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Paper No. 441. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

DEVELOPMENT OF A GIS-BASED EARTHQUAKE DAMAGE AND LOSS ESTIMATION METHODOLOGY

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ABSTRACT

Regional damage and loss estimation methods have been greatly enhanced in recent years with the advances made in spatial data analysis tools such as geographic information systems (GIS), database management systems (DBMS) and knowledge based expert systems (KBES). In this paper we present a general methodology for earthquake risk mitigation that utilizes GIS, DBMS and (KBES). The main components of the methodology are (i) site hazard estimation, (ii) damage evaluation and (iii) loss estimation. For the purposes of site hazard analysis, two approaches are considered: a deterministic scenario event formulation and a probabilistic hazard analysis that integrates the contribution from all seismic sources and all possible earthquakes over the life of a structure. Site hazard effects include ground shaking, liquefaction potential, landslide potential and differential fault displacement. Damage estimation is based on fragility analysis of structures in different building classes. Buildings as well as lifelines are considered in the overall formulation. Currently, only losses resulting from direct damage to structures in the affected region are included. The methodology, however, can be extended to include secondary economic losses such as these due to relocation, down time, and unavailability of goods and services. The regional damage and loss methodology was applied to two regions in the world: Palo Alto, California, and Akasaka and Azabu Juban in Tokyo, Japan. Results from these applications are briefly summarized in this paper.

KEYWORDS

Earthquake hazard, risk, damage, loss, regional loss, earthquake motion-damage relations, structural classification, geographic information systems.

INTRODUCTION

Earthquake disasters within the past decade have resulted in billions of dollars in losses. The January 17, 1995 Hiyagi-ken Nanbu earthquake in Kobe, Japan and the January 17, 1994 Northridge, California earthquakes are dramatic examples of the great destructive power of seismic events. These earthquakes have demonstrated the enormous destruction that can take place of all types of structures within the infrastructure of a region when an earthquake occurs in the heart of a major metropolitan region.

As our resources diminish, it has become increasingly important to evaluate the potential for natural disaster and project potential losses in a reliable and timely manner. It is only after such forecasts are made that mitigation measures can be undertaken and appropriate emergency plans can be developed. The technological revolution of the past decade has provided tools that have greatly facilitated the implementation of complex models and data structures for risk analysis and management purposes. The problem of risk assessment for earthquake hazards can be considered to consist of three main components:

(a) Modeling of the earthquake phenomenon;
(b) Modeling of the seismic exposure;
(c) Risk evaluation and management.

A general methodology that integrates these components in a coherent manner was developed under a joint project between a California Universities for Research in Earthquake Engineering (CUREe) consortium composed of Stanford University, University of California at Los Angeles, and University of California at Berkeley, and researchers from Kajima Corporation. The methodology was formulated within the framework of a geographic information systems as shown on Figure 1. The goals of the methodology are to provide the tools for (i) assessing the seismic hazard exposure over a large region including secondary site hazards such as liquefaction and landslides; (ii) modeling the inventory of the infrastructure of a region which includes buildings and all lifelines; (iii) evaluating the damage exposure of a region; (iv) estimating the potential direct economic and human losses in the affected area; and (v) identifying critical facilities where critical facilities are defined for example, as structures that are important for the functionality of a region following a major disaster or structures that can result in large number of casualties. In order to demonstrate the utility of this methodology, two regions were used as case studies. The two regions are Palo Alto, California and the areas within Tokyo known as Akasaka and Azabu Juban.

In this paper, the general methodology is briefly summarized and preliminary results from the study regions are presented. The application to the two regions in Tokyo was conducted by the Kajima research team, and the application to Palo Alto was performed by the CUREe team.

SEISMIC HAZARD EXPOSURE MODELING

Geologic hazards most frequently considered in seismic risk assessment include assessment of severe ground shaking, liequefaction, landslides, lateral spreading and differential fault displacement. Each of these hazards are typically forecasted through analytical models. The forecasts are in terms of probabilities of occurrence or exceedence of a hazard parameter, of in terms of a hazard severity index. For example, the potential ground shaking from future earthquake events can be expressed as the peak ground acceleration that corresponds to a specified probability of exceedence. Most frequently peak ground acceleration and spectral acceleration are used to characterize the ground shaking severity.

The analytical models require extensive spatially distributed data and the output of the models are also spatially distributed information. Thus, at points in a region or for polygons within the region, the respective hazard parameters need to be evaluated. The probability of exceedence for each hazard (or hazard curve is developed) given by the following generic equations:

$$P\{A \geq a, (0,t)\} = f_1(\nu, M_{min}, M_{max}, f(r,a,s,m)) \quad (1)$$

$$P\{L_l \geq l, (0,t)\} = f_2(N, \rho, \nu_s, a, t_d) \quad (2)$$

$$P\{L_d \geq d, (0,t)\} = f_3(\theta, \rho, a) \quad (3)$$

$$P\{F_d \geq f, (0,t)\} = f_4(M, h) \quad (4)$$

where A is ground motion parameter, t is the forecast time, ν is the frequency of different magnitude events, M_{min} and M_{max} are respectively the smallest and largest earthquake magnitudes of interest, M is the magnitude of event, $f(r,a,s,m)$ is the attenuation of ground motion as a function of the magnitude m, the distance from the fault to the site r and the local soil conditions s, L_l is the liquefaction potential index, L_d is the landslide potential index, F_d is the surface fault dislocation, h is the type of fault (e.g., strike slip, trust, subduction zone), N is the blowcount of soil, ρ is the density of soil, v_s is the shear wave velocity of soil, t_d is the duration of shaking per event, θ is the slope of the terrain, $f(\bullet)$ is a function of $\bullet$, and $P\{\bullet\}$ is the probability of $\bullet$.

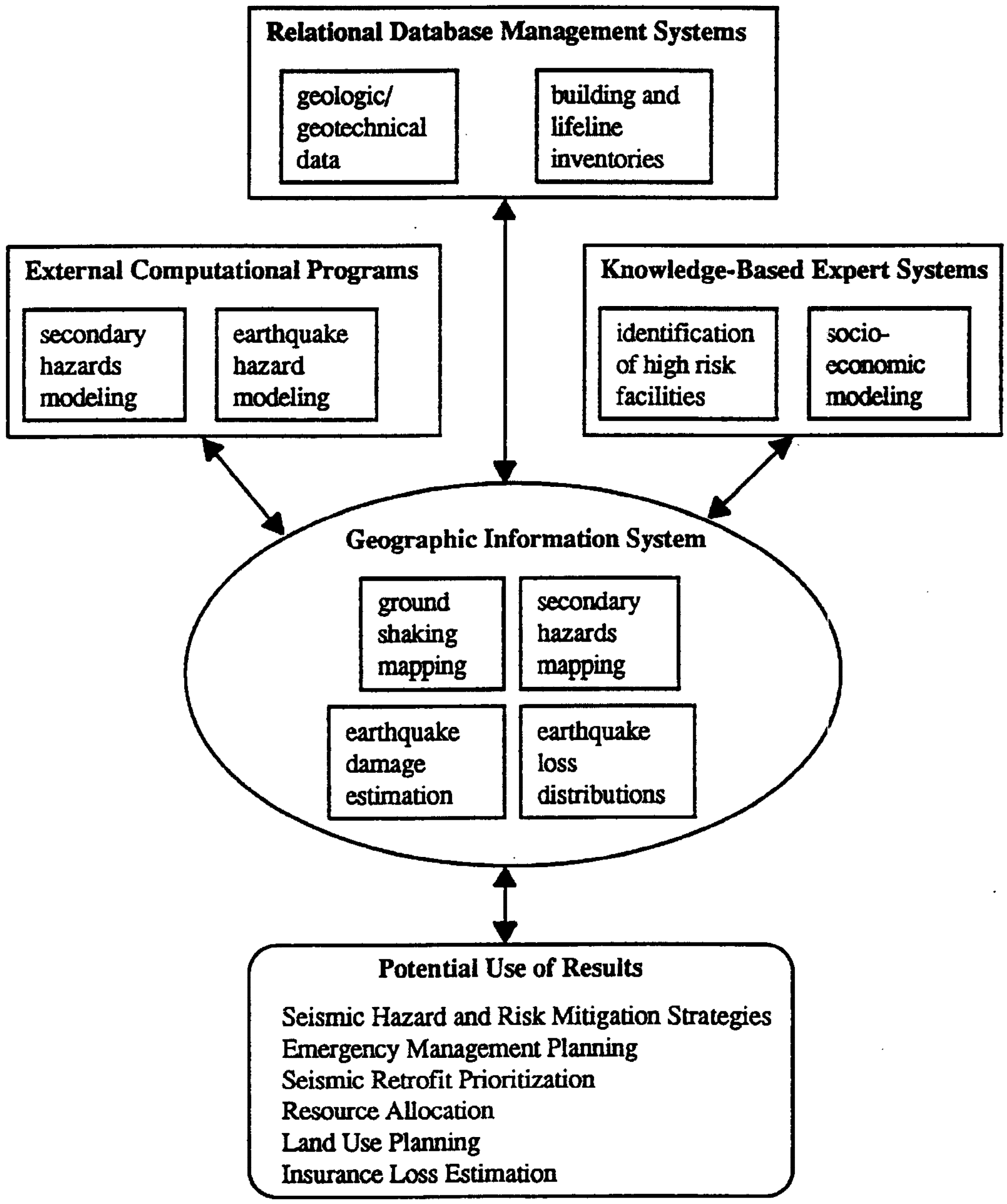

Fig. 1. General framework for GIS-based earthquake damage and loss estimation.

Data needed for the analytical modeling and hazard forecasting include maps, such as geologic and fault maps, data tables of earthquake occurrences and ground shaking time histories, and other parameter inputs. The output from the various models is presented through GIS in terms of point, line or polygons each describing different information and each output can be a different layer of information. The geographic information system has the capability to overlay and integrate the information from different layers by combining polygons, line and point features in a unified map representation. This capability of the system represents a major improvement in the management of the spatially distributed data and information. Until the advent of GIS, spatial data required point by point integration rather than area by area integration.

In order to evaluate the total hazard $P\{H|E_i\}$ from a given event E_i, it is necessary to combine all the hazards over a region. Thus the total site hazard can be represented as follows:

$$P\{H|E_i\} = \sum_j v_j \cdot P\{H_j|E_i\} \tag{5}$$

where v_j is a weighting factor for the various hazards.

REGIONAL DAMAGE AND LOSS METHODOLOGY

The distribution of damage and loss over a large geographic region will depend on the hazard exposure, and the structural characteristics of the built environment within the region. In its simples and most generic form, the expected damage within a polygon or an area can be estimated as follows:

$$E(\text{loss}) = \sum_{D_i} \sum_{S_j} \sum_{H_k} \sum_{E_l} P\{D_i|S_j, H_k, E_l\} \cdot P\{H_k|E_l\} \cdot P\{E_l\} \tag{6}$$

where D_i is damage state i, S_j is structure in class j, H_k is site hazard exposure k given by either equation 5 or one of equations 1 to 4, and E_l is the earthquake event. Losses over the region can be estimated by translating damage states to dollar losses and summing over all structures.

In equation 6, it is assumed that the probability of damage given the site hazard exposure is available for all structural types. Such relationships are typically expressed in terms of damage probability matrices (DPM) or fragility curves. Two studies that provide such relationships are ATC-13 (1985) and NIBS (1995). Fragility curves have also been developed for individual structural types (e.g., Singhal and Kiremidjian, 1995). Considerable amount of additional effort is required to obtain damage functions for all structural classes that realistically represent the behavior of structures under various earthquake exposure regimes.

In order to evaluate equation 6 or its extension to loss computation, it is necessary to have information on all structures within the region including buildings and lifelines. Such inventories, however, are difficult to develop because the information is scattered in several different databases or may be in paper format, making it difficult to translate into electronic format. Building and lifeline inventories require information on geographic location (longitude and latitude, or street name and address, city, county, state and country), age of the structure, total square footage, elevation, structural type (e.g. wood frame, concrete frame, concrete shear wall, etc.), occupancy type (e.g., hospital, residential, steel factory, etc.), number of occupants (day and night), and seismic upgrading. Such databases are typically generated in existing relational database management systems (RDBMS) which enable easy access and manipulation of the information. Links between RDBMS and GIS currently exist for a wide range of these systems making it particularly easy to import data into the GIS. Building inventories by themselves can provide very useful information for risk management and mitigation. Display of hazardous building in a region on a GIS map can identify areas of high risk and the extent of that risk. In addition to map displays, other information can be easily imbedded and retrieved upon demand on the screen through the use of GIS. For example, tables containing pertinent information relating to a point on the map can be shown in an icon. If data on the number of unreinforced masonry buildings and number of residences are required for the highest damage area, a table can be called by clicking on the highest damage area polygon and the information displayed. The mechanism for retrieving such information has to be built within the system.

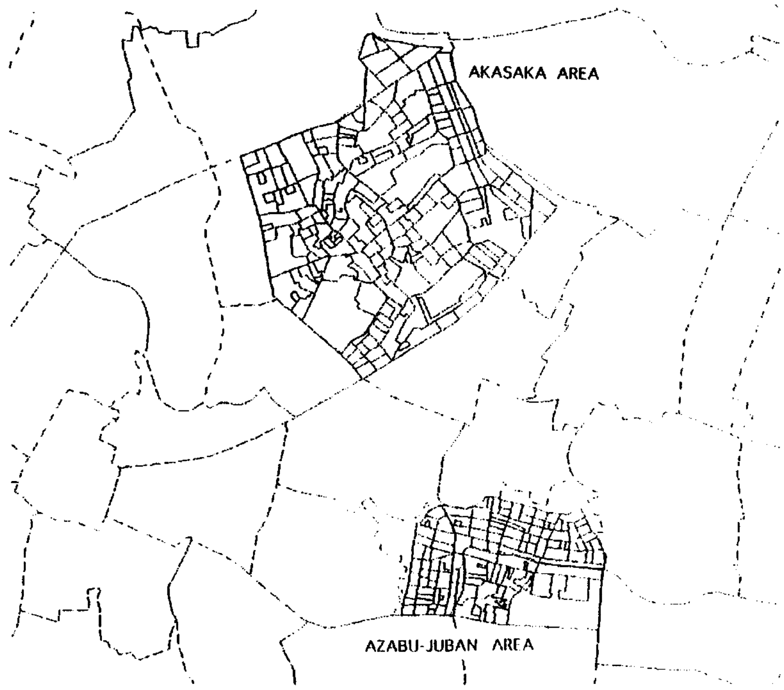

Fig. 2. Census tracks of Akasaka and Azabu Juban, Tokyo, Japan

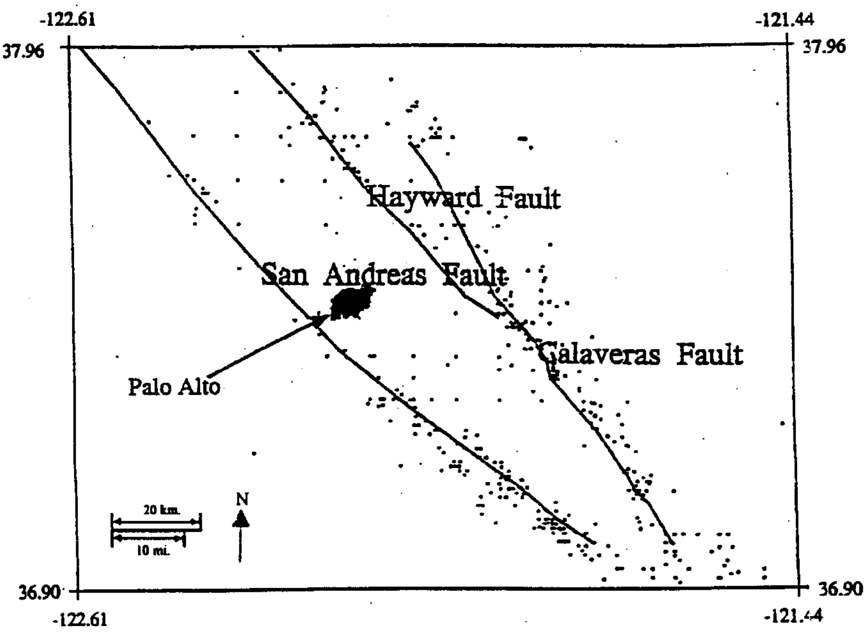

Fig. 3. Major faults and epicenter data in the vicinity of Palo Alto, CA.

APPLICATION OF METHODOLOGY TO PALO ALTO, CALIFORNIA AND TOKYO, JAPAN

The system described in this paper was developed simultaneously at Stanford and Kajima in joint cooperation. In order to illustrate the utility of the system, two examples were executed: one in Palo Alto California and the second in two areas within Tokyo, Japan known as Akasaka and Azabu Juban. The study regions were selected for their high potential of seismic activity, diversity in structural types, infrastructure congestion, and variations in occupancy. For example, Palo Alto is within 4 to 5 km of the San Andreas fault zone. Azabu Juban is characterized by mostly older residential structures and Akasaka is populated primarily by newer highrise commercial and industrial structures. Figures 2 and 3 show respectively the areas in Tokyo and Palo Alto.

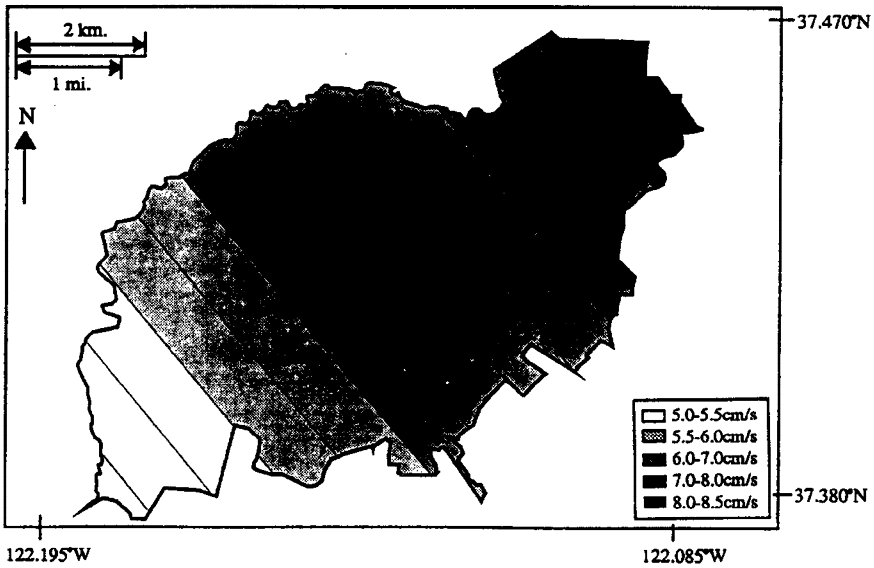

Fig 4. Bedrock ground shaking map for Palo Alto, CA from an M 7.5 event on the San Andreas fault.

Figure 4 shows the ground shaking polygons in Palo Alto for a scenario event of 7.5 on the San Andreas fault. Several other scenario events and probabilistic seismic hazard analysis were also performed but are included in this paper. The local geology map classified according to geologic units is displayed on Figure 5. Ground surface map which integrates the information from Figures 4 and 5 is shown on Figure 6.

Inventories of buildings and lifeline systems were developed for both study regions. Figures 7 and 8 show the transportation systems in these regions. The damage and loss was estimated for each area. Figure 9 shows the distribution of dollar loss per square foot of built area within individual census blocks in Palo Alto.

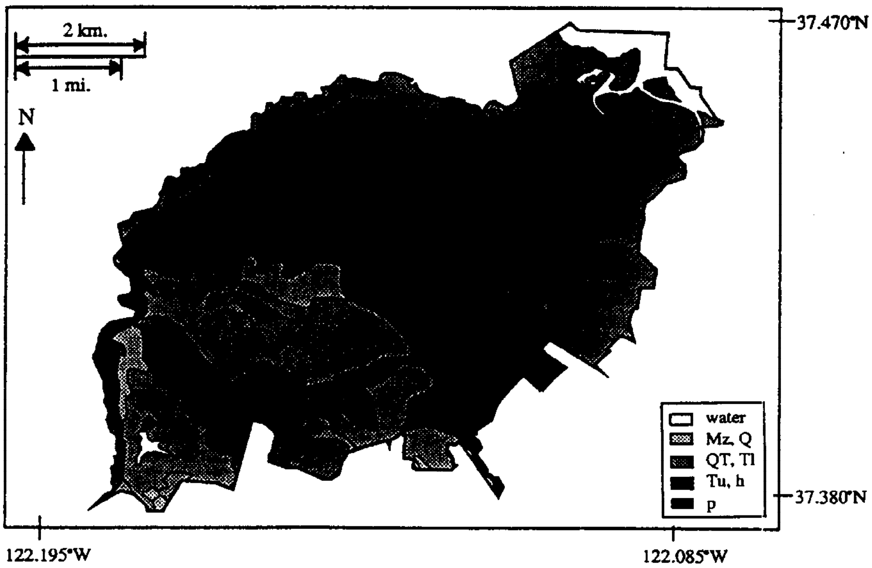

Fig. 5. Map of simplified surface geology in Palo Alto, CA.

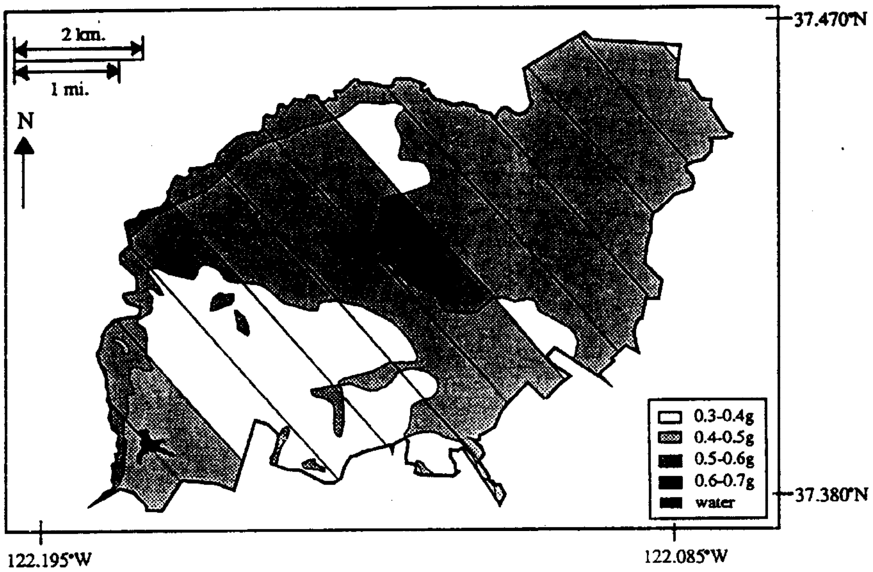

Fig. 6. Surface PGA in Palo Alto, CA for M7.5 on the San Andreas fault.

CONCLUSIONS

The general methodology presented in this paper can be implemented in a wide range of geographic areas in the world. Two applications are used to illustrate some of the features of the system. For example, the loss estimates obtained for the Palo Alto area can be used to identify high risk facilities, where high risk may be defined as high dollar loss facility. The transportation systems shown on Figures 7 and 8 are currently being investigated to identify links within the system that are critical for emergency response and may need to be retrofitted. In addition, the utility of geographic information systems and database management systems is demonstrated. Such systems can be particularly useful for disaster planning and mitigation decision in high seismic risk areas.

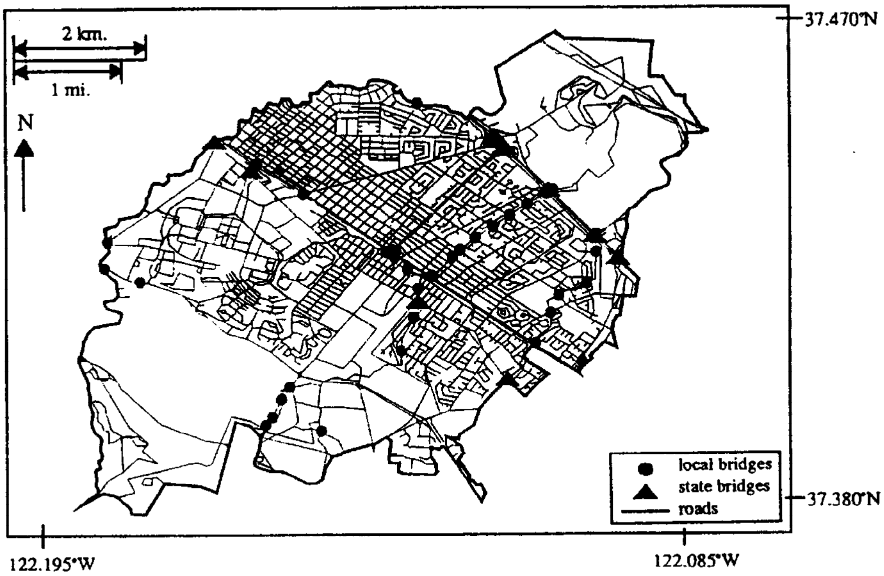

Fig. 7 Transportation systems in (a) Palo Alto, CA

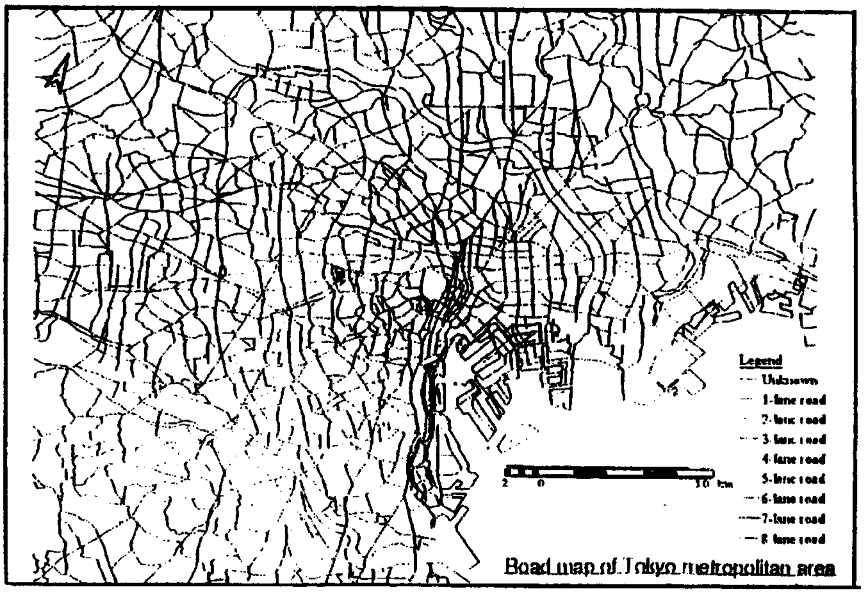

Fig. 8 Transportation systems in Tokyo, Japan

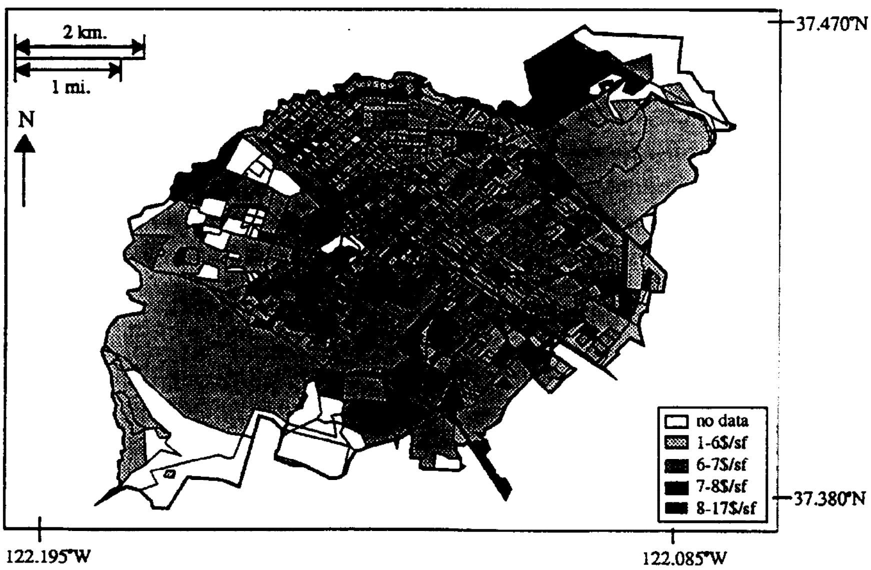

Fig. 9. Distribution of dollar loss per square foot of built area in census tracks in Palo Alto, CA.

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