A GIS-Based Regional Risk Analysis Approach for Bridges

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ABSTRACT

A GIS-based regional risk analysis program to interactively study the vulnerability of bridges in a regional highway network is described. The analysis utilizes three major components. The use of a GIS system as the integrating environment to display geographic data, to handle inquiries and to display the results of a query. A risk model for bridges which can predict the level of damage due to a particular intensity of ground motion at a bridge site. A ground motion attenuation model to predict the intensity of ground motion at a particular bridge. The interactive components are supported by data files which encode characteristics such as potential earthquake sources and magnitudes, and characteristics of the bridges which are important for damage and failure analysis.

1 INTRODUCTION

This paper describes a GIS-based regional risk analysis approach for the vulnerability and risk assessment of bridges subjected to earthquakes and other natural hazards. Particular emphasis is placed on the use of Geographic Information Systems to rapidly analyze the potential spatial impacts of natural hazards. Such a procedure could improve the basis for short and long-term planning by government agencies and private organizations.

The use of a GIS-based approach provides a platform to integrate the wide variety of information needed to evaluate the impact of earthquakes or other natural hazards on a regional network of primary and secondary bridges. The GIS is used to provide real-time interactive capability, for efficient database management, and as a tool to integrate earth science, structural characteristics, topological road system characteristics and other vital information forming a risk based model which can be utilized for decision making.

Initial development was carried out using Erie County in Western New York as the study region although the approach is general and could be applied to any geographic region for which data is available. Data for bridge performance and failure under earthquake and natural hazard loadings were collected from published sources. Although the data presently available are not large,the methodology is designed to improve as more data are collected. This type of approach will also be

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helpful in identifying what type of data would be most useful in future analysis and decision making. The use of the GIS-based approach provides a valuable tool for risk analysis of bridges in a regional transportation system. A major part of the effort is the generation of the various types of GIS databases used in the analysis. It is, therefore, desirable to design the system to be compatible with other efforts which are generating GIS data sc that this data can be directly utilized in the analysis. Arc/Info is the GIS system used in this study as it is in wide use in the SUNY at Buffalo university system.

2 GENERAL APPROACH

The overall approach involves three major interactive components:

(a) The use of GIS to provide the interface to display geographic data, to handle queries and to display the result of a query.

(b) A risk model for bridges which can predict the expected level of damage due to a particular intensity of ground motion at the bridge site.

(c) A ground motion attenuation model to predict the intensity of ground motion at a particular bridge due to energy release at a potential source.

These interactive components are supported by data files which encode characteristics such as potential earthquake sources and magnitudes, and bridge characteristics which are important for damage and failure analysis. As is usual in a GIS system, these files can be generated externally but in a format compatible with the GIS system.

3 GEOGRAPHIC DATA

The assembly of geographic data for a particular application requires the consideration of many parameters such as scale and resolution, feature detail, organization of layers for information, coordinating system and others. For this particular study, an enhanced tiger data file for Erie County, New York was obtained from American Digital Cartography in a form which could be readily input into the ARC/INFO system. Although spatial resolution of the Tiger files only provide the location of a bridge within 75 feet, it was felt that this was quite adequate for this study, particularly in view of the uncertainties inherent in the earthquake source data and the attenuation models available.

4 RISK ASSESSMENT OF BRIDGES

A simplified model for GIS-Based risk analysis of bridges in regional environments was developed for this study. The procedure followed was to first collect as much data as could be readily found in the published literature regarding bridge failures and damages from earthquakes. Relatively complete data sets were found for 74 bridges which were damaged or failed during an earthquake. These data were examined to establish a suitable classification scheme which could encompass the major variables related to bridge performance, damage and failure. Some of the features considered are bridge type, design specification used, types of components which were involved in damage or failure, and characteristics of loading. The latter item is related to potential earthquake source mechanisms and earthquake ground motion attenuation which is discussed in a later section of this paper.

A major problem in extracting damage and failure information from published sources was the lack of any standard for reporting such data. In order to attempt to establish a reasonably consistent procedure for data evaluation, a series of levels of classification were established. On an overall or macro level, the parameters can be grouped in loading environment or site intensity due to a given earthquake, degree of damage, soil conditions, foundation type and structural parameters such as pier details, materials used and details such as bearing type. Clearly, bridge failures or damage could be initiated by liquefaction or surface faulting, however, in order to reduce the number of parameters to be considered in this study, these types of failure conditions were deferred for future study and primary consideration was placed on damage or failure due to ground shaking rather than ground failure. The 74 bridges used in this study excluded these types of failure.

A series of general (or perhaps fuzzy) categories were selected for the initial work on this problem. These categories are rather broad as the data available is also rather fuzzy and a high degree of precision does not seem appropriate. Some examples of the parameters selected are:

Intensity of peak ground acceleration
Year of design specification under which the bridge was constructed or modified.
Type of superstructure.
Shape of superstructure.
Material of superstructure.
Internal hinges.
Type of Pier.
Type of foundation.
Height of pier.
Material of substructure.
Irregularity in geometry or stiffness.

A more complete listing of parameters is given in Table 1. One important consideration in selecting parameters is the information which is available for bridges in the area to be studied and displayed using the GIS system.

For the identification and characterization of the bridges in Erie County, New York which was used as the demonstration area, a tape of the New York State bridge inventory and inspection data were obtained through the courtesy of the New York State Department of Transportation. The bridges in Erie County were then extracted from the larger state data base along with the desired standard data categories for these bridges. The data selected for damage or failure evaluation from bridges actually subjected to damaging earthquakes were matched to the data available from the NYS inventory.

After data identification and classification was completed, a statistical analysis was performed utilizing a standard multiple regression technique. Four intensities of ground motion were selected using peak acceleration value as the defining criteria. These categories are shown in Table 1. The regression analysis simply evaluates the potential contribution of each parameter to the level of damage for each bridge in the data base used. The resulting damage equation y_j has the following form:

$$y_j = \sum_{i=1}^{N} \beta_i \cdot X_i + C$$

where y_j is the damage or failure level as indicated in Table 2. These damage levels were known for each of the 74 bridges in the data set used and N=14 corresponds to the number of primary categorization parameters selected. The system of 74 equations were solved to determine values for the beta's and C. The beta's, X's and C are shown in Table 1. This type of data analysis based on statistical concept provides a practical indication of how each parameter contributes to the level of damage or failure for bridges in regional environment.

The model developed above represents the damage probability for the entire ensemble of bridges in the data set available. It is also necessary to determine the level of reliability which will result when this model is applied to one individual bridge in the set.

Using the 3 group classification shown in Table 2 the actual and predicted rank of seismic vulnerability of bridges were compared. The results are shown in Table 3. This table shows that the ranks of seismic vulnerability of 57 bridges among the 74 bridge data set are predicted correctly. In other words, for this set there is a 77% probability of correct prediction, which seems to be good enough for this initial GIS-based study. Due to the procedure used, the probability of correct prediction is almost even for bridges in different ranks of seismic damage as shown in Table 4.

Many other damage or failure models could be formulated. For example, another approach would be to evaluate the level of damage to each class of bridge to the particular code which was in effect when the bridge was designed or modified. Ultimately it would be desirable to develop a damage or failure model which could be directly evaluated from the actual bridge design.

5 EARTHQUAKE SOURCE DATA AND ATTENUATION MODEL

For a given study area, the locations of possible earthquake sources which release energy and the variation of surface intensity of ground motion with distance from the source are needed. Clearly each of these topics could be and has been the subject of intense study on their own. As the focus of this study is not on earthquake sources or attenuation laws, information available from sources such as the U.S. Geological Survey, the Electric Power Institute and the National Center for Earthquake Engineering Research were utilized. Possible earthquake sources and attenuation relationships from published literature were used for the study. The risk analysis procedure is a general methodology and when once developed can easily accommodate different source data or attenuation relationships. Because the data on probable magnitudes is extremely sparse, the GIS-based procedure is set-up to allow a user to assign various magnitudes to source events to evaluate the potential consequences.

A recent research supported by the Electric Power Research Institute (EPRI)[4] studied the eastern United States with respect to various seismicity parameters and estimated the maximum magnitudes that a given seismic source might generate. Additional information is available from the U.S. Geological Survey and from the National Center for Earthquake Engineering Research. Attenuation relationships have been studied by a number of researchers[2,3,4,5,6]. Problems which must be addressed involve estimating a value for epicentral surface intensity for a particular source and set of geological conditions and then to estimate the attenuation relationship for a given geographic region. The problem is further complicated because surface ground motion intensity is also highly sensitive to local soil or geological conditions and to frequency content of the waves propagated from the source and repropagated from geological discontinuities both below and at the surface.

For this study attenuation relationships reported in the literature were selected for use in the risk analysis procedure. For example, the study by Atkinson[2] developed surface peak acceleration relationships in terms of earthquake magnitude. It is apparent that problems exist with most of the relationships currently available and a defensive position is to use a relationship which seems to fit data as close as possible for the study region being considered. For this study, the model developed by Atkinson was used for initial analysis. As further information becomes available, improved relationships can be substituted. It is desirable to specify sources in terms of magnitude as this is the type of parameter most planners are accustomed to.

6 INTERACTIVE GIS-BASED ANALYSIS

With the basic procedures for risk analysis defined, the integration with the GIS system can be formulated. One of the first steps consists of taking the NYSDOT bridge database for Erie County and digitizing the location of each bridge along with the associated attributes. As the inventory of bridges ranges from interstate bridges to local bridges, a system of icons to identify the bridges and their importance in the regional transportation network is required. For each bridge a table or file is prepared containing the attributes which are required for the evaluation (i.e. soil conditions, foundations, piers, etc.).

An attribute table is also prepared for possible sources and their data encoded or digitized. Each source can include potential ranges of magnitudes and their probabilities. As an option the user can specify an arbitrary source and magnitude and display impacts on the bridge network.

Menu bars are defined to display choices such as source locations, bridge types and similar information. For each of these classes, a submenu offers choices such as sources likely to have magnitudes greater than a certain level or between certain bounds.

The overall flow diagram for the program is shown in Fig. 1.
Graphic data are stored in layered databases and tabular data are interactive with the graphic data. New information generated is contained in mapoverlays. Topological data relating bridges and sources are generated. An internal or external language can be used to generate special data related to the risk assessment model.

Standard features of a GIS program are used for map file input, zooming, print-out and report generation.

Fig. 2., which is a result of a peak ground motion of 0.2 g predicted by the model developed, shows that 2 of the 33 bridges in the study area have a high seismic vulnerability, 4 bridges in the study area have a moderate seismic vulnerability, 27 bridges have a low vulerability to damage.

The use of the GIS system provides a new dimension for engineering analysis and planning.

7 CONCLUSIONS

GIS systems provide new opportunities for interactive analysis of problems such as regional or spatial risk analysis. The GIS system by itself is only an added tool and does not remove the necessity to formulate appropriate analysis techniques for evaluation of problems such as risk assessment for bridges. A valuable feature of the GIS-based approach is that it provides a general methodology in which components such as the damage model or even type of hazard could be easily modified or substituted without having to remanufacture the entire system. The risk analysis model developed for this study could be additive, as more factors and research findings are gathered and the accuracy of correct expectation of future damage state will be further improved. The role of GIS in integrating these modules into a harmonic interactive system will find increasing use in the future for studying large-scale engineering problems.

Table 1. Components of Risk Assessment Model

VARIABLES	CLASSIFICATION	BETA'S & C
y = Degree of Damage	o;no 1;minor 2;moderate 3;severe 4;falling-off of super structure	
X1 = Intensity of Peak Ground Acceleration	1; A<0.1G 2; 0.1G≤A<0.2G 3; 0.2G≤A<0.3G 4; 0.3G≤A	0.222
X2 = Design Specification	1; before 1940 2; 1940-1971 3; 1972-1980 4; after 1981	-0.358
X3 = Type of Superstructure	1; simply supported girder-2 spans or more or 2 level or more elevated model 2; simply supported girder-single span or continuous girder 3; arch, frame, cable-stayed, or suspension bridges	-0.234
X4 = Shape of Superstructure	1; straight 2; skewed or curved	0.500
X5 = Material of Superstructure	1; steel 2; RC or PC 3; timber, masonry or other old materials	-0.098
X6 = Internal Hinge	1; not exist 2; exist	0.373
X7 = Type of Pier	1; solid or frame 2; individual columns-2 or more 3; individual columns-single	-0.065
X8 = Type of Foundation	1; spread footing 2; footing on piles 3; foundations designed by 1983 specification or later	0.231
X9 = Material of Substructure	1; steel 2; concrete 3; timber, masonry or other old materials	0.514
X10 = Height of pier	1; H<15 Ft 2; 15≤H<30 Ft 3; H≥30 Ft	0.101
X11 = Irregularity in Geometry or in Stiffness	1; no 2;yes	0.562
X12 = Site Condition	1; type 1 2; type 2 3; type 3 (AASHTO 1988) (ref.1)	0.421
X13 = Effect of Scouring	1; none 2; recognized	-0.273
X14 = Seat Length	1; good 2; fair 3; poor	0.478
		C=-2.243

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Table 2. Rank of Seismic Vulnerability

Rank of Damage Degree	Rank of Vulnerability
0: no damage 1: minor damage	C: Low
2: moderate damage	B: Moderate
3: severe damage 4: falling- off of Superstructure	A: High

Table 3. Comparison of Actual and Predicted Rank of Seismic Vulnerability

Rank		Predicted Vulnerability Rank			Total
		A	B	C	
Actual Vulnerability Rank	A	14	4	0	18
	B	3	13	1	17
	C	1	8	30	39
Total		17	26	31	74

Table 4. Probability of Correct Prediction

A	78%
B	76%
C	77%
Total	77%

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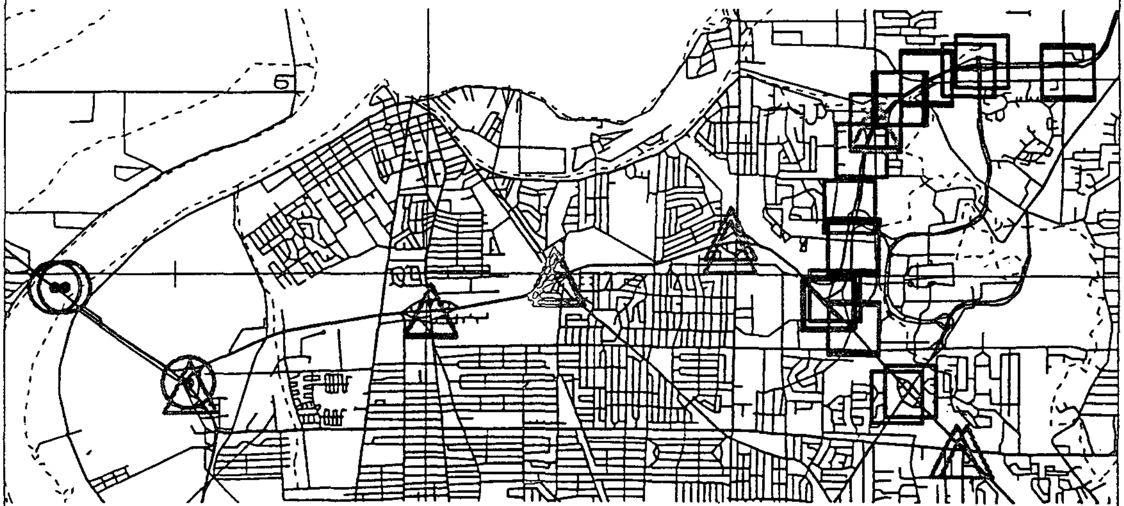
Figure 2.

Seismic Vulenrability Of Bridges When A = 0.2 g (Model A)

Northwestern Part Of Erie County, NY



□ Bridges in Low Seismic Vulnerability

△ Bridges in Moderate Seismic Vulnerability

⊙ Bridges in High Seismic Vulnerability

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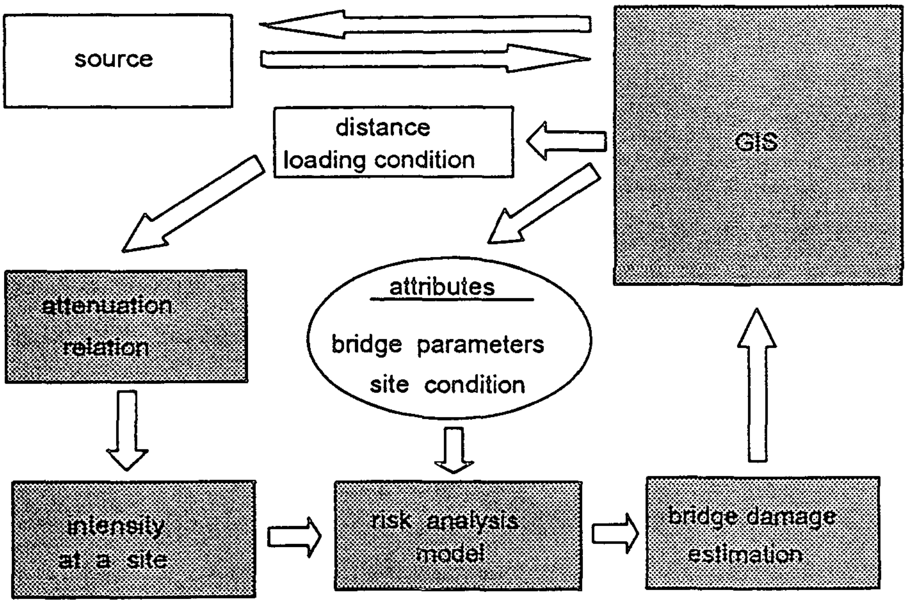
Figure 1. GIS - Model Interaction Flowdiagram



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