USING THE GIS TECHNOLOGY AS A TOOL IN RISK MANAGEMENT FOR NATURAL DISASTERS

Dr Jahid Aybet
Department of Computer Engineering
aybet@iku.edu.tr
Dr Tülin Yazgaç
Department of Industrial Engineering
t.yazgac@iku.edu.tr
Istanbul Kultur University, Istanbul, Turkey

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Abstract

Most of the data sets which are used or expected to be used in risk and disaster management have a common characteristic, namely, a geographic reference, defining the location, size and other characteristics of any object which occupies a place in the three-dimensional space. Geographic Information Systems (GIS) offer excellent tools to handle the geo-referenced data sets. Risk Management deals with pre-disaster activities that result in mitigation and preparedness. The analytical work in risk management process generally involves: (i) vulnerability analysis, (ii) impact analysis and (iii) consequence analysis. Therefore this paper attempts to look into the risk management issues, bearing in mind an earthquake disaster situation, from the point of view of GIS technology and its application to these issues.

As the location, size and other attributes of spatial objects and the topological relations between them change rapidly over the time in a disaster situation, GIS as an information system needs to be capable of making time series analysis by keeping a track of transitional status of spatial objects. Therefore spatial data should be processed together with temporal data.

Introduction

The data sets to be used in risk and disaster management may vary considerably from earth surface characteristics to socio-economic characteristics of societies, from transportation to population census data depending on the nature and the purpose of the management problem to be dealt with. However, most of the data sets which are used or expected to be used in risk and disaster management have a common characteristic, namely, a geographic reference. Generally, geographic references in information systems are used to define the location, size and other characteristics of any object which occupies a place in the three-dimensional space. The systems that handle the geographically referenced data sets are Geographic Information Systems (GIS) which offer excellent tools to handle the geo-referenced data sets. The GIS technology, which has reached a mature state in recent years, has numerous applications in Risk and Disaster Management.

"Risk Management" refers to the management issues in a pre-disaster situation which deals with the factors effecting the state of preparedness before a natural disaster. "Disaster Management" refers to the issues related to the managing of a post-disaster situation which deals with the factors effecting the communities and services immediately after a natural disaster. This paper deals with risk management part of the overall emergency management.

Risk Management

Risk Management, being the first part of overall emergency management, deals with pre-disaster activities that result in mitigation and preparedness (Waugh Jr, WL, 1998). Mitigation covers all pre-disaster activities involving the assessment of risks and reducing the potential effects of disaster. Mitigation efforts require detailed information on existing land use, land cover, transportation routes, building stocks, building regulations, hazard controls, insurance programs, etc. Such information is usually stored in and made available through local authority GIS (Geographic Information Systems) databases. Preparedness is again the result of pre-disaster activities that involve readying for the expected threats. Preparedness efforts include contingency planning, organising the cooperative efforts of official and civil response agencies, allocation of resources, dissemination of information and training.

Mitigation and preparedness processes often overlap with the disaster response and recovery activities. They are not more than functional categories which facilitate several managerial tasks before, during and post disaster periods. From administrative point of view, they indicate the responsibilities that both central and local authorities should undertake in preparing various disaster management programs which are relevant to the dangers faced by the communities from the likely natural disasters. Risk management is all about preparing ways and means for change and adaptation under rapidly changing adverse circumstances.

In order to result in mitigation and preparedness for natural disasters in pre-disaster situations, the analytical part of risk management process generally involves (Harrald JR, et al, 2000):

(i) Vulnerability/ exposure analysis,
(ii) impact analysis and
(iii) consequence analysis.

Therefore this paper attempts to look into the risk management issues, bearing in mind an earthquake disaster situation, from the point of view of GIS technology and its application to these issues.

Considering the likelihood of natural disasters, the probability of an event occurring multiplied by the impact of the event will give the value of the risk. The events that are encountered in natural disasters have low probability and high consequence.
Risk assessment involves the quantitative determination of the likelihood and extent of harm that may result from hazards. The analysis and quantification of risk involves

the employment of different tools such as simulation, expert systems, statistical analysis of historical data (e.g. regression analysis), and fault tree analysis.

Vulnerability Analysis

Within the process of vulnerability analysis, two main steps are identified:

(i) Determining the existing situation with regard to building stock, public utilities infrastructure, location and distribution of public facilities and location and distribution of population.

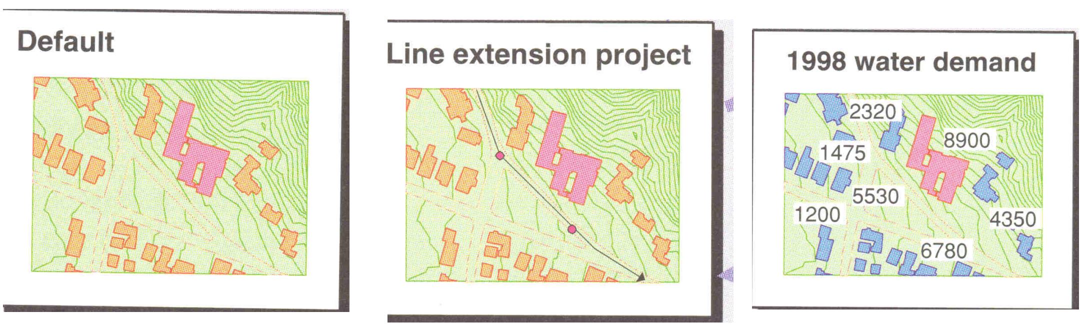
(ii) Definition of the zones with various degrees of vulnerability within the region under study.

<u>Determining the existing situation:</u>

The information about the existing situation with regard to all the relevant data about the physical environment (land use, building stock, transportation networks), infrastructure (public utilities) and demographic information is captured and stored in a GIS database. Almost all the GIS software products in the Information Technology market are capable of providing this information. The important thing is that the GIS database needs to be updated continuously to provide upto date information if and when the disaster strikes. There is a wealth of literature on GIS technology describing the systems capable of doing this (Hogdson ME, Palm R, 1992), (Towers A, Gittings BM, 1995). Studies on crisis solving and response to crisis define the first two steps of the process as search for information and analysis of the current information (Heath R, 2000). Accurate information about the conditions of buildings, roads and other public utilities is vital to build a true picture of the existing situation.

In a disaster situation changes occur very fast, people move from one place to another as buildings become uninhabitable, buildings' usage changes, for example, a school can be used for residential purposes or a warehouse may be used as a school. Therefore, from technological point of view the most important aspect of a GIS database is its capability to capture, store and analyse spatial data with time dimension. The GIS as an information system needs to be capable of making time series analysis by keeping a track of transitional status of spatial objects. The location, size and other attributes of spatial objects and the topological relations between them change rapidly over the time. Therefore spatial data should be processed together with temporal data. Current GIS software products provide capabilities to use temporal data as one of the attributes of a spatial object, but it would not be an efficient way of tackling this problem. Each spatial object should be defined by (x,y,z,T) T being the time of creating or modifying this spatial object so that any number of different versions of the same data set with different time stamps can be stored in the GIS database.

Some GIS software products provide a solution to this problem as versioning the spatial objects for the geodatabase (Zeiler M, 1999).



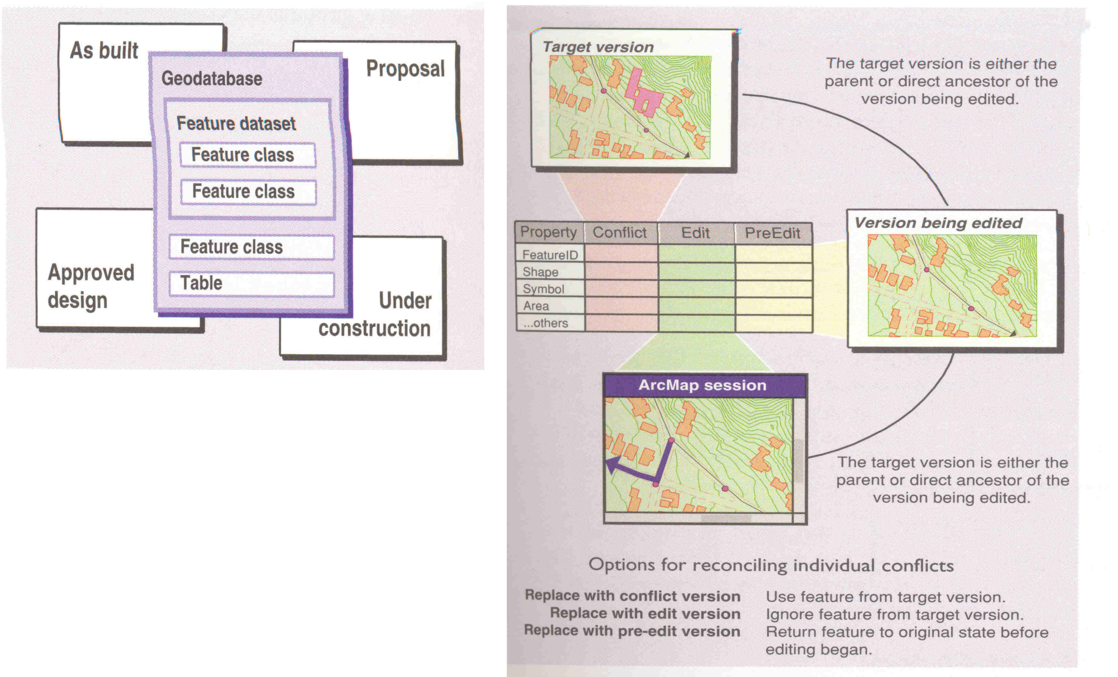


Fig.1 Versioning the main data set to represent different versions of data

Spatial objects belong to features and features belong to feature classes. When a feature dataset is versioned, all of its tables and feature classes are also versioned. Different versions of data represent different features, or the changes to the same feature at different times. This method provides a “snapshot view” of features at a particular point in time.

The method proposed by (Kakumoto, et al, 1999) uses a “space-time approach” model to incorporate the time dimension into the spatial data set. This method was used to develop a new spatial-temporal GIS called DiMSiS to handle the disaster data after the Kobe earthquake in Japan.

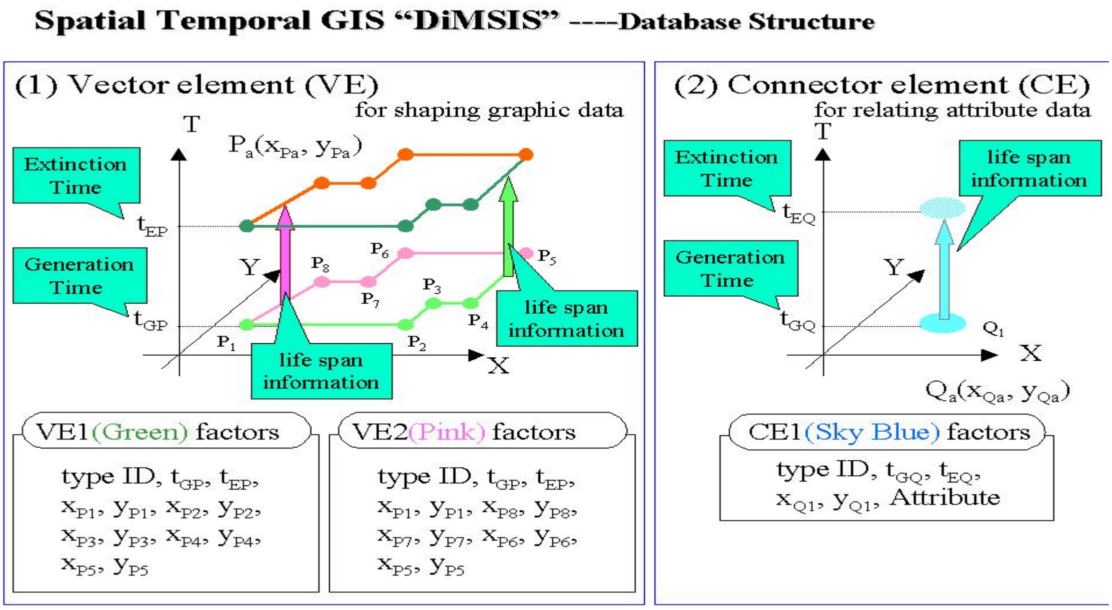


Fig.2 Spatial-temporal data organisation principle of DiMSiS

In order to determine the existing situation with regard to potential disasters (earthquakes in particular) the spatial-temporal GIS database should store data for the following data items as a minimum data set as a basis for a vulnerability analysis application.

Baseline data:
- public infrastructure
- building stock/ housing
- roads/ transportation networks
- complete land use/ land cover
- topography/ shoreline
- soil types
- vegetation.

Disaster specific data:
- fault lines
- soil moisture
- land slide activities
- earthquake activities.

<u>Definition of vulnerability zones:</u>

The second phase of the work involves analysis of the existing situation to delineate the problem areas, definition of zones with respect to various degrees of vulnerability within the region under study.

The spatial-temporal information system (GIS) should be used to create the following for the region (at-risk area) under study:

- Building inventory by location,
- Infrastructure inventory by type and location,
- Business inventory by location,
- Population density and the distribution of population across the area.

As a result of this analysis the GIS can delineate the boundaries of vulnerable areas with varying degrees of vulnerability on the existing (default) maps and store the relevant data about these areas in the database.

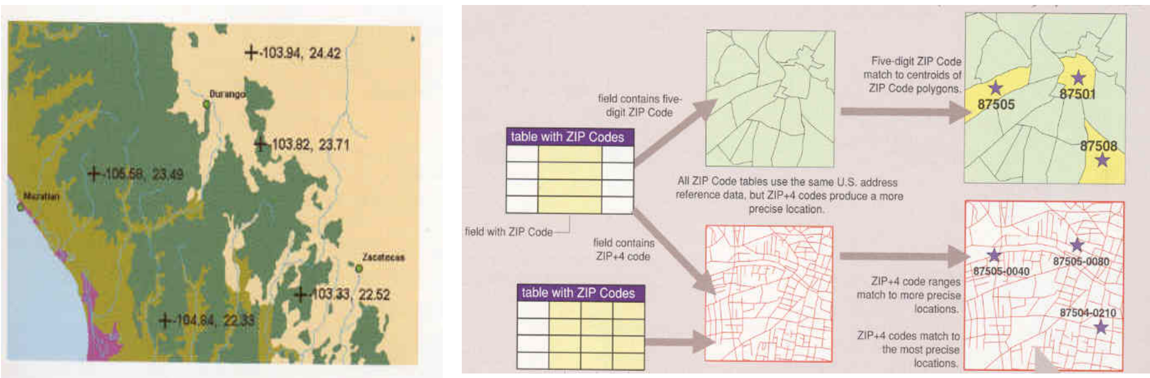


Fig.3 GIS systems provide facilities to create areas of common characteristics such as “Vulnerability areas” on the default maps and link them to the relevant database tables to store data about each vulnerability area.

Impact Analysis

This phase analyses the impacts given by the vulnerability/ exposure analysis. It considers the likely impacts of the disaster at varying degrees, for example earthquakes at different magnitudes. Using models to predict the likely effects on building stock, public utilities infrastructure, on the existing population and human activities would help to create disaster event scenarios in connection with earthquakes' magnitude levels.

After the identification of the potential disaster event scenarios, the probability of each scenario is estimated. The results of these scenarios should indicate the number of buildings with different damage degrees, number of fatalities and injuries, cost of building loss, and damage of public utilities infrastructure (effects on transportation, power, water supply, and telecommunications networks).

An example of impact analysis is Damage Simulation Model (Markus M, et al, 2000) which was based on disaster event scenarios to demonstrate the potential damage and loss and to measure the variations of impact with time. The model developed provides facilities for checking building height information from air-borne laser scanning and compares them with the existing height data in the GIS database. Such models are also used to measure the efficiency of different mitigation strategies.

Consequence Analysis

The last phase of risk management analyses the consequences given by the impacts. In other words, the likely consequences of the disaster obtained from the Impact Analysis are used to estimate the loss of human life in accordance with the results of different vulnerability scenarios. Analysis of the likely consequences of failures in public utility infrastructure and hence in public services, to estimate the effects of disruptions to public services are the expected results of this phase.

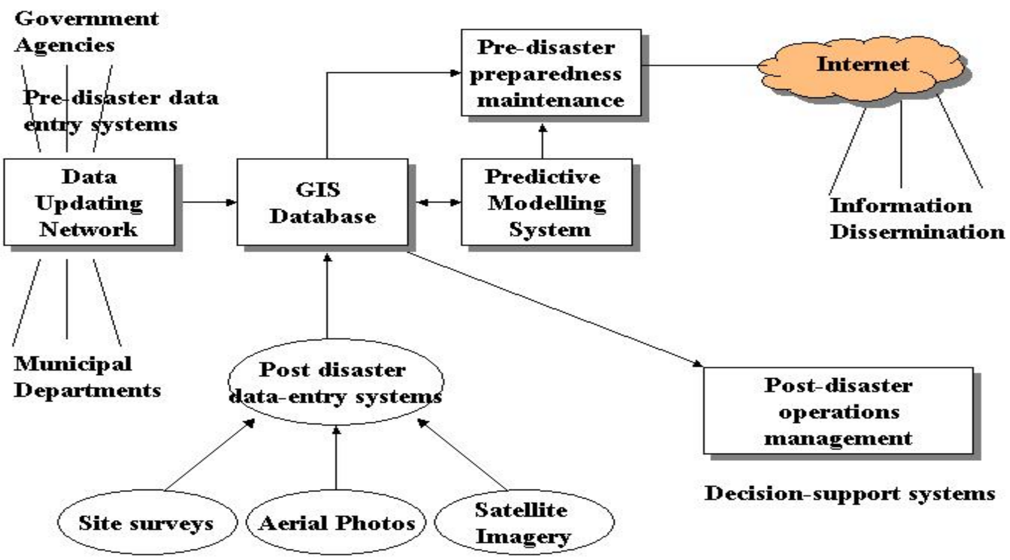


Fig.4 General outlines of system architecture for a risk and disaster management information system

GIS can provide a powerful analytical tool, but it has no predictive capability. In order to overcome this shortcoming GIS has to be integrated with a predictive modelling system. Main problem area with this method is data transfers between the modelling system and the GIS database. The output from the modelling system should be transferred to GIS for display as an overlay on the default maps, or used as an input into the network analysis or simply stored in the database together with other spatial and attribute data. Again it would be necessary to emphasise the temporal capabilities of the GIS in use, as the provision of services/ facilities and their utilisation would be in dynamic nature on the time dimension. The integration of GIS and modelling system would provide the capability to display spatial representation of predictive information in conjunction with the other vulnerability analysis data.

Some proprietary GIS software products provide network analysis modules which can be integrated with model-based methods, location-allocation modelling in particular (Birkin, et al, 1996). Location-allocation models are a class of multi-facility location problems which are concerned with the location of facilities so as to serve the distribution of population in the best way. Thus, they aim at determining both the location of the facilities, and the allocation of individuals to those facilities (Francis RL, et al, 1992), (Birkin M, et al, 1996). These models simultaneously optimise the location of facilities such that their accessibility to individuals is maximised, and the network of facilities is efficient with respect to scarce resources. The most important of these class of models is the “p-median problem” with the objective of finding the optimal locations for p facilities (hence, the name “p-median”) relative to q demand points or demand zones (Birkin M, Wilson A, 1986):

$$\underset{\{Sj\}}{\text{Minimize}} \quad Z = \sum_{j=1}^{p} \sum_{k=1}^{q} X_k h_{jk} c_{jk}$$

subject to:

$$\sum_{j=1}^{p} h_{jk} = 1 \qquad \forall k \qquad (1)$$

$$h_{jk} = \begin{cases} 1, & \text{if demand zone } k \text{ is allocated to facility } j \\ 0, & \text{otherwise} \end{cases} \qquad \forall j,k \qquad (2)$$

where:

$\{S_j\} = (x_j, y_j)$ is a facility location,

X_k is the demand at k,

c_{jk} is the distance between j and k.

In the basic model, optimisation refers to accessibility (distance to facilities) minimisation. Constraint (1) assures that each demand zone will be served by a single facility, and the zero-one variables in (2) display the allocation feature of the problem. The distance between j and k is measured and given by the GIS according to the results of impact analysis, subject to the availability of the open routes under different disaster event scenarios.

Conclusions

Apparently, it is essential that spatial data and attribute data should be used together with temporal data in order to meet the information demands of a risk and disaster management system. Geographic Information Systems can handle spatial-temporal data either by creating different versions of spatial objects with different time stamps or by incorporating the time dimension into the spatial object that may provide a faster system performance. GIS creates a model of the existing situation in terms of location and topological relations of spatial objects and efficient analytical tools for vulnerability analysis and impact analysis. However it needs to be integrated with a predictive modelling system to be used in consequence analysis. The most crucial task in integration process is data transfers especially providing a seamless data transfer facility so that the results of the predictive model can be displayed in conjunction with the other GIS data.

In short, Geographic Information Systems provide a powerful Information Technology tool as a basis for an information system to be used in risk and disaster management.

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Short Biographies

Dr Jahid Aybet, currently Professor and Head of Computer Engineering Department at Istanbul Kultur University, Istanbul, Turkey. Previously a Senior Lecturer at the University of Luton, Department of Computer Science and Information Systems in the United Kingdom, prior to that a Principal Consultant with LOGICA UK ltd., a software and systems integration company in the UK. Research interests, GIS and Remote Sensing integration, data mining with spatial databases, information systems for risk and disaster management.

Dr Tülin Yazgaç, currently Associate Professor and Head of Industrial Engineering Department at Istanbul Kultur University, Istanbul, Turkey. Research interests include mathematical modelling, multi-criteria decision analysis, and supply chain management.