

Article

# GIS-Based Seismic Hazard Prediction System for Urban Earthquake Disaster Prevention Planning

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**Abstract:** It is of great significance to conduct seismic hazard prediction in mitigating the damage caused by earthquakes in urban area. In this study, a geographic information system (GIS)-based seismic hazard prediction system for urban earthquake disaster prevention planning is developed, incorporating structural vulnerability analysis, program development, and GIS. The system is integrated with proven building vulnerability analysis models, data search function, spatial analysis function, and plotting function. It realizes the batching and automation of seismic hazard prediction and the interactive visualization of predicted results. Finally, the system is applied to a test area and the results are compared with results from previous studies, the precision of which was improved because the construction time of the building was taken into consideration. Moreover, the system is of high intelligence and minimal manual intervention. It meets the operating requirements of non-professionals and provides a feasible technique and operating procedure for large-scale urban seismic hazard prediction. Above all, the system can provide data support and aid decision-making for the establishment and implementation of urban earthquake disaster prevention planning.

**Keywords:** GIS; urban seismic risk assessment; seismic hazard prediction

## 1. Introduction

An earthquake is one of the most severe natural disasters facing humanity today, especially in urban regions [1]. Recent earthquakes both within and outside China [2–4] have shown that it is important to implement urban earthquake disaster prevention planning before the disaster to reduce losses due to earthquakes. Therefore, to tackle earthquake hazards in China, it is necessary to establish urban earthquake disaster prevention planning in China [5]. Seismic hazard prediction is one of the basic methods that can be employed for earthquake disaster prevention.

A geographic information system (GIS) is a computer system that can collect, store, analyze, and display geo-referenced information. City buildings are characterized geographically by their types, functional diversity, and large quantity. Hence, it is efficient to apply GIS in the dynamic spatial analysis of city buildings, and it will also be of benefit in some related activities, such as fast post-earthquake loss evaluation and disaster relief.

GIS has been used for earthquake disaster prevention for more than 20 years. Research in America and Japan is relatively established such that the system developed by these two countries is universally applied in civilian areas [6–8]. China started late in this field, but has also recorded great success [9,10]; GIS-based information management systems for urban earthquake disaster prevention have been set up successively in Yunnan, Langfang, and Hefei.

However, the application of GIS for earthquake disaster prevention in China has concentrated more on the management and acquisition of basic data and research results [11], which cannot meet

the growing need for damage evaluation and display. In addition, seismic hazard prediction involves investigating and calculating varied structural characteristics and parameters of buildings in a large area. It does not only generate a large amount of on-site investigation and analysis, but requires a professional background for the participants.

Based on the above background and previous research, a seismic hazard prediction system for urban earthquake disaster prevention planning was developed based on ArcGIS. From the practical demand for urban earthquake disaster planning, the system uses data acquisition and a processing procedure to predict building seismic hazard, in order to minimize human intervention and make it more applicable. Meanwhile, the system realizes visual management of urban seismic hazard prediction, assisted planning of disaster prevention, and decision-making in emergency rescue. Finally, Weifang Street in Pudong New Area, Shanghai was selected as the test area in this study. Compared with results from previous studies, results from this study are essentially the same and even slightly better, which highlights the reliability of the analysis method implemented in this system.

Data used in this study was from the Pudong branch of the Shanghai Institute of Surveying and Mapping.

## 2. System Framework Design and Function Realization

The seismic hazard prediction system developed in this study is based on ArcGIS. The system has three toolboxes: the statistics toolbox of seismic hazard matrix, the prediction toolbox of earthquake damage evaluation, and the assignment toolbox of the construction time and predictive results. The flow chart of the system is illustrated in Figure 1.

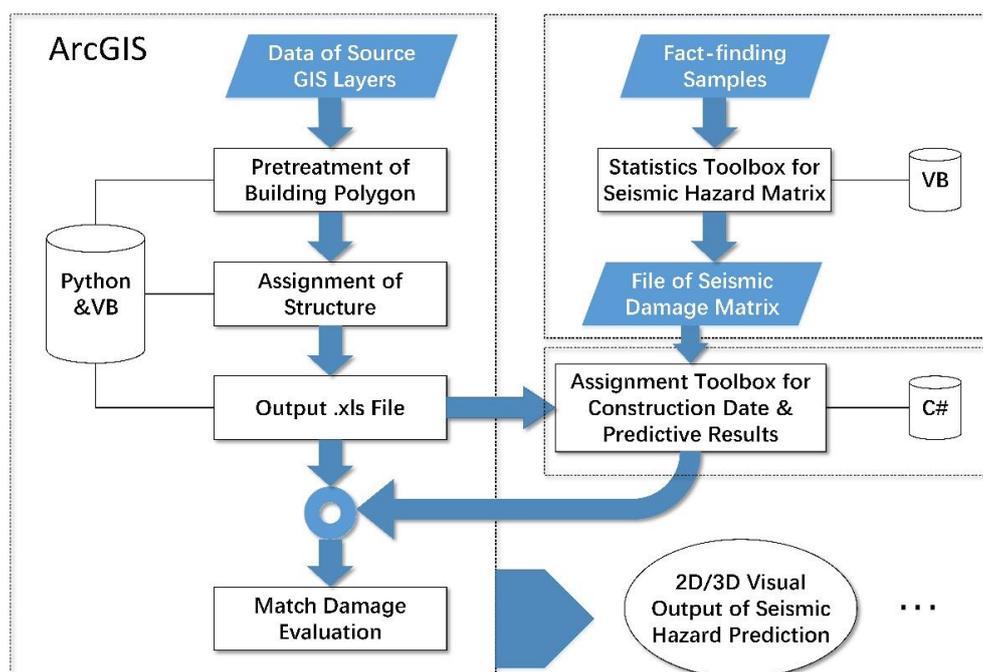


Figure 1. Framework of seismic hazard prediction system.

### 2.1. Statistics Toolbox of Seismic Hazard Matrix

The statistics toolbox of the seismic hazard matrix, which can be regarded as a database system, is developed on VB 9.0. The major function of the system is to realize the batch input, calculation and statistical analysis of data through simple interaction, so as to establish seismic hazard data in the working area. Building vulnerability analysis models are embedded in the toolbox. After inputting fact-finding samples, it implements batch computing and statistical analysis of data through simple interaction and generates a separate project file. The file includes parameter information and analysis

results of all samples, the earthquake damage matrix of all buildings in various structure types, and the damage index calculated chronologically. Only structural types were considered in assigning predictive results to buildings in a previous study [12]; however, in reality, the seismic capacity of buildings is obviously related to the construction time. Therefore, the construction time of buildings was taken into account in this study and, as a result, the prediction accuracy improved as one more dimension was added [13]. The project file will be inputted into the assignment toolbox of the construction times and predictive results as data source.

Buildings were classified into six types: multistory masonry structure, reinforced concrete structure, inner frame and bottom frame masonry structure, single-story industrial building, empty house, old house, and important building. Vulnerability analysis models were established for each building type.

## 2.2. Prediction Toolbox of Earthquake Damage Evaluation

The integrity of the feature attribution of building layer files in GIS is the foundation for building seismic hazard prediction. Attribution assignment consists of structural types and construction time. The prediction toolbox of earthquake damage evaluation contains different workflows generated by the ArcToolbox and Model Builder under ArcGIS Engine, scripted in Python 9.3 and VB 9.0. The toolbox is based on the perfection of building structural types and a data connection with external programs. There are four submodules of the prediction toolbox: the pretreatment module of building polygon, the assignment module of structure attribution, the output module of xls file, and the match module of damage evaluation, as shown in Figure 2.

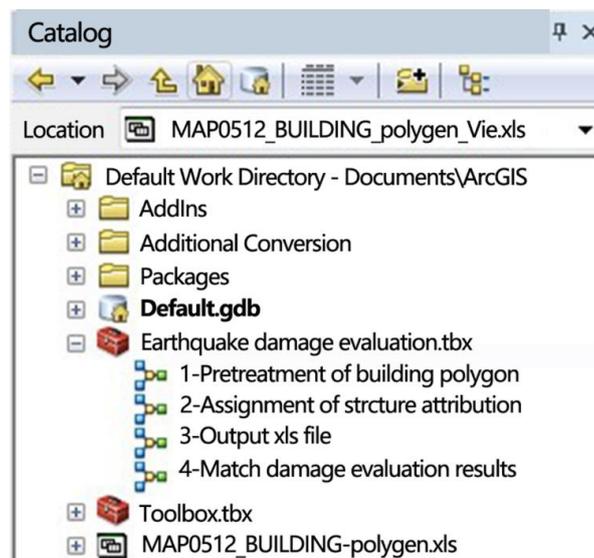


Figure 2. Prediction toolbox of earthquake damage evaluation.

The pretreatment module of building polygon chiefly pretreats layer files, including deleting redundant field information, calculating total area of buildings, screening important buildings, such as schools and high-rise buildings, and defining their attribution fields. The field-processing function of the data management tools in the Arc Toolbox was used and some codes were used for reclassification [14]. Through the pretreatment module, important buildings can be defined, but approximately half of the buildings still lack structural types.

To further perfect structure attributions, the assignment module of structure attribution was developed using the space connection function of the overlay analysis tool in the Arc Toolbox. Space connection means that attributions are transferred to feature classes according to the space relationship between two features [15]. As long as specified space relationships or matching options were found,

the attribution of connection features will be added in the target features. In building layer files, features with intersection relationships can be considered to belong to one building with identical structural type. Except for the attribution transfer according to the intersection relationship between surface features, comprehensive screening and fuzzy classification of building information, such as name, use, area, and number of stories can be carried out to perfect the structural types of features.

After the assignment module, nearly 100% of the layer data are assigned with structural type features. A text area before and after pretreatment is taken as an example, as illustrated in Figure 3. Before pretreatment, there were many features with unassigned structure attributions and the structure type was single; however, after pretreatment, almost all features were well-defined and in rich structural types.



**Figure 3.** Distribution of structural types before and after pretreatment. (a) Distribution of structural types before pretreatment. (b) Distribution of structural types after pretreatment.

The output module of the xls file writes the layer files processed in xls files. The attribution data of the GIS layer was in dbf format; therefore, it cannot be read by other external software. Therefore, a program was scripted in Python to export layer attributions to the default working directory of ArcGIS for the assignment toolbox of the construction time and predictive results for recall [16].

The match module of the damage evaluation results sets a connection between layer files and the exported files of the assignment toolbox of the construction time and predictive results, in order to obtain results of seismic hazard prediction and attribution values of the construction time while sorting data formats for laying the foundation for the final 2D/3D visualized presentation of the predictive results. The processed layer attributions contain intact and visual information as shown in Figure 4.

NAME	STOREY	SHAPE AREA	TOOTALAREA	STRUCTURE	FUC	SIX INS	SEVEN INS	EIGHT INS	AGE
WEIFANG VILLAGE #4	6	610.734929	3664.409571	MS MASONRY	RES	SLIGHT	MIDDLE	MIDDLE	1984-01
WEIFANG VILLAGE #4	6	482.437442	2894.624654	MS MASONRY	RES	SLIGHT	MIDDLE	MIDDLE	1984-01
WEIFANG VILLAGE #4	6	317.666624	1905.999741	MS MASONRY	RES	SLIGHT	MIDDLE	MIDDLE	1984-01
WEIFANG VILLAGE #8	6	485.002876	2910.017254	MS MASONRY	RES	SLIGHT	MIDDLE	MIDDLE	1985-06
TAISHAN METAL FACTORY	4	1239.01211	4956.04844	MS MASONRY	RES	BASIC INTACT	MIDDLE	MIDDLE	UNKNOWN
WEIFANG VILLAGE #8	6	254.503384	1527.020304	MS MASONRY	RES	SLIGHT	MIDDLE	MIDDLE	1985-06
PUZHONG MANSION	1	11.62605	11.62605	RC STRUCTURE	RES	BASIC INTACT	MIDDLE	MIDDLE	-
DONGMING VILLAGE	6	334.72363	2008.341782	MS MASONRY	RES	SLIGHT	MIDDLE	MIDDLE	1985-12
DONGMING VILLAGE	6	390.589718	2343.538309	MS MASONRY	RES	SLIGHT	MIDDLE	MIDDLE	1985-12
DONGMING VILLAGE	5	232.237223	1161.186115	MS MASONRY	RES	SLIGHT	MIDDLE	MIDDLE	1985-12
DONGMING VILLAGE	6	290.958751	1505.752509	MS MASONRY	RES	SLIGHT	MIDDLE	MIDDLE	1985-12
DONGMING VILLAGE	6	230.366178	1382.197068	MS MASONRY	RES	SLIGHT	MIDDLE	MIDDLE	1985-12
WEIFANG VILLAGE #4	6	351.570489	2109.422933	MS MASONRY	RES	SLIGHT	MIDDLE	MIDDLE	1984-01
WEIFANG VILLAGE #8	6	464.762115	2788.572669	MS MASONRY	RES	SLIGHT	MIDDLE	MIDDLE	1985-06
XINMIANG KINDERGARTEN	2	65.778729	131.557457	MS MASONRY	COM	BASIC INTACT	MIDDLE	MIDDLE	UNKNOWN
ZHONGXIN APARTMENT	4	293.997194	1175.988778	MS MASONRY	RES	SLIGHT	MIDDLE	MIDDLE	1996-06
ZHONGXIN APARTMENT	4	278.814935	1115.259742	MS MASONRY	RES	SLIGHT	MIDDLE	MIDDLE	1996-06
TAISHAN METAL FACTORY	3	66.277581	198.832742	MS MASONRY	RES	BASIC INTACT	MIDDLE	MIDDLE	UNKNOWN
ZHONGXIN APARTMENT	4	285.899213	1143.596853	MS MASONRY	RES	SLIGHT	MIDDLE	MIDDLE	1996-06
ZHONGXIN APARTMENT	4	286.385643	1145.542571	MS MASONRY	RES	SLIGHT	MIDDLE	MIDDLE	1996-06
WEIFANG VILLAGE #1	6	501.854905	3011.128433	MS MASONRY	RES	SLIGHT	MIDDLE	MIDDLE	1981-02
WEIFANG VILLAGE #8	6	370.565143	2223.390859	MS MASONRY	RES	SLIGHT	MIDDLE	MIDDLE	1985-06
WEIFANG VILLAGE #8	6	379.005029	2274.030175	MS MASONRY	RES	SLIGHT	MIDDLE	MIDDLE	1985-06
DONGMING VILLAGE	6	341.387716	2048.326296	MS MASONRY	RES	SLIGHT	MIDDLE	MIDDLE	1985-12
DONGMING VILLAGE	6	345.068309	2070.409854	MS MASONRY	RES	SLIGHT	MIDDLE	MIDDLE	1985-12

Figure 4. System-processed attribution table of building layers.

### 2.3. Assignment Toolbox of the Construction Time and Predictive Results

The structure attributions of the building features processed through the modules of the ArcGIS prediction toolbox of the earthquake damage evaluation have been perfected; however, it is still necessary to supplement the construction time of buildings in subsequent works. It will be difficult to import information about thousands of buildings in an area, even in a city, manually; it will consume enormous manpower and resources.

The assignment toolbox of the construction time and predictive results in the system was developed in C#, and web crawler was applied to complete the construction time of buildings. Web crawler is an important part of a search engine that accesses webpages tactically without user intervention [17] as shown in Figure 5.

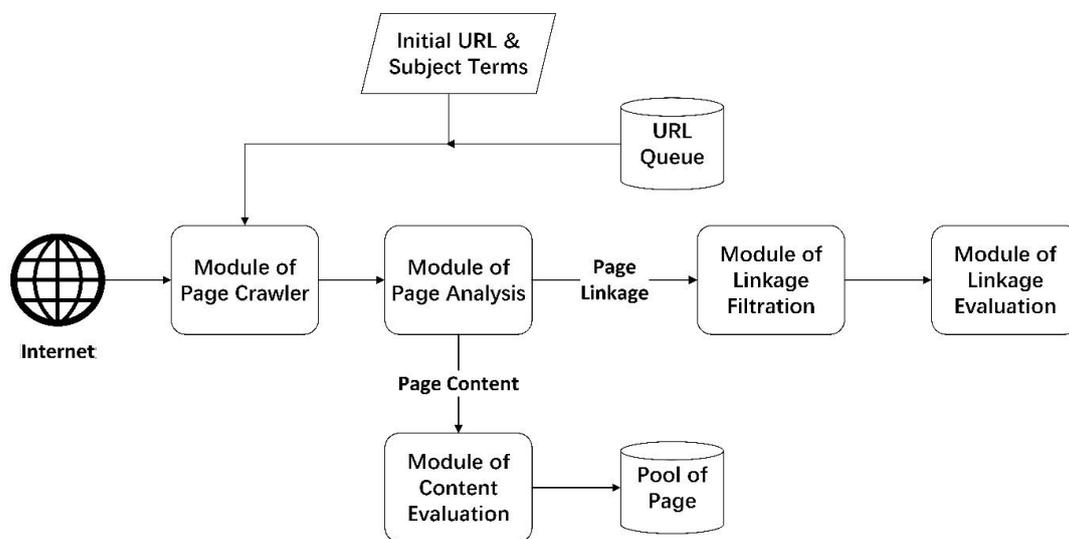


Figure 5. Operating principle of web crawler.

The tool takes attribution files exported from ArcGIS as data source, fetches building names therein to search subject terms, roams the network from an initial URL, and evaluates the dependency between subject terms (the construction times of buildings) and contents in pages. Meanwhile, the tool weights and transmits the significance of parent pages through the chain structure of pages.

The key problem that web crawlers need to deal with is how to determine the relevance of a link to a topic, that is, its data value. This means that crawled URLs are ranked by their qualities, and the pages with high relevance can be accessed first. Currently, the two most widely used methods are the evaluation based on content and link structure.

Content-based evaluation is in accordance with subject terms and current linkage text, including the similarity among URL character strings and anchor texts. A common algorithm called best-first search was adopted in this study [18]. Its general formula is:

$$sim(q, p) = \frac{\sum^{k \in q \cap p} f_{kq} \cdot f_{kp}}{\sqrt{(\sum^{k \in q} f_{kq}^2) \cdot (\sum^{k \in p} f_{kp}^2)}} \quad (1)$$

In the above equation,  $q$  is the subject,  $p$  indicate the crawled pages,  $f_{kq}$  is the appearance frequency of the word  $k$  in  $q$ , and  $f_{kp}$  is the appearance frequency of the word  $p$  in  $q$ .

The web is a type of semi-structured document, including large structural information, such as outlink and inlink. The evaluation method based on link structure weights the significance between linkages through the mutual reference among pages. The most representative one is the PageRank algorithm [19]. It is described by:

$$R(i) = (1 - d) + d \times \sum_{j \in B(i)} [R(j)/N(j)] \quad (2)$$

In Equation (2),  $B(i)$  is the assemblage of the pages orientating page  $i$ ,  $N(i)$  is the number of hyperlinks orientating other pages in page  $i$ ,  $R(i)$  is the significance of page  $i$ , and  $d$  is the decay factor. Decay factor means that the significance of the  $d$  parts of every page is passed on average to the sub-links.

Pages with high dependency and significance will be listed in candidate queues to be accessed first, while pages beside subject terms will be discarded. If the accessed page contains the construction time of buildings, data will be written in the attribution files under the default working directory of ArcGIS [20].

After the assignment of the construction time, select the project file generated by the statistics toolbox of the seismic hazard matrix so that predictive results can be assigned according to the construction time and structural types of buildings.

### 3. Analysis on Application Examples

In this study, Weifang Street in Pudong New Area, Shanghai was selected as the test area owing to its rich structural types and long construction time.

#### 3.1. Verification of System Reliability

The feature classes of the buildings in the test area were analyzed and assigned according to the seismic hazard prediction system developed in this paper. In order to verify the reliability of the system, the processed attribute distribution of the buildings was compared with the data of the actual investigation, as shown in Table 1. The system has a relatively high precision in the interpretation and classification of structure type, especially for multistory masonry structures, reinforced concrete structures, and important buildings. The statistical relative error of old houses and single-story industrial buildings and empty houses is about 10%. But the building area of these two types is small,

so it can be considered that the system effectively identifies each building with fine precision. The inner frame and bottom frame masonry structure structures were not recognized by the system. This is because it is difficult to distinguish the inner frame and the bottom frame masonry structure from the multi-story masonry according to planar geometric features and height; also, these features were not defined on the source layer, which needs to be improved in further research. In general, however, the system can meet the needs for seismic hazard prediction in urban areas.

**Table 1.** Comparison on the system-processed results and actual data.

Structure Type	Multistory Masonry Structure	Reinforced Concrete Structure	Important Building	Old House	Single-Story Industrial Buildings and Empty Houses	Inner Frame and Bottom Frame Masonry Structure	Total
Processed area (m <sup>2</sup> )	1915896	2576957	1444557	6632	3144	0	5947187
Percentage	32.22%	42.33%	24.29%	0.11%	0.05%	0.00%	100.00%
Investigated area (m <sup>2</sup> )	1838400	2421800	1538900	5980	3510	12420	5821010
Percentage	31.58%	41.60%	26.44%	0.10%	0.06%	0.21%	100.00%
Absolute error (m <sup>2</sup> )	77496	155157	94343	652	366	12420	1261774
Relative error	4.04%	6.02%	6.53%	9.83%	11.65%	100.00%	2.12%

### 3.2. Discussion of Results

Buildings were sampled according to the relative specification that the cumulative area of valid samples was approximately 8% of the total area of buildings in the test area. The seismic hazard prediction system developed in this study was applied to analyze samples and run statistics of the seismic hazard matrix. The research results (as shown in Table 2) are compared with those from the Shanghai Institute of Disaster Prevention and Relief in 1993 [21] (as shown in Table 3) and the Institute of Engineering Mechanics, China Earthquake Administration in 2003 [22] (as shown in Table 4), and it can be concluded that the predictive results presented in this paper are essentially the same as the results of 2003 and slightly better than the results of 1993. This is because the seismic behavior of new buildings is generally better than existing buildings; meanwhile, information on construction time was added based on the original methods, which improved the dimension of building information and made predictive results more objective and exact. Therefore, it is believed that the fragility analysis method applied in this system is reliable.

**Table 2.** Seismic hazard results of multistory masonry under different construction time.

Construction Time	Seismic Hazard Level		
	Intensity VI	Intensity VII	Intensity VIII
Before 1970	Slight damage	Heavy damage	Collapse
1970–1980	Slight damage	Middle damage	Heavy damage
1980–1990	Slight damage	Slight damage	Middle damage
1990–2000	Basic intact	Slight damage	Middle damage
After 2000	Basic intact	Slight damage	Slight damage
Total	Basic intact	Middle damage	Middle damage

**Table 3.** Seismic hazard results of multistory masonry in 2003.

Intensity	VI	VII	VIII
Seismic hazard level	Basic intact	Middle damage	Heavy damage

**Table 4.** Seismic hazard results of multistory masonry in 2003.

Intensity	VI	VII	VIII
Seismic hazard level	Basic intact	Middle damage	Middle damage

### 3.3. Visualization Results

The seismic hazard prediction system developed in this study was integrated in ArcGIS with powerful drawing and display functions [23]. According to the damage index calculated by the system, 2D and 3D seismic hazard prediction maps of the test area were drawn.

The 2D seismic hazard prediction map characterizes the global seismic behavior of buildings in a certain area through the mean damage index as shown in Figure 6. The damage index is a non-dimensional index to evaluate the seismic hazard of a certain structure or component under seismic action, and it is an important indicator that evaluates quantitatively the seismic hazard of a structure. The mean damage index is the mean of the damage index of all buildings [24]. It can be calculated by the following equation:

$$D_z = \sum (D_j \times A_j) / \sum A_j \quad (3)$$

In Equation (3),  $D_z$  is the area mean damage index under a certain seismic intensity,  $D_j$  is the damage index corresponding to the damage classification  $j$  under a certain seismic intensity,  $A_j$  is the area of the building corresponding to the damage classification  $j$  under a certain seismic intensity.

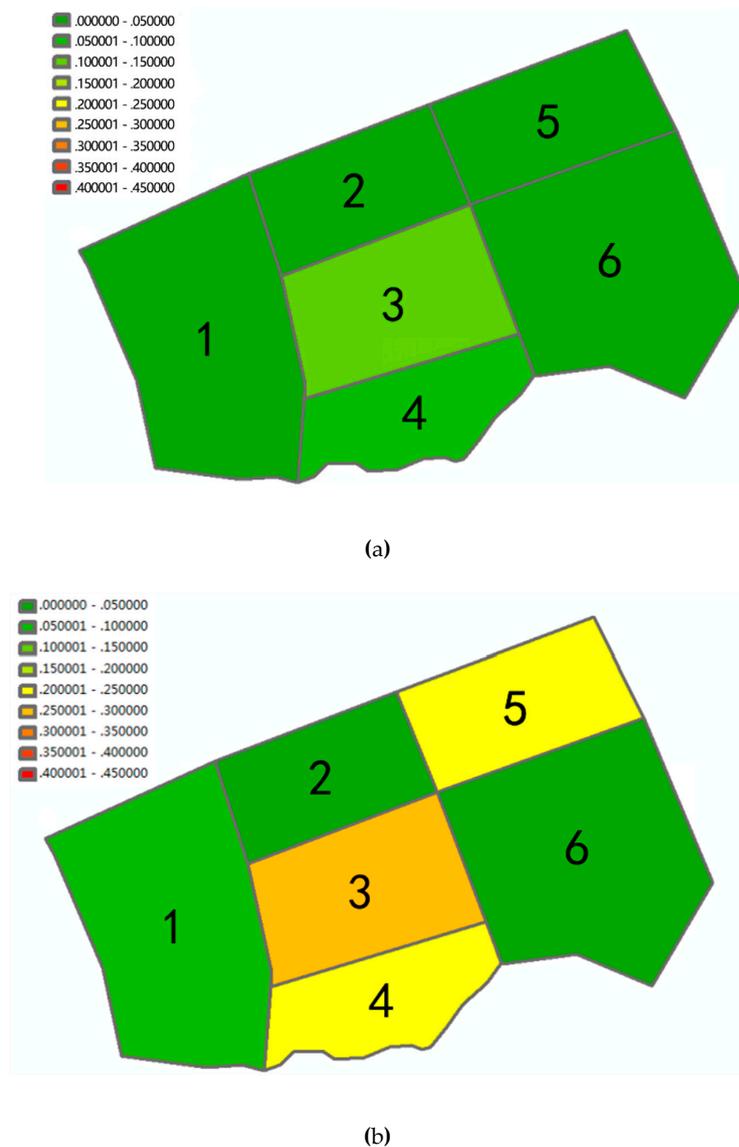
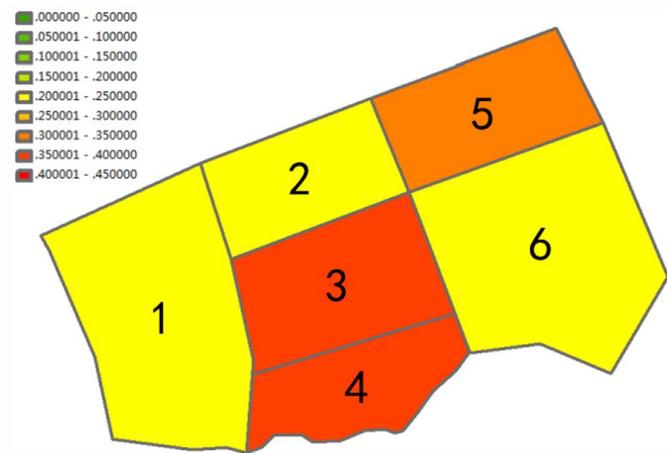


Figure 6. Cont.



(c)

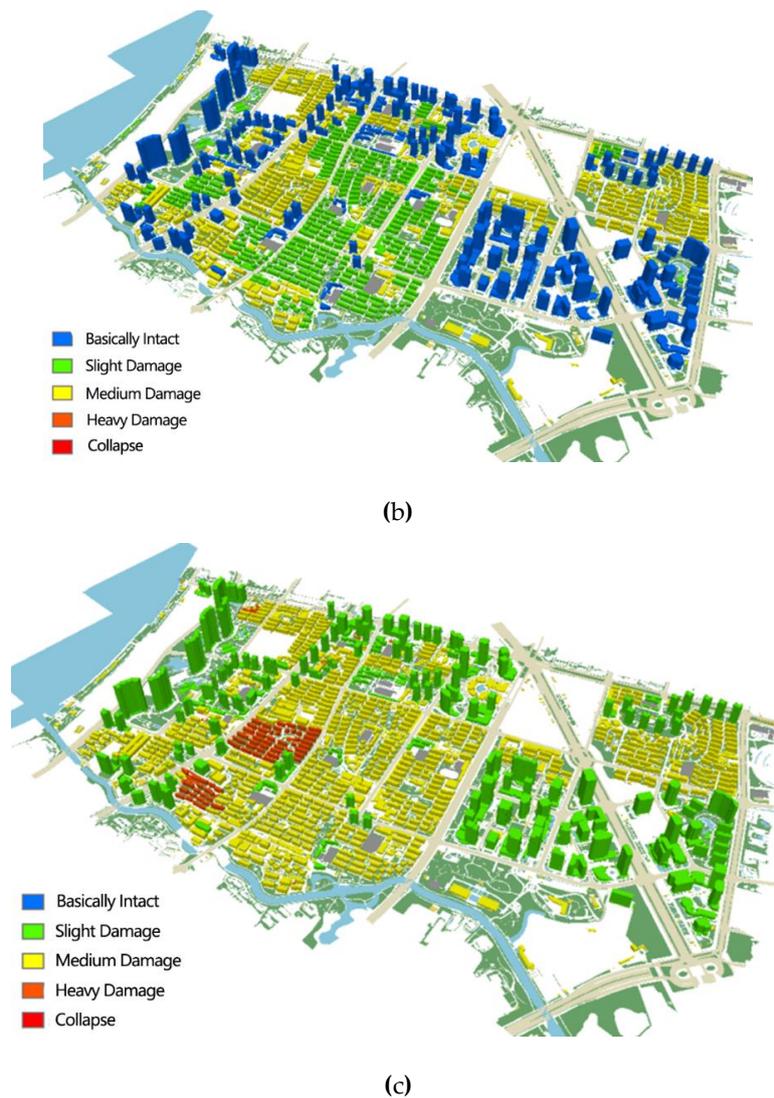
**Figure 6.** 2D seismic hazard prediction map. (a) Seismic hazard under intensity VI. (b) Seismic hazard under intensity VII. (c) Seismic hazard under intensity VIII.

The 2D seismic hazard prediction map characterizes the macroscopic seismic behavior of buildings rather than the seismic hazard of various structural types. Based on the damage evaluation results in various levels generated by the system, the ArcScene module in ArcGIS was used to create 3D scene models to display visually the predictive results of buildings as shown in Figure 7. The 3D seismic hazard prediction map characterizes the impact of structural types, building function, and construction time on seismic behavior. There are numerous multistory masonry buildings that present different seismic hazards according to the variety of construction time and function in the test area. As a result, the prediction accuracy improved greatly compared with the previous prediction results when only structural types were considered.



(a)

**Figure 7.** Cont.



**Figure 7.** 3D seismic hazard prediction map (a) Seismic hazard under intensity VI. (b) Seismic hazard under intensity VII. (c) Seismic hazard under intensity VIII.

#### 4. Conclusions

In this study, a GIS-based seismic hazard prediction system was designed and developed in VB, Python, and C#. Weifang Street in Pudong New Area, Shanghai, was used as a test area to verify the effect and reliability of system. The conclusions are as follows:

- (1) By inputting the layer data of buildings in GIS and the sample data in the test area, the system could intelligently conduct the analysis of buildings' vulnerability, the statistics of seismic hazard matrix, and the assignment of predictive results. The system covers the entire process of seismic hazard prediction with high system integration, which can provide feasible technical methods and operational procedures for seismic hazard prediction in urban areas.
- (2) Based on a web crawler, the assignment toolbox of the construction time and predictive results was developed. Layer attribute files were used as resource data to allow the toolbox to access and automatically grab network data in batches, in order to match the attributes of constructive time for various features. Moreover, applying the prediction toolbox of the earthquake damage evaluation meant that fuzzy classification and attribute matching could be conducted with only a small amount of manual intervention. The system realized the batching and automation of seismic hazard prediction.

- (3) The system was applied in Weifang Street in Pudong New Area, Shanghai (test area), and the results were compared with previous studies to verify the reliability of the system. Results from this study were comparable with previous studies and even slightly better in some cases. Based on the prediction system, related departments can reinforce buildings in weak areas and improve the level of seismic hazard prediction and aid decision-making.

**Author Contributions:** Y.Z. designed the research idea, supervised this research and suggested extensive revisions during the research work. Q.O. collected the data and drafted the research methodology. S.C. analyzed the data and drafted the final manuscript. All authors read and approved the final manuscript.

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