SPATIAL RELATIONSHIP BETWEEN CHELUNGPU FAULT AND DAMAGED BUILDING AREAS

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ABSTRACT

It is believed that there is a relation between faults and damaged areas. In other words, the closer the distance between a fault and a building, the higher probability the building may be damaged. Employing the technique of geographical information systems, we analyze the spatial relationship between Chelungpu Fault and damaged building areas in the case of the Chi-Chi (Taiwan) Earthquake based on the following data sets: (1) maps of fully and partially damaged buildings, which were investigated by the Construction and Planning Administration, Ministry of Interior; (2) maps of existing buildings before the earthquake; (3) zoning maps of 14 urban areas along the fault; (4) the map of Chelungpu Fault at 1:5000, made by the Central Geological Survey, Ministry of Economic Affairs. After making buffer areas at every 5 meters along the fault and calculating proportions of fully and partially damaged buildings to existing buildings in terms of built areas, we find that there is a strong relation between the proportion of fully damaged buildings and the distance from the fault; however, partially damaged buildings and the distance from the fault display no relationship. Furthermore, we find that the proportion of damaged buildings on the eastern side of the fault is higher than on the western side. These observations are further analyzed by fitting transformed normal distribution functions and linear regression functions. The result is very helpful for considering recovery, renewal, and restricted building areas in urban planning.

I. MOTIVATION

Earthquake is a natural hazard that may cause many losses: lives, property, buildings, and facilities. People may suffer from psychological damage for a long time. Although earthquakes cannot be prevented, the damage they do can be greatly reduced through prudent planning and preparedness, such as making

restricted or prohibited building zones. For example, the Alquist-Priolo Earthquake Fault Zoning Act, California, U.S.A., asks local governments to determine Earthquake Fault Zones (EFZ), that are buffer zones of 500 feet along the traces of major faults and 200 - 300 feet along minor ones on maps of 1:24000 scale. Based on the fault zone maps, human occupancy is disallowed within buffer zones of 50 feet along the

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traces of faults (Depineres, 1995; Huang, 1998).

It is believed that there is a relation between faults and damaged areas. In other words, the closer the distance between a fault and a building, the higher probability the building may be damaged. However, this belief needs to be proved and further elaborated by observed data.

At local time 01:47 am, 21 September, 1999, the Chi-Chi (Taiwan) Earthquake of magnitude $ML=7.3$ occurred near the center of Taiwan, about 160 kilometers (100 miles) SSW of Taipei, the capital city of Taiwan (Shin, 1999). It was a shallow (8 km) thrust earthquake, caused by the collision between the Philippine Sea and Eurasian plates. A surface rupture along Chelungpu Fault with a length of about 80 km is observed with the largest measured vertical offset reaching more than 5 meters. Chelungpu Fault passes through many urban and village areas (Fig. 1). As of October 13, 1999, 2333 persons had died, 10,002 were injured, more than 100,000 buildings and many roads, bridges, and public facilities were damaged in this earthquake. Along with search and rescue operations, many field investigations concerning the traces of the fault, geological conditions, damaged buildings, urban areas, construction, and social-economic impacts were also being conducted by many governmental and private organizations. Based on these investigations, a spatial relationship between Chelungpu Fault and damaged buildings can be analyzed to help in determining restricted and prohibited building buffer zones along the fault.

This article will focus on the observations and analyses of the distribution of fully and partially damaged buildings in urban and village areas, and on the eastern and western sides along the fault line. Section 2 introduces the data sets from various sources. Section 3 gives the definition of notation for further discussion. Section 4 explains spatial data process and preliminary observations. Section 5 further analyzes the result by fitting curves and linear regression. Section 6 has a conclusion and calls for further study.

II. DATA COLLECTION

Four kinds of data are used in this study. These data were collected from various sources at different scales and production times. Additionally, these data were preprocessed in digital form as ArcView™ (Environmental System Research Institute, Inc.) shape file formats for spatial data processing by geographical information systems (GIS).

- The map of the trace of Chelungpu Fault at 1:5000 was made by the Central Geological Survey, the Ministry of Economic Affairs, a month after the earthquake.
- Existing buildings before the earthquake were

Fig. 1 Urban and village areas along Chelungpu fault

identified from topographical maps at 1:25,000, which were made around 1990 by the Ministry of Interior.

Fig. 2 An example of a field investigation map of damaged buildings produced by the Construction and Planning Administration, the Ministry of Interior

- Based on topographical maps of urban areas at 1:1000 or 1:3,000 and village areas at 1:5,000, fully and partially damaged buildings were investigated by 21 academic and professional organizations, who were sponsored by an investigation project of the Construction and Planning Administration (CPA), the Ministry of Interior (CPA, 1999). An example is illustrated in Fig. 2. It is noted that the definitions of fully and partially damaged buildings vary in different investigation projects associated with different purposes, methods, criteria and potential uses. In the CPA's investigation, fully and partially damaged buildings are characterized in terms of physical condition. In other words, buildings where more than 50% of the area have to be demolished and rebuilt are considered fully damaged. On the other hand, buildings that only need minor repair or less than 50% rebuilding are considered partially damaged.
- Zoning maps at 1:1000 of 14 urban areas along the fault were generated according to the coordinates of monuments of zoning plans, or directly digitized from zoning maps.

It is noted that the Institute of Architecture Research (IAR), the Ministry of Interior, has conducted another field investigation on building damage and plotted the result on a 1:5000 scale topographical map (IAR, 1999; Loh, 1999). However, this investigation records location points of damaged buildings but not their shapes and areas, which are essential in this

Fig. 3 A calculation example showing the proportion of damaged buildings to existing buildings in an area with respect to the buffer zones away from a fault

study. Thus, the result of the IAR is used for cross checking in this study only.

III. NOTATION

The proportion of damaged buildings to existing buildings in an area with respect to the buffer zones away from a fault is denoted by $prop_{i,j,k,l}$, where subscript i can be U (urban area) or V (village area), j can be F (fully damaged) or P (partially damaged), k can be W (the western side) or E (the eastern side), and l is the distance of a buffer zone away from the fault. Areas of buildings across buffer lines are calculated separately. For example, in Fig. 3, the farthest left building across the buffer lines of 5 meters is divided into $B1$ and $B2$. Then, various proportion values in an urban area are calculated according to building areas B_s as follows.

$$prop_{U,F,W,5} = (B6+B9)/(B2+B4+B6+B9+B11) \quad (1)$$

$$prop_{U,P,W,5} = B2/(B2+B4+B6+B9+B11) \quad (2)$$

$$prop_{U,P,W,10} = B1/(B1+B3+B8) \quad (3)$$

$$prop_{U,P,E,5} = (B7+B12)/(B5+B7+B10+B12) \quad (4)$$

...

Accordingly, distance effect ($DE_{i,j,k}$) is defined as a distribution of corresponding $prop_{i,j,k,l}$ with respect to distances from buffer zones. In addition to the instances of subscripts described above, subscript i can also be T (the total area including urban and village areas), j can also be D (damaged buildings including full and partial ones), k can also be S (both sides), and a generic instance X can appear in any subscript place for all possible instances. For example, $DE_{U,X,S}$ stands for two distance effect

Fig. 4 5-meter buffer lines overlaid on a topographical map

Fig. 5 Proportion of damaged buildings in urban area

Fig. 6 Proportion of damaged buildings in village area

Fig. 7 Proportion of damaged buildings in urban and village areas

distributions, $DE_{U,F,S}$ and $DE_{U,P,S}$, which in turn correspond to distance effect distributions of fully and partially damaged buildings in urban areas on both sides along the trace of the fault.

IV. SPATIAL DATA PROCESSING AND OBSERVATION

The collected spatial data is processed as follows by employing ArcView™.

1. Buffer areas at every 5 meters, up to 200 meters, surrounding the fault are generated. Accordingly, i -meter buffer zone is used for referring to the buffer zone between $i-5$ meters and i meters buffer lines.
2. Buffers are overlaid on maps of existing buildings to identify existing buildings in each buffer zone. Thus, areas of buildings across buffer lines are calculated separately.
3. Buffers are overlaid on maps of damaged buildings to calculate fully and partially damaged buildings in each buffer zone (An example is illustrated in Fig. 4). Damaged buildings across buffer lines are also separately calculated.
4. Urban and village areas are identified according to zoning maps.
5. Proportions of fully and partially damaged buildings to existing buildings in urban and village areas on each side, *i.e.*, $prop_{i,j,k,l}$, are calculated.
6. Distance effect distributions $DE_{i,j,k}$ are plotted.

Figures 5, 6 and 7 illustrate distance effects $DE_{U,X,S}$, $DE_{V,X,S}$ and $DE_{T,D,S}$ respectively. It is observed that distance effect $DE_{X,F,S}$ is significant for the fully damaged buildings either in urban or village areas. In other words, the closer an area is to the trace of the fault, the higher the proportion of fully damaged buildings is. Within 25-meter buffer zones, the distance effects associated with fully damaged buildings are around 50%. It rapidly decays to 20% at the 95-meter buffer zone. Then it slowly decay to 10% at the 200-meter buffer zone. However, distance

Fig. 8 Proportion of damaged buildings on both sides along the fault line in urban area

Fig. 10 Proportion of damaged buildings on both sides along the fault line in urban and village areas

Fig. 9 Proportion of damaged buildings on both sides along the fault line in village area

effect $DE_{X,P,S}$ associated with partially damaged buildings is not significant. $DE_{X,P,S}$ stays around 10%. Furthermore, the proportion of partially damaged buildings is lower than that of full damaged ones, i.e., $DE_{X,P,S} < DE_{X,F,S}$, which coincides with a similar finding in the field investigation conducted by IAR(1999), where 63% of damaged buildings are in severe condition, 18% are medium and 19% slight.

Figures 8, 9 and 10, which illustrate $DE_{U,D,X}$, $DE_{V,D,X}$ and $DE_{T,D,X}$, show that the proportion of damaged buildings on the eastern side is higher than that on the western side. The distance effect distributions are of bell shape with a long right tail. In particular, $DE_{X,D,E}$ associated with the eastern side has the highest value of $prop_{X,D,E}$ around the 35-meter buffer zone, while the peak of $DE_{X,D,W}$ associated with the western side is around the fault.

Fig. 11 A normal distribution η with mean=0 and standard deviation=0.4

V. DATA ANALYSIS: CURVE FITTING

According to the observation on the distribution forms of preliminarily processed data, this study further uses normal distribution function and linear regression function to analyze the relationship between the proportion of damaged buildings and distance from the fault. Furthermore, correlations are calculated for measuring the appropriateness of fitted curves with respect to observed data (Walpole, 1974).

To fit $DE_{X,F,S}$, $DE_{U,D,X}$, $DE_{V,D,X}$ and $DE_{T,D,X}$, a normal distribution η with mean=0 and standard deviation=0.4, such that the value of normal distribution function $f(0;0,0.4)=1$, is used as a prototype of distance effect distributions. Nine fitting points A to I in Fig. 11 will be transformed to corresponding points in distance effect distributions. Points between fitting points are evenly interpolated. In other words, let $x_{\eta i}$, $x_{\eta j}$ and $x_{\eta k}$ be x coordinates of two

Table 1 Fitting Points of Proportion Distribution Functions

fitting point	urban areas				village areas				total			
	the eastern side		the western side		the eastern side		the western side		the eastern side		the western side	
A	0	56	0	60.73	10	55.93	0	37.86	5	57.45	0	56.69
B	5	56.08	1	60.74	20	56.69	1	37.87	10	58.9	1	56.7
C	20	73.23	2	60.75	25	68.45	2	37.88	20	69.27	2	56.71
D	30	83.9	4	60.76	30	77.04	5	37.89	30	82.26	5	56.72
E	35	87.22	5	60.77	35	77.14	10	46.03	35	84.79	10	57.82
F	40	85.18	10	60.27	40	79.28	15	41.91	40	83.7	15	51.16
G	55	66.91	40	37.19	70	48.57	35	22.37	60	58.1	35	34.72
H	95	44.14	100	22.65	95	29.52	70	11.96	100	38.42	80	22.1
I	200	35.23	200	18.46	200	24.56	200	11.95	200	38.09	200	17.07
correlation	0.996834176		0.984289679		0.988255894		0.978647671		0.99693629		0.981933695

Fig. 12 Proportion of damaged buildings with respect to distance from the fault on the eastern side in urban area

Fig. 13 Proportion of damaged buildings with respect to distance from the fault on the western side in village area

consecutive fitting points i and j and an intermediate point k between them on the normal distribution η , and $x_{\phi i}$, and $x_{\phi j}$, be x coordinates of corresponding points i and j on the distance effect distribution ϕ to be fitted, $x_{\tau k}$ be the interpolated point, the transformation function of x coordinates from normal distribution η to the fitted curve τ with respect to distance effect distribution ϕ is defined as follows.

$$x_{\tau k} = x_{\phi i} + [(x_{\eta k} - x_{\eta i}) / (x_{\eta j} - x_{\eta i})] \times (x_{\phi j} - x_{\phi i}) \quad (5)$$

Similarly, the transformation function of y coordinates can be defined as follows.

$$y_{\tau k} = y_{\phi i} + [(y_{\eta k} - y_{\eta i}) / (y_{\eta j} - y_{\eta i})] \times (y_{\phi j} - y_{\phi i}) \quad (6)$$

Please note that $x_{\tau k} = x_{\phi j}$, and $y_{\tau k} = y_{\phi j}$, when $k = j$. That means the fitted curve τ coincides with distance effect distribution ϕ at fitting points. Table 1 shows the fitting points on distribution effect distributions and their correlation. Figs. 12-14 illustrate the

Fig. 14 Proportion of damaged buildings with respect to distance from the fault on the eastern side in village area

comparisons between the fitted curve τ and distance effect distribution ϕ in urban and village areas.

On the other hand, $DE_{X,P,S}$ is first fitted by linear regression functions with respect to distance d (in meters) of buffer zone away from the fault as follows.

$$prop_{U,P,S}(d)=8.512554+0.00742d \quad (7)$$

$$prop_{V,P,S}(d)=6.78453-0.02075d \quad (8)$$

However, the correlations of Eqs. (7-8) are 0.1148 and 0.261, respectively. The small values of correlations mean that the proportion of partially damaged buildings is irrelevant to the distance away from the fault, and one cannot use these equations to predict the proportion. Yet, the means and standard deviations of $prop_{U,P,S}$ and $prop_{V,P,S}$ can still give us an idea about the degree of damage. The mean (9.27%) of the proportions of partial damaged buildings in urban areas ($prop_{U,P,S}$) is higher than that (4.66%) in village areas ($prop_{V,P,S}$), while the standard deviation (1.28%) associated with urban areas ($prop_{U,P,S}$) is smaller than that (1.96%) associated with village areas ($prop_{V,P,S}$).

VI. CONCLUSIONS

By employing the technique of GIS, the spatial relationship between the proportion of damaged buildings and the distance away from Chelungpu Fault in the Chi-Chi (Taiwan) Earthquake is analyzed. It is found that the distance effect associated with fully damaged buildings is significant, while that of partially damaged buildings is lower and insignificant. Furthermore, the distance effect on the eastern side of the fault is stronger than that on the western side. Most distance effect distributions are well fitted by transformed normal distribution functions.

It is noted that various factors may cause building damage. The distance away from the fault is only one possible reason. Additionally, since the original data are at different scales and map production times, it is inevitable that there is potential inaccuracy in the result. Therefore, this preliminary result calls for further study. For example, more factors, such as the design, shape, type, height, construction quality and age of buildings, the type of soil and rock under each building, and the direction and quantity of displacement, can be taken into account at the same time. Other field data, such as IAR's investigation, can be cross checked. By doing so, it is expected that spatial information can be further inferred.

The finding that the distance effect is very strong with a 50-meter buffer zone on the eastern side of the active fault and 25 meters on the western side is very important for the Construction and Planning Administration (CPA), the Ministry of Interior, to determine the restricted and prohibited building areas. In January 2000, CPA announced that rebuilding in the 50-meter buffer from the fault was temporarily prohibited for two years to allow further study in detail. Additionally, the result of this paper is also expected

to be very useful for considering recovery, renewal, and restricted building areas in urban planning where fault maps are available.

NOMENCLATURE

- $prop_{i,j,k,l}$ the proportion of damaged buildings j to existing buildings in an area i with respect to the buffer zones l away from a fault, where subscript variables and possible instances are as follows.
- i can be U (urban area), V (village area), or T (total area),
 - j can be F (fully damaged), P (partially damaged), or D (fully and partially damaged),
 - k can be W (the western side), E (the eastern side), or S (both sides),
 - l is the distance of a buffer zone away from the fault,
 - X is a generic instance, which can appear in any subscript place for all possible instances.
- $DE_{i,j,k}$ distance effect, which is defined as a distribution of corresponding $prop_{i,j,k,l}$ with respect to distances of buffer zones from fault line.
- η a normal distribution with mean=0 and standard deviation=0.4, such that the value of normal distribution function $f(0;0,0.4)=1$.
- φ distance effect distribution, i.e., $DE_{i,j,k}$
- τ fitted curve
- $x_{\alpha i}$ x coordinate of point i on distribution function α , which can be η , φ , or τ
- $y_{\alpha i}$ y coordinate of point i on distribution function α , which can be η , φ , or τ
- d distance (in meters) of buffer zone away from the fault

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建物損壞率與斷層線之空間關係

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摘 要

一般認為，震災之建物損壞率與其距離斷層線的遠近有關。換言之，距斷層線愈近，建物損壞率將越高。本文利用地理資訊系統的技術分析集集大地震之建物損壞率與車籠埔斷層之間的空間距離關係。本研究所使用的資料包括了營建署的建物調查圖、都市計畫圖、災前經建版地形圖、以及中央地質調查所的斷層線位置圖。沿著斷層線，進行每五公尺之環框分析，吾人發現，全倒建物之比率與距離呈明顯之關係，但半倒建物之比率則與距離無關，且較全倒建物比率為低。另一方面，位於斷層東側之建物損毀率亦較西側為高。這些資料並以常態分配曲線及線性迴歸分析其趨勢。此一分析結果對於災區禁限建、都市更新、建築法令修正等工作均有所助益。

關鍵詞：地震，斷層線，建築物損毀率，地理資訊系統。