resulting from (a) structural damage; (b) non structural contents and architectural components of the building; (c) down time or unavailability; (d) relocation of occupants; and (d) cleanup and security. In addition to these, there are also losses due to secondary hazards that can cause greater losses than the primary hazards. Examples of these are conflagration, such as the fires that followed the 1906 San Francisco earthquake, and inundations, such as these that may result from the failure of a dam.

Losses from severe earthquakes are likely to be dominated by direct structural damage, non-structural damage and down time. Losses from moderate earthquakes are usually dominated by non-structural damage. Herein, losses from direct structural damage only are included. Losses from non-structural damage and economic losses from secondary causes will be the subject of future investigations.

Various parameters have been used to characterize the severity of damage to a structure or its content. Among these, the most commonly used parameter is the damage factor, DF, defined as the percent dollar loss divided by the dollar replacement cost of the structure. This definition of damage is adopted in this paper. However, the methodology presented is general and other damage definitions can be used instead of the damage factor.

Damage to a specific structural class is frequently expressed in terms of a motion damage relationship. Such relationships are represented as damage probability matrices, DPM, (Whitman et al., 1973; ATC-13, 1985), as graphs between mean damage ratio and ground motion intensity (Algermissen and Steinbrugge, 1984) and as fragility curves (Kircher and McCann, 1983). Table 1 shows an example of a damage probability matrix. Figures 1 and 2 show graphs of mean damage ratio as a function of ground motion intensity and fragility curves, respectively.

Damage probability matrices describe the probability that the structure is in a particular damage state given the level of ground shaking. These damage probability matrices are derived from the probability distribution of damage given the ground shaking intensity level, $f_{D|Y}(d|Y)$, which is often assumed to be

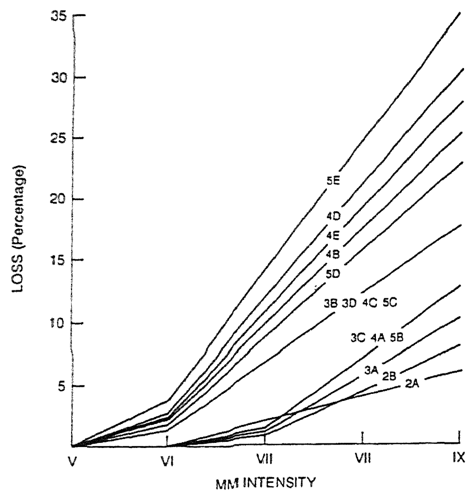

Figure 1. Mean damage ratio versus Modified Mercalli Intensity for different construction classes (from Algermissen and Steinbrugge, 1984)

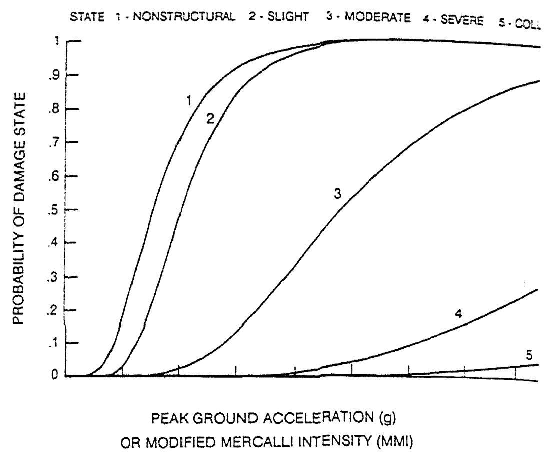

Figure 2. Example fragility curve (from Kircher and McCann, 1983)

Table 1. Example of Damage Probability Matrix (from ATC-13, 1985)

Damage State	Damage Factor (%)	Central Damage Factor	Probability of Damage State (in %) for given intensity I				
			VI	VII	VIII	IX	X
1.	0	0.0	95	49	30	14	3
2.	0-1	0.5	3	38	40	30	10
3.	1-10	5.0	1.5	8	16	24	30
4.	10-30	20.0	0.4	2	8	16	26
5.	30-60	45.0	0.1	1.5	3	10	18
6.	60-100	80.0	---	1	2	4	10
7.	100	100	---	0.5	1	2	3

Beta or lognormally distributed. Fragility curves describe the probability that a specified damage level will be exceeded given the ground motion intensity, $P\{D \geq d|Y\} = 1 - F_{D|Y}(d|Y)$. The two representations are analytically related. The probability density of damage conditional on the ground motion, $f_{D|Y}(d|Y)$, is the more elementary form of the two and will be used in this paper without imposing any limitations on subsequent damage and loss computations. Parameters for the probability densities of damage as functions of ground motion intensity for 42 classes of structures in California are available in ATC-13 (1985).

For liquefaction hazard, a qualitative correlation between damage and liquefaction severity index S was proposed by Youd and Perkins (1987). An abbreviated version of their liquefaction damage relationship is listed in Table 2.

For hazards other than strong ground motion and liquefaction, it is hypothesized that similar relationships can be developed between the damage

Table 2. Qualitative descriptions of damage for various liquefaction severity levels (simplified from Youd and Perkins, 1987).

Liquef. Severity Index S	General character of liquefaction effects	Damage State (%)
5	very sparsely distributed; some sand boils; fissure openings up to 0.1m and ground settlements of up to 25mm	2 (0-1)
10	sparsely distributed ground effects; sand boils with aprons up to 1m; ground fissures; slumps of few tenths of a meter at steep banks.	3 (1-10)
30	generally sparse but locally abundant ground effects; sand boils up to 2m; some fences and roadways noticeable offset; ground settlement as much as 0.3m.	4 (10-30)
50	abundant effects; sand boils with aprons up to 3m; fissures up to 1.5 m wide; fences and roadways are offset or pulled apart as much as 1.5 m; ground settlement of more than 0.3 m.	5 (30-60)
70	abundant effects; many large sand boils; long fissures with openings as wide as 2 m; frequent ground settlements of more than 0.3 m.	6 (60-100)
90	very abundant ground effects; numerous sand boils covering as much as 30 % of an area with fresh sand; many long fissures; large slumps; widespread settlements of more than 0.3m.	7 (100)

factor and the site hazard Z. Thus, for each hazard Z it is necessary to have the probability density $f_{D|Z}(d|Z)$.

2.3 *Building Damage and Loss Formulations*

For a building within a region the questions of interest include: (i) what is the expected loss to the structure over time (0,t) and (ii) what is the expected annual loss resulting from various direct earthquake hazards. Without loss of generality, we consider the case of discrete damage states similar to those defined in ATC-13 (1985). The case of a single hazard Z is presented first. In the following development, variations in economic value over time due to inflation are not included. Adverse economic effects following an earthquake are not included either. Such extreme effects may be: increase in replacement value due to increases in the price of row materials or due to increase in labor costs because of high demands at that time. Thus the damage and loss forecasts may be underestimates of actual losses.

Recalling that the rate of all events is λ, then the mean damage factor over t years denoted by $v_D(t)$ can be evaluated as follows:

$$v_D(t) = \lambda t \sum_{d_1}^{d_{max}} \int_z f_{D|Z}(d_i|Z)\, f_Z(z)\, dz \qquad (7)$$

where d_1 and d_{max} are respectively the smallest and largest damage states considered. In equation 7 $f_Z(z)$ is the probability density of the hazard Z and $f_Z(z)dz$ can be interpreted as the probability of observing a hazard between z and z+dz exactly once in time (0,t). To determine this probability, it is recalled that the site hazard equations define the probability that the hazard Z will exceed a value z in time t at least once. Thus, we can write

$$G_Z(z) = P\{Z \geq z \text{ at least once in } (0,t)\}$$

$$= 1 - P\{\text{no. events with } Z \geq z \text{ in } (0,t)\}$$

$$= 1 - e^{-\lambda t Q_Z(z)} \qquad (8)$$

where $Q_Z(z)$ is the complementary cumulative distribution of Z and $f_Z(z) = -dQ_Z(z)/dz$. Using equation 8, the expression for $\lambda t\, f_Z(z)dz$ becomes:

$$\lambda t\, f_Z(z)\, dz = -\frac{dG_Z(z)}{1 - G_Z(z)} \qquad (9)$$

The mean damage factor over time t is evaluated by numerical integration of the following expression

$$v_D(t) = -\sum_{d_1}^{d_{max}} \int_z f_{D|Z}(d_i|Z)\, \frac{dG_Z(z)}{1 - G_Z(z)} \qquad (10)$$

If the hazard Z is discretized into K states, Z_k, k=1,2,...K, and the mean damage factor given each Z_k is known, then equation 10 is further simplified as follows:

$$v_D(t) = \sum_{D=d_1}^{d_{max}} \mu_{D|Z}(d_i|Z) \ln\left\{\frac{1 - G_Z(z_{i+1})}{1 - G_Z(z_i)}\right\} \qquad (11)$$

Equations 10 and 11 represent the expected loss over time t and reduce to the annual expected loss for a structure when $G_Z(z)$ represents the annual hazard Z.

If two or more hazards are present at the site where the structure is situated, then the total mean damage ratio over time t needs to include the contribution of each hazard. Following an earthquake, what is observed is the net damage resulting from all hazards. It is difficult to distinguish the damage caused by ground shaking from that caused by liquefaction or landslides. As a result functional relationships between the damage caused by the different hazards cannot be developed. Shah et al. (1991) use the damage probability matrices from ATC-13 (1985) and increase the intensity of ground shaking to reflect the presence of other geologic hazards. In this paper the hazards and their respective damage functions are considered separately. Thus, it is proposed that a weighting scheme be used to combine the damage contribution of each hazard. The total mean damage over time t is then written as

$$v_D^T(t) = \sum_Z \omega_i v_D^i(t) \qquad (12)$$

where ω_i are the weighting factor such that $\sum_i \omega_i = 1$ and the sum is over the different hazards Z = {Y, S, U, L}. If a particular hazard is not present, then $G_Z(z)$ will be zero for that hazard and consequently the contribution to damage will be zero. The weighting factors are determined heuristically, assigning a percentage to each hazard.

The mean dollar loss for the structure over time t is evaluated by

Mean dollar loss to one structure in time t =

$$E\{DL\} = v_D^T(t) \cdot \{\text{dollar replacement value}\}.$$

The dollar replacement value depends on the social function of the building and the local codes and regulations in place. For example, the replacement value for a wood frame structure will be depend on whether the structure is to be used for a dwelling or as an office building. Also, local codes may require that the damaged structure be replaced with a structure that meets the building code in force at the time. Thus the replaced structure may have a different classification than the original structure. Unreinforced masonry construction is not currently permitted in California, thus any existing unreinforced structure that will need to be replaced by another type of structure. If the damaged structure in this example is a dwelling, then the replaced structure will most likely be a wood frame. The interpretation of the long term expected losses that consider the damage from several earthquakes can be questioned. With the proposed model, it is not possible to consider changes in structural classifications within the time of damage forecast. The replacement of one class of structure with another one can be included in a simulation scheme.

3. BUILDING CLASSIFICATION AND INVENTORIES

A key component in the regional damage estimation methodology is the availability of a comprehensive building inventory. Such an inventory should contain information on several attributes describing the physical characteristics of the structure. For example, the location, the structural type, the height, the year of construction, presence of vertical or floor irregularities, occupancy, use, and value. The creation of such databases represents a major difficulty for any region in the world. Building-by-building inventory accumulation is neither practical nor feasible. Existing data bases are frequently incomplete and often in paper format requiring considerable effort to transfer to electronic format.

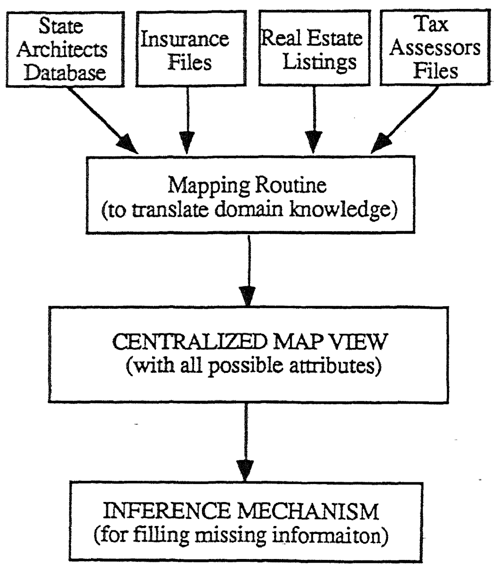

Figure 3. Inventory databases integration scheme (after Vasudevan, 1991)

Various sources for building inventories and methods for consolidating the information from these inventories were identified by Vasudevan (1991), Rentzis (1992) and Rentzis et al. (1992). Sources for building inventories in California, for example, include: (i) the county tax assessors' files, (ii) Office of the State Architect's files; (iii) insurance companies' files; and (iv) real estate files. In addition, many municipalities have their own inventories.

Most of these files contain incomplete information. An approach was proposed by Vasudevan (1992) and Rentzis et al. (1992) to consolidate and integrate the information from the various data sources although in actual applications, the data from the County Tax Assessor's files was the most complete and readily available. Thus the County Tax Assessor's files were used as the primary source of building inventory. Other files were used to modify the data in these files.

In their approach a data structure referred to as BUILDING scheme for each building is defined first. The BUILDING scheme contains a vector of attributes $A = \{A_1, A_2, \ldots A_N\}$. Each attribute A_i is further defined in terms of other descriptors a_{ij}. The following is an example of a building scheme (Rentzis et al., 1992):

BUILDING (Location, Structural_info, Year _constructed, Soil_type,Occupancy, Value, Pounding, Hazardous_contents)

The list of items in parenthesis represents the vector of attributes referred to as the primary key of the relation. Each of the attributes is further defined by their sub-attributes. For the above example the attribute list is defined as follows:

LOCATION (Coordinate, Address)
COORDINATE (Longitude, Latitude)
ADDRESS (Street_name, Street#, Apt#, Building _name, City, State, Zip_Code)
STRUCTURAL_INFO (Plan_irreg, Vertical_irreg, Area, Type, Exterior, Year_constr, Upgrading)
PLAN_IRREG (Shape, Torsional_irreg, Diaphragm _discontinuity, Non-parallel_system)
VERTICAL_IRREG (Soft_story,Weight_irreg, Short _columns, Vertical_geometric_irreg, LMH-rise)
TYPE (Building_type, Material, Wall_type, Roofing, Partitions, Foundation)
EXTERIOR (Overhangs, Parrapets, Setback, Ornamentation, Marquees, Balconies, Chimneys, Signs, Signs, Towers, Roof_ tanks)
UPGRADING (Date, Scheme, Purpose)
OCCUPANCY (Occupancy_type, Occupants/Unit area)
VALUE (Replacement cost at current rates)
AREA (Gross useful square footage)

The information from the various inventory sources is combined through relational schemes. This consolidation of information is performed within the framework of relational database management systems (RDBMS). The database management system ORACLE^{TM}, is utilized in our work (e.g., Vasudevan, 1991; Rentzis, 1992; and Rentzis et al., 1992). Figure 3 shows schematically the data consolidation scheme for building inventories. In order to translate some of the information from one database to another, knowledge base expert systems were developed. For example, data on the time of construction, time of upgrades and the original and subsequent social functions of the structure may be used to infer its structural class. In this case the age of the structure would lead to several predominant construction types for the particular social function class. If several structural classes are possible for a given structure, a probability distribution is developed for the possible structural classes based on a sample of structures that already have been classified. In this case, the structures in the simple have characteristics similar to the structure to be classified. Because the data is sparse, usually several possible structural classes may be possible requiring the probability

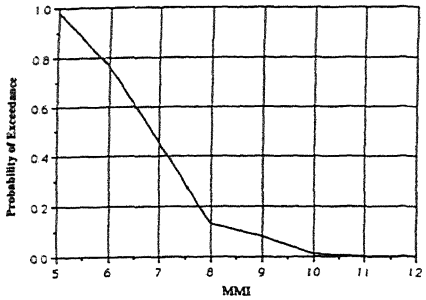

Figure 4. Ground motion hazard in 50 years for census block 101 in Palo Alto, Calif.

distribution that describes the likelihood that the structure is in one of the structural classes.

It is important to recognize that building inventories will be incomplete regardless of the level of sophistication of the data integration scheme. The completeness and accuracy of the consolidated inventory depend on the completeness and accuracy of the individual inventories and the accuracy of the integration scheme. Integration, however, is helpful in verifying repeated information and complementing information that may be missing from one database but is available in another database. The difficulties with inventory accumulation and error determination are discussed more extensively in Vasudevan (1991) and Rentzis (1992).

The list of attributes needed in the building inventory is for the purposes of classifying a building according to structural and use classification schemes. The most comprehensive building classification scheme was developed in ATC-13 (1985). The classification scheme presented in that publication was developed for buildings in California. However, it can serve as a guide for other regions of the world. To implement their approach, it is necessary to identify the differences in design and construction practices between California and other regions. Currently, there are efforts in the United States to devise building structural and use classification schemes for other states in the country.

4. REGIONAL LOSS INTEGRATION ALGORITHMS

Regional damage and loss can be expressed in terms of mean damage factor in small areas containing several types of buildings. The approach described by Vasudevan (1991) and Rentzis et al. (1992) appears most promising. The expected dollar loss in time (0,t) for a census block is estimated from the following equation

$$E\{DL\} = \sum_{k=1}^{n} v_{D,k}^{t} TR_k \qquad (13)$$

where:

$v_{D,k}^{t}$ = the mean damage factor for all buildings in structural class k in the census block and for all possible events in time t;
TR_k = total replacement value of all buildings in structural class k in the census block;
n = total number of structural classes in the census block.

If the replacement value of each structure in the census block is available through the inventory process, then, the total replacement value will be just their sum. Most often, however, that information is not available in the inventory. The total replacement value TR_k of all buildings in structural class k in the census block can be estimated from the following:

$$TR_k = \sum_{j=1}^{m} A_{k,j} \cdot R_j \qquad (14)$$

where

$A_{k,j}$ = total area of buildings belonging to social function class j and structural class k in the census block;
R_j = average replacement value per unit area for social function class j;
m = total number of social function classes found in the census block.

Replacement values per unit area for various social function classes are region dependent.

Equation 13 can be used to determine the mean damage distribution in a region over a future time t or on annual basis (i.e., for t = 1). The same equation can be used to estimate the mean damage for select group of buildings in an area.

5. EXAMPLE APPLICATION

The method for regional damage estimation was applied to the City of Palo Alto by Vasudevan (1991) and further modified by Rentzis et al. (1992). The example is included in this paper for illustrative purposes. Damage only from ground motion hazard was estimated.

The building inventory for the City of Palo Alto was consolidated from the County Tax Assessor's files. Other building inventories were also consulted to complement the Tax Assessor's files. These included the Office of the State Architect files, which contain primarily state owned buildings, and the hazardous buildings file published by various counties. It was determined that the inventory was 90% complete. Buildings excluded from the inventory are most likely non-taxed and non-state owned properties. A total of 18,378 buildings were included in the inventory.

Building addresses were corrected and standardized by matching addresses with U. S. Postal Service catalog for the City. Building classes were inferred using a knowledge based expert system that utilizes information from the various attributes. The structural classification corresponds to the ATC-13 (1985) classification scheme. The map of Palo Alto

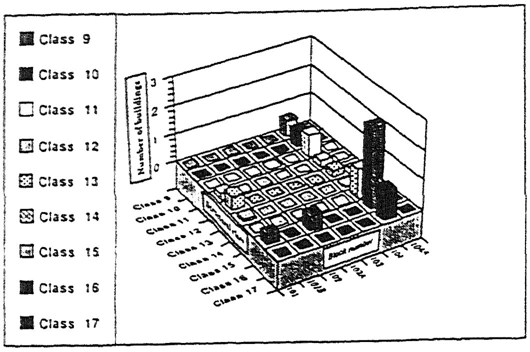

Figure 6. Distribution of different structural classes in census blocks.

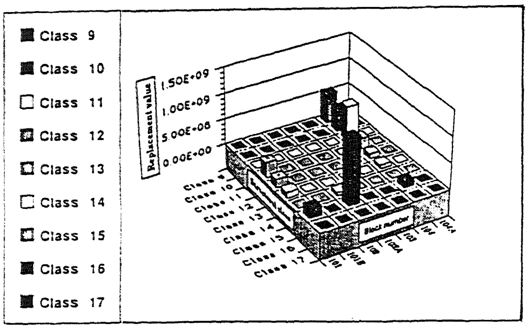

Figure 7. Distribution of dollar replacement value for structural classes in census blocks.

was delineated into census blocks using TIGER files available from the U. S. Bureau of the Census. The census blocks were mapped further into polygons in the geographic information system ARC/INFO^{TM}. There were 179 census blocks that contained inhabitable buildings (Rentzis, 1992). Census blocks

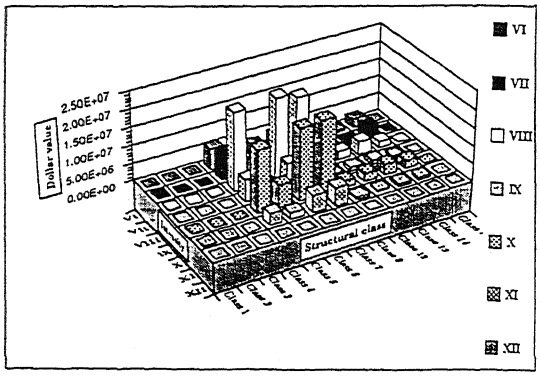

Figure 8. Distribution of mean dollar loss for different census blocks as function of MM intensity.

that did not contain such buildings were not included in the study.

The ground shaking hazard for each census block in Palo Alto was computed using the program SHA (Lamarre, 1988). Figure 4 shows the ground shaking hazard curves for one census block. The hazard curve shows the probability of exceeding an intensity level in the next 50 years. The ground shaking parameter is the Modified Mercalli Intensity scale. Figure 5 shows the hazard distribution in the City. The hazard corresponds to 10% chance of exceedence in 50 years.

A total of seventeen structural classes are identified for the study region. Figure 6 shows an example of the distribution of structural classes in several census blocks. Dollar replacement values were estimated for different social function and structural classes. Figure 7 shows the total dollar replacement value for different structural classes in several census blocks. The mean damage factor for each census block was evaluated and mapped in ARC/INFO. The distribution of mean dollar loss as a function of structural class and the intensity of shaking is shown in Figure 8. Figure 9 shows the distribution of damage throughout the City of Palo Alto. The mean damage factor shown in this figure is for 50 years. The highest damage is found to be in census blocks that contain unreinforced masonry buildings. The expected damage factor for most of the City is between 4% and 6% in 50 years. In majority of these blocks the predominant type of construction is low rise wood frame buildings.

Other hazards were not considered in this analysis. Palo Alto sits on a relatively flat terrain. The exceptions are two census blocks that are in the hills at the outskirts of the city. Thus landslide hazard is limited only to these areas. Liquefaction hazard is concentrated in the part of the city close to the San Francisco Bay. Fault rupture hazard is limited only to smaller local faults none of which are believed to be capable of causing displacements of significance for damage estimation. This does not preclude, however, the potential for local fissuring or the occurrence of secondary faulting as a result of large fault deformations on the San Andreas fault which border to the west of the city. The analysis of these is beyond the scope of this paper. Insufficient amount information was available at the time of this paper to include liquefaction and landslide hazard. However, these will be included in future studies.

6. ACKNOWLEDGEMENTS

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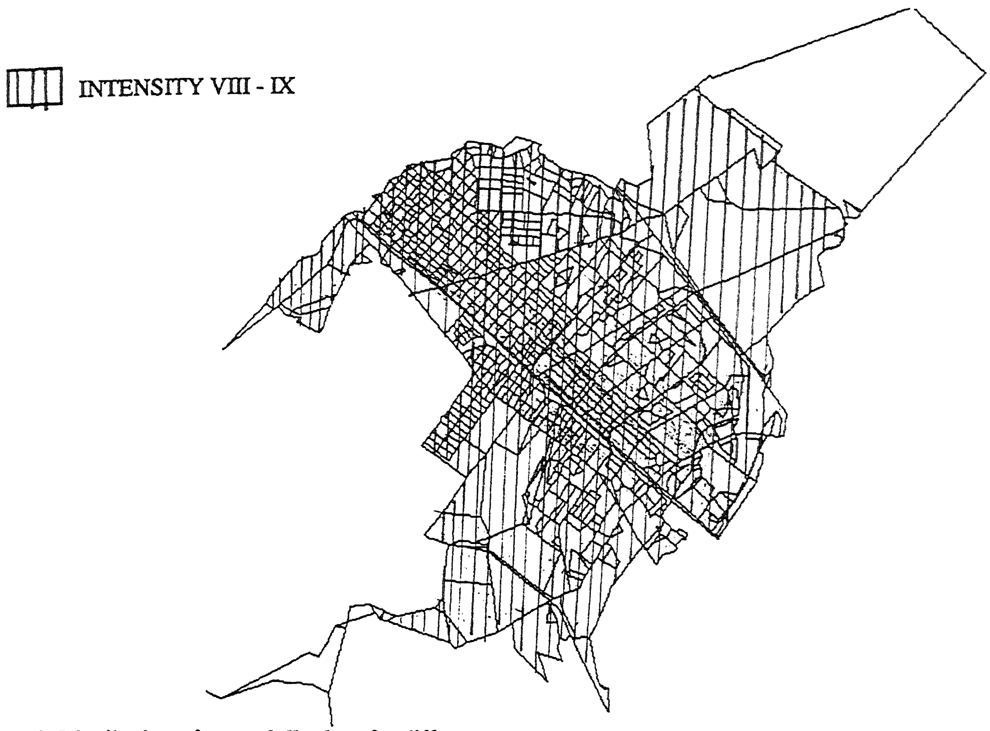

Figure 8. Distribution of mean dollar loss for different census blocks as function of MM intensity.

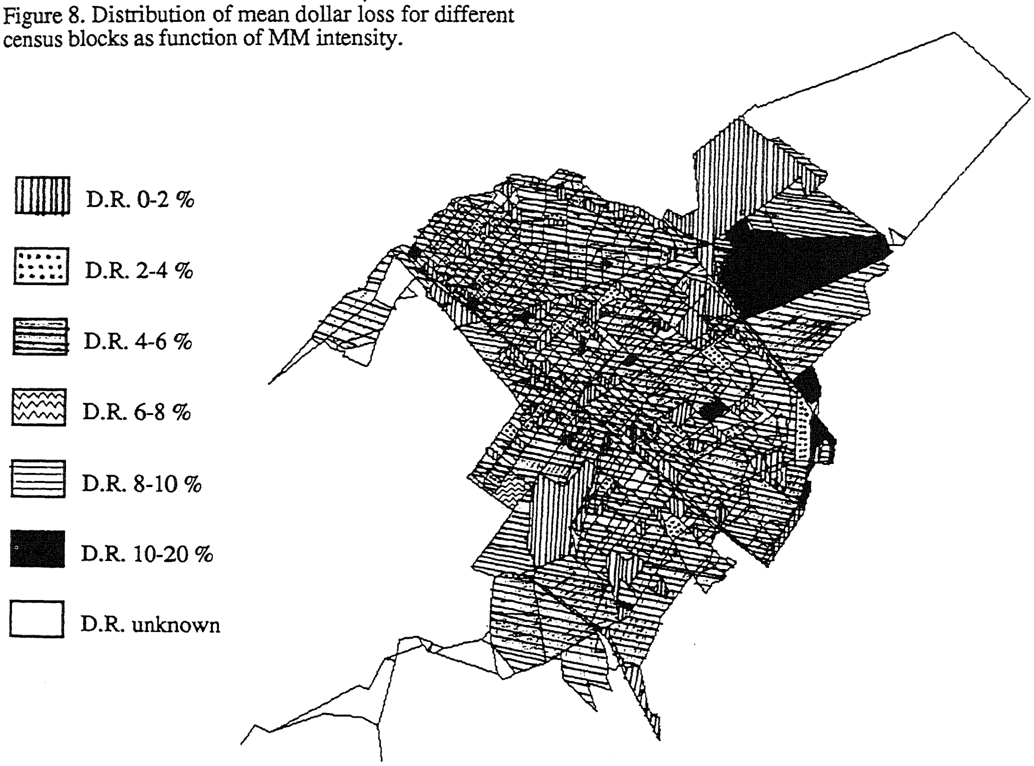

Figure 9. Mean damage distribution for 50 years in the City of Palo Alto, Calif.

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