13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 2542

A STUDY ON NEAR-FAULT MORTALITY FROM THE 1999 TAIWAN CHI-CHI EARTHQUAKE

Chih-Hung PAI[1,2], Yong-Ming TIEN[3], Der-Shin JUANG[4] and Yi-Liang WANG[5]

SUMMARY

Issues relating the spatial distribution of mortality caused by the 1999 Taiwan Chi-Chi Earthquake are presented in this paper. The human fatality data from the Chi-Chi Earthquake had been collected by comprehensive filed visits. The location where each victim stayed was allocated by using the Global Positioning System (GPS). Geographic Information Systems (GIS) was then used to analyze the collected fatality data, which were presented in terms of the spatial distribution, the types of buildings in which victims stayed, and the ground accelerations intensity. Correlated models for the mortality resulted from the Chi-Chi earthquake as functions of the distance to the Chelungpu fault, the mean PGA, and the building types are presented. The difference in mortality between hanging-wall and footwall block is also discussed. The major findings of this research are summarized below.

a) The shorter distance to the Chelungpu fault the higher mortality is observed. In the near fault regions, the mortality for the residents lived in hanging-wall block is significantly higher than that in footwall block.
b) The correlated relationships between the accumulative number of victims and the types of buildings which victims lived and the distances to the fault explicitly show that the collapse of mud-brick residences and un-reinforced masonry buildings was the major cause of great loss of lives in the near fault areas; but the number of victims stayed in RC and reinforced masonry buildings was relative low.
c) The mortality is nearly zero in the areas experienced mean PGA below 220 gals. On the other hand, for areas experienced mean PGA exceeds 400 gals, the mortality increases dramatically from 0.2% up to 2%.

INTRODUCTION

[1] Ph.D. Candidate, Civil Engineering Department, National Central University, Taiwan.
[2] Lecturer, Civil Engineering Department, Nanya Institute of Technology, Taiwan.
[3] Professor, Civil Engineering Department, National Central University, Taiwan. Email: ymt@cc.ncu.edu.tw
[4] Associated Professor, Civil Engineering Department, National Central University, Taiwan.
[5] Master of Science, Civil Engineering Department, National Central University, Taiwan.

In 1999, the Chi-Chi Earthquake with a magnitude of M_L7.3 struck central western Taiwan at 1:47 a.m. local time on 21 September (UTC 17:47, 20 September) [1]. According to the reports published by the Architecture and Building Research Institute (ABRI), Ministry of Interior of Taiwan, the Earthquake had caused 2492 deaths, 739 severely injured [2], and 51,778 and 53,852 buildings to totally and partially collapse, respectively [3]. Because the earthquake struck central Taiwan in the early morning, almost all residents were sleeping at home. About 94% of deaths lost their lives as their dwelling places collapsed [4].

In general, it is believed that the movement of Chelungpu fault was the key factor of this great loss caused by the Chi-Chi earthquake. Then the Executive Yuan proposed building sites that were at least 15 m from an identified region of the Chelungpu fault, and 30 m from west and 50 m from east side of an unidentified region of the fault in Jan 1,1990 [5]. Based on above regulations, the Fault zoning for prohibiting buildings construction was covered 15 towns and the whole area is equal to 363 hectares. The causes of earthquakes are complex and earthquake hazard evaluations relating to active faults are lack of overall and quantified data. Therefore, it is difficult to decide whether the lands of fault zoning are prohibited to build or not. In this paper, the human fatality data from the Chi-Chi earthquake had been collected by comprehensive filed visits. During the field investigations, the positions where victims died were allocated one by one by using GPS. The collected fatality data, which are expressed in terms of spatial distribution, the types of buildings in which victims lay, and ground acceleration intensity, are the analyzed by using GIS. It is helpful to clarify the relations between the Chelungpu fault and the mortality caused by the Chi-Chi earthquake.

LITERATURE REVIEW

It has been well recognized that most disastrous earthquake are commonly caused by the movement of active faults. Consequently, it is made a comprehensive survey about the Acts of fault zoning for prohibiting buildings construction in the worldwide. According to Taiwan Building Code and Regulations revised in 1998, it is clearly defined the building construction regulations for sloped sites. Building sites are at least 100 m away from the fault zone when the maximum historic earthquake magnitude (M) is over or equal to 7.0, and 50 m ($7.0 > M \geqq 6.0$) and 30 m ($M < 6.0$ or the case of no earthquake records) away from the fault zone (as shown in Table 1) [6].

Table 1. The building construction regulations for sloped sites By Taiwan Building Code and Regulations

Maximum historic earthquake magnitude (M)	Regions for prohibiting buildings construction (Distance away from the fault)
$M \geqq 7.0$	100 m
$7.0 > M \geqq 6.0$	50 m
$M < 6.0$ or no earthquake records	30 m

In Japan, there is no special limitation about the Acts of prohibiting building construction along active faults as Japan encountered the Kobe earthquake before and after. However, “the Alquist-Priolo Earthquake Fault Zoning Act” and “the Seismic Hazards Mapping Act” are proposed to prevent the construction of buildings which is used for human occupancy on the surface trace of active faults in California, USA. Regulations are interpreted as “Maps noting the parcel numbers of proposed building sites that are at least 50 feet from an identified fault and a statement that there is not any more recent information to indicate a geologic hazard.” in Section 2621.7, Alquist-Priolo Earthquake Fault Zoning Act [7, 8].

After the attacks of the Chi-Chi earthquake, different administrative districts took place various earthquake disastrous losses. The ABRI and the National Center for Research Institute (NCREE) mobilized more than 1,200 scientists and engineers to conduct investigations and to collect data immediately in order to learn as much as possible from this catastrophe. The investigations collected the number of floors, building ages, building usages, construction type etc of 8773 totally or partially collapsed buildings [9]. Nevertheless, the data associated with human fatality, one of the most important indices for describing disaster caused by an earthquake, were not included in the reports. Tien et al. almost finished the complete statistical data of human fatality according to the death certificates, the relief cash lists, and construction types of buildings of victims [4]. Because of the lacks of the database of the earthquake losses, it is preferred to incline the exploration of a single earthquake disaster case rather than the statistic analysis of overall earthquake losses about the reports of hazard degree of both sides of the Chelungpu fault zone after the Chi-Chi Earthquake happened. Through establishing of the database of the human fatality and analyzing of the relations between the near-fault mortality and the Chelungpu fault in our researches, it will make clearer whether the regulations of fault zoning for prohibiting buildings construction effectively reduce the problems of earthquake losses or not.

METHODOLOGY

The Chi-Chi earthquake caused a total of 2492 deaths. To present the spatial relation between near-fault mortality and the Chelungpu fault completely, the attributes database of victims had been built through gathering of various data of victims and GPS positioning of victims. Among the total of 2492 victims there were 2039 positioned victims (82%). In the victims who were positioned by GPS, there were 752 (36.9%) and 1082 (53.1%) victims who lived in Nantou and Taichung County. There were only 205 (10%) victims in other Counties. As for the parts of un-positioned victims, there were 453 deaths (18%) among the total victims. And a large part of 453 deaths lived in regions far away from the Chelungpu fault. Therefore, it is not affected to the analysis of relations between spatial distribution of victims and the Chelungpu fault based on the amounts of statistical resource which are available. A detail description of the research methodologies is provided in the following subsections. Emphasis is given to the estimation of near-fault mortality associated with the Chi-Chi earthquake human fatalities data.

GPS Location and the Attribute Database of Victims

Although Tien et al. had reached the research results of investigation and statistical analysis of the characteristics of buildings in which victims stayed, but to process the spatial analysis and related researches just by the human fatalities data of the earthquake is not sufficient according to human fatalities data of the earthquake. It took us for a two-year time, manpower of many graduated students and property costs to finish the GPS location of victims through our research team after the Chi-Chi earthquake happened. Every positioned victim not only had its own GPS coordinates but also had the ID number which we arranged, name, address which victims were found, buildings type and age, floor numbers, the buildings destruction situation adjacent areas, in-site photo, investigation staffs and dates and so on. It was not easy to get the GPS locations of all the victims of this earthquake. Therefore, it usually spent a whole working day just to finish 3-5 victims' data in order to advance the percentage of positioned victims in a later stage of field investigation and GPS location of victims. By way of assembling the data of victims which I have mentioned, the attribute database of victims were built to conveniently carry out the following research works and a series of spatial analysis of victims.

Analysis and Operation of GIS

The Geographic Information System (GIS) computer software Arcview is the major tool of analysis and operation in this paper. It is helpful to integrate the attribute database of victims from our research team with various digital maps including to 1:25,000 scale regional geologic maps in Taiwan from NCREE and 1:1,000 scale the Chelungpu fault maps from CGS by Arcview software. The Taiwan digital regional geologic maps which we used are the finest and covered the smallest administrative districts called tsuen (villages) within a county and li (town districts) within a city in Taiwan. It was finished a series of overlaying of geological figures, numerical operations and treatment of data and analytical results applying the peculiar characteristics and functions of the spatial analysis and statistical operations of GIS. Therefore, important research data are obtained especially aimed at a study of relation between the near-fault mortality and the fault.

Mortality Estimation Method

In this research, the population and area of each tsuen or li collected at the end of June 1999 which was about three months before the Chi-Chi earthquake by Population Affairs Administration, Ministry of Interior, about three months before the occurrence of the Chi-Chi earthquake, is used to be one part of important data for the estimation of the near-fault mortality. Through the Peak Ground Acceleration (PGA) attenuation contour lines of three components, it was quite obvious that the regression of ground motion was mainly dependent on distance to the fault rather than distance to epicenter by Wang et al. [10].Therefore, the Chelungpu fault was blamed as the leading role for the disastrous events. The numbers of victims are calculated in various distances to the Chelungpu via the GIS operation functions including to the Create Buffers, Geoprocessing Wizard and so on. The results are shown in Table 2.

Table 2. Accumulative number of victims, population and mortality with respect to closest distance to the Chelungpu fault

Closest Distance to the Fault (m)	Accumulative Number of Victims	Population (No.)	Mortality (%)
10	42	3197	1.31
20	86	6375	1.35
30	128	9541	1.43
40	145	12699	1.02
50	162	15856	1.02
100	232	31872	0.73
200	265	62128	0.43
300	300	90387	0.33
400	333	116402	0.29
500	363	141351	0.26
600	376	166347	0.23
700	402	190749	0.21
800	480	214936	0.22
900	519	239232	0.22
1000	529	263283	0.20
2000	712	519599	0.14
5000	1322	1305427	0.10
10000	1562	2327196	0.07

In any of the specific distance to the Chelungpu fault, they are finished with regard to the calculations of enclosed areas by GIS, the ratio of population divided by area from the data of Population Affairs Administration before the occurrence of the Chi-Chi earthquake, and then the summation of populations in each tusen or li. At the end, the near-fault mortality was reached through dividing of the numbers of victim by the summation of populations of each tusen or li in all distances to the Chelungpu fault. These estimation methods serve to the procedures as shown in Figure 1.

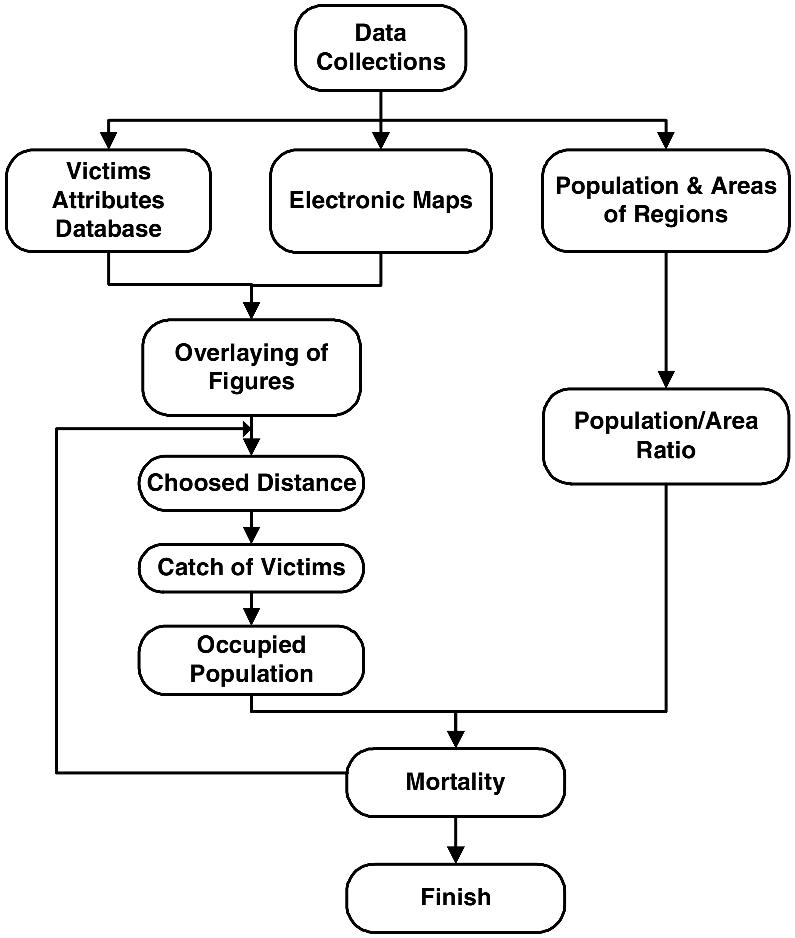

Figure 1. The procedures of mortality estimation methods

RESULTS AND DISCUSSION

Spatial Distribution of Victims

The victims of the Chi-Chi earthquake could be found in Taiwan everywhere. But in the regions of both sides near the Chelungpu fault, there were 1945 victims (95%) among the 2039 victims through the statistical results of victims' attributes database. There were 1387 (68.0%) and 558 (27.4%) victims lay in the hanging-wall areas east of the fault and footwall areas west of the fault correspondingly. The spatial distribution of victims was easy to present in various scales and supply many victims' attributes data by Arcview software (as shown in Figure 2).

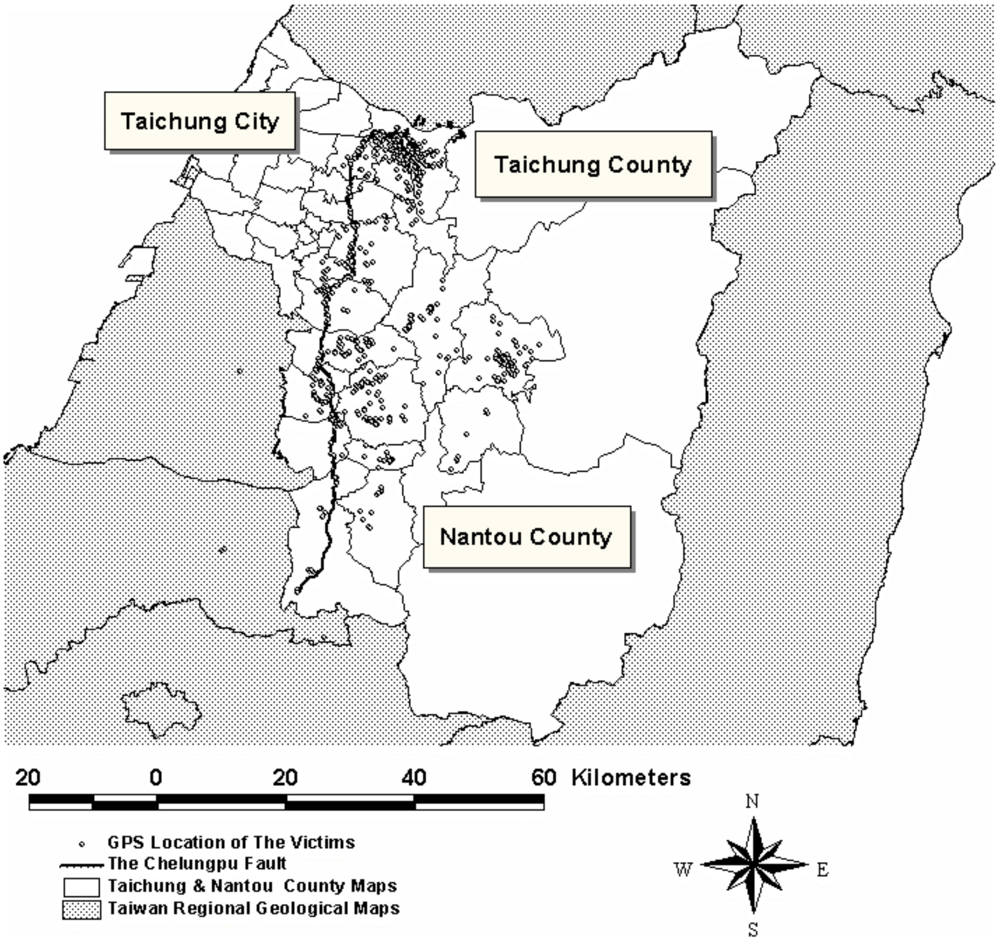

Figure 2. The spatial distribution of victims

Near-fault Mortality

According to our study, Figure 3 shows the relations of the mortality and distance to the fault through the operation results of GIS. The attenuation relationship is indicated by the regression line. The tendency is quite clear that the shorter distance to the Chelungpu fault the higher mortality is observed, and vice versa. The attenuation relationship has the following form:

$$M_T = \frac{(1.626 + 0.0007\,d)}{(1 + 0.0125\,d)} \quad (1)$$

Where M_T is the mortality in the specific distance to the fault (%) and *d* is the closest distance to the fault (m). There were 65 victims lived in regions that were 15 m from both sides of the Chelungpu fault (2.6%) among the total of 2492 victims. As far as the proportion of population is concerned the numbers of victims are lower. To reduce human fatalities through proposing of building sites that were at least 15 m from an identified region of the Chelungpu fault based on the fault zoning for prohibiting buildings construction regulations by The Executive Yuan is not effective.

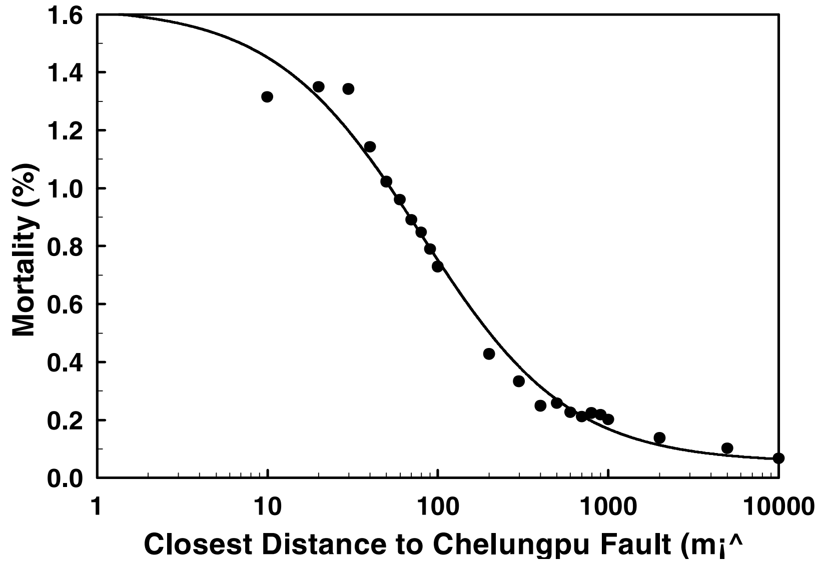

Figure 3. Relations of the mortality and closest distance to the fault

Building Types Which Victims Lived

Based on a series of analysis results of victims, it provides to confer with the correlations between the building types which victims lived and the distances to the fault. There are three building types mud-brick, masonry (including reinforced masonry), and RC shorter than 6 stories were used in this research. Table 3 shows the statistics of victims in various building types and distances to the fault. The relations between accumulative number of victims based on the types of buildings which victims lived and the distances to the fault explicitly show that the collapse of mud-brick residences and masonry buildings was the major cause of great loss of lives in the near fault areas; but the number of victims stayed in RC and reinforced masonry buildings was relative low (as shown in Figure 4(a) & 4(b)).

Table 3. The statistics of victims in various building types and distances to the fault

Closest Distance to the fault (m)	Accumulative Number of Victims		
	Mud-brick	Masonry	RC
10	26	8	7
20	40	16	7
30	52	31	18
40	59	38	18
50	63	43	22
60	73	57	23
70	79	64	25
80	82	69	26
90	85	74	27
100	88	74	28
500	139	96	63
600	146	101	64
700	146	113	78
800	157	119	91
900	175	134	95
1000	180	136	97

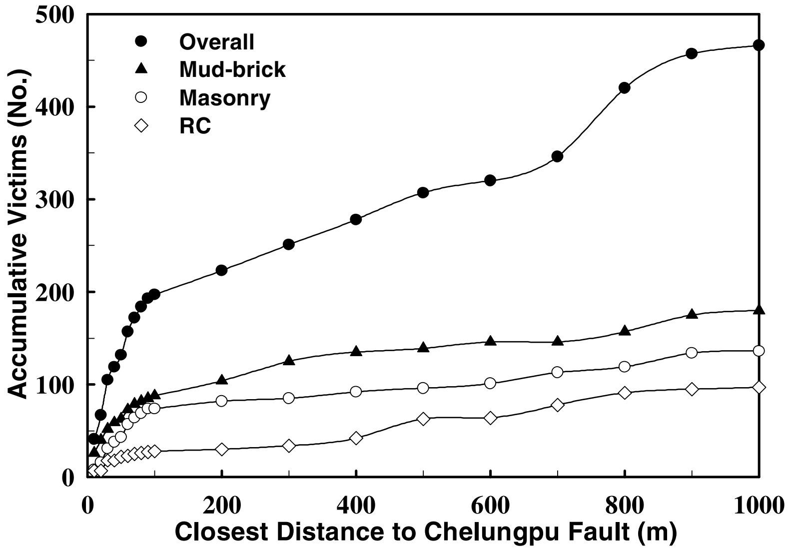

Figure 4(a). Relationship between accumulative number of victims and closest distance to the fault (Distance range: 0-1000 m)

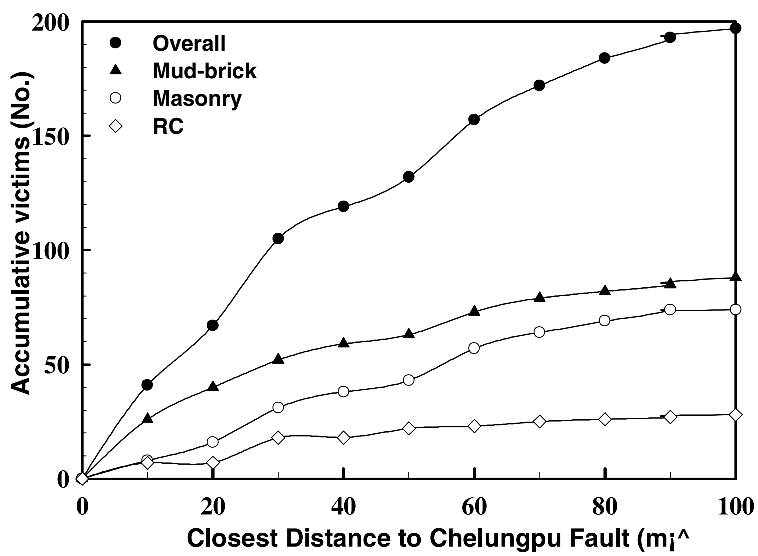

Figure 4(a). Relationship between accumulative number of victims and closest distance to the fault (Distance range: 0-100 m)

Mortalities of Hang-wall and Footwall Block

The Chi-Chi earthquake was caused by sudden rupture of the N-S-striking Chelungpu fault for a total length of about 100 km [11, 12]. In the meantime, rupture of the fault generated violent ground motion throughout Taiwan. Due to the unique nature of thrust faulting, distribution of ground motions intensity was highly asymmetrical about the fault trace [13]. The rupture of the fault and ground motions definitely influenced the spatial distribution of mortalities in areas east and west sides of the fault. Therefore, it is helpful to understand and verify the difference of mortalities between hanging-wall (east side of the fault) and footwall block (west side of the fault) through the correlated modes for mortality resulted from the Ch-Chi earthquake as functions of the distance to the Chelungpu fault in great detail. It is reached that the results of accumulative number of victims and mortality of hanging-wall and footwall block in various distances to the Chelungpu fault as given in Table 4. Figure 5 shows that the mortality for the residents lived in hanging-wall block is significantly higher than that in footwall block especially in areas of 1 km from both sides of the Chelungpu fault. According to the statistical results, there were 1348 and 557 victims who lived in hanging-wall and footwall block correspondingly. The ratio is approximately 2.4:1.

Table 4. The results of accumulative number of victims, mortality of hanging-wall and footwall block in various distances to the Chelungpu

Closest Distance to the fault (m)	Accumulative Number of Victims		Mortality (%)	
	Hanging-wall	Footwall	Hanging-wall	Footwall
10	34	8	2.33	0.46
20	61	25	2.05	0.73
30	75	53	1.59	1.10
40	87	58	1.39	0.9
50	95	67	1.22	0.83
60	109	76	1.13	0.79
70	122	78	1.09	0.69
80	133	84	1.04	0.65
90	140	87	0.98	0.60
100	142	90	0.90	0.56
200	162	103	0.53	0.32
300	173	127	0.40	0.27
400	195	138	0.28	0.22
500	207	156	0.34	0.19
600	213	163	0.31	0.17
700	213	189	0.28	0.16
800	220	260	0.27	0.20
900	250	269	0.29	0.18
1000	256	273	0.28	0.16
2000	378	333	0.32	0.08
5000	824	494	0.37	0.05
10000	1056	494	0.35	0.02

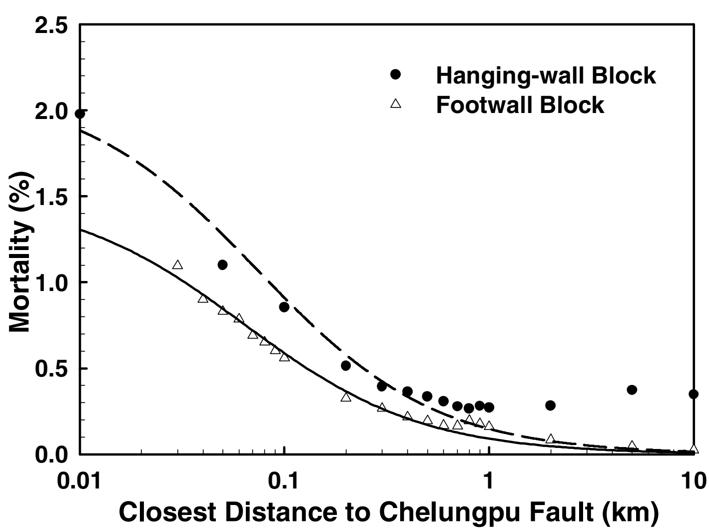

Figure 5. Relationship between mortality and closest distance to the fault in areas of hanging-wall and footwall block

The Effect of Ground Motions

After the chi-chi earthquake, the recordings of more than 400 free-field ground-motion stations deployed throughout Taiwan by the Central Weather Bureau (CWB) were received [14]. These data were recorded to be a huge number of waveforms and invaluable for ground-motion studies, as well as for the study of human fatalities. To thoroughly understand the relations of the characteristics of ground motions, mortality of victims and the distances to the Chelungpu fault in this research, PGA data of 63 ground-motion stations in adjacent areas from both sides of the Chelungpu fault were gathered. The contents of data were included to the GPS location, PGA values of three components and the closest distance to the fault of every ground-motion stations. Among the 63 stations, there were 8 stations in the hanging-wall block and 55 stations in the footwall block. Figure 6 shows the spatial distribution of these ground-motion stations.

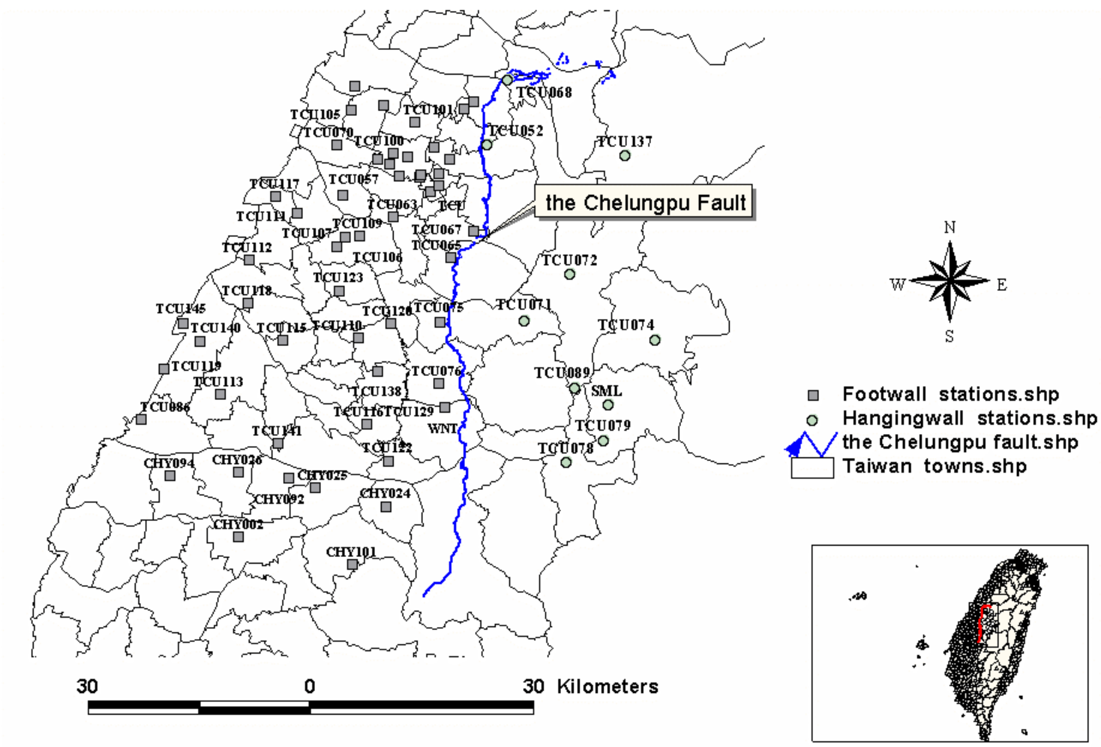

Figure 6. The spatial distribution of ground-motion stations in areas from both sides of the fault

In this paper, we defined the Mean PGA Index (MPI) to be the value which represents the ground-motion stations. The MPI is the mathematic mean calculated from the PGA values of three components of every ground-motion station. In the meantime, we reached the closest distances between the Chelungpu fault and ground-motion stations according to the GIS operations. Figure 7 shows the relations between the MPI and the closest distance to the Chelungpu fault of every ground-motion station. The relationship is indicated by the regression line and has the following form:

$$MPI = 451.34 - 95.34 * \ln(d + 1.13) \tag{2}$$

Where MPI is the mathematic mean value which calculated from the PGA values of three components, and d is the closest distance to the Chelungpu fault (km). Throughout the combination of Eq. (1) and Eq. (2), Figure 8 shows the fragility curve of the MPI value and mortality resulted from the Chi-Chi earthquake as functions of the closest distance to the Chelungpu fault of every ground-motion station. We clearly find that the mortality is nearly zero in the areas experienced the MPI below 220 gals. But on the other hand, the mortality increases dramatically from 0.2% up to 2% when the MPI exceeds 400 gals.

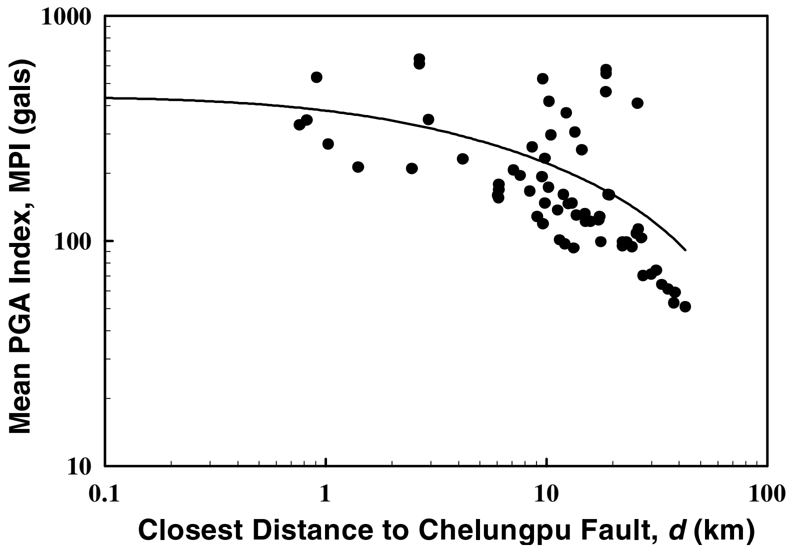

Figure 7. Relationship between mean PGA index and the closest distance to the fault

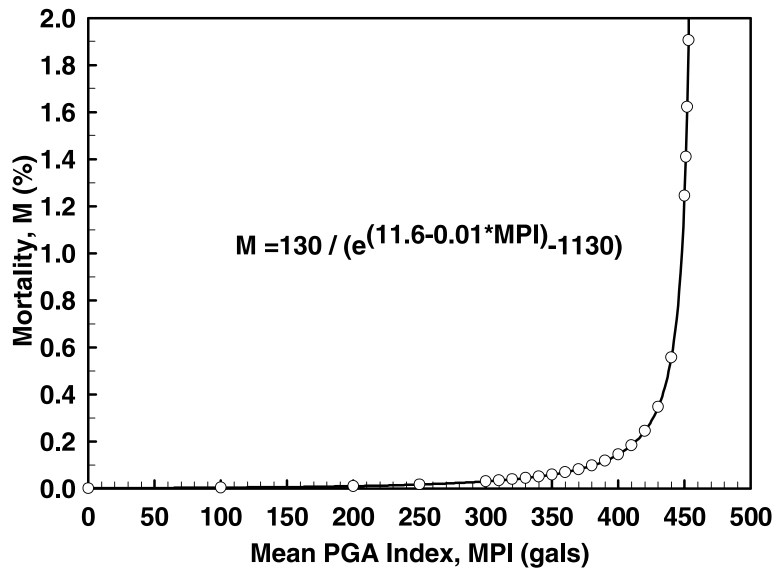

Figure 8. Relationship between mortality and mean PGA index

CONCLUSIONS

Human safety has been a primary goal of most modern earthquake protection programs. However, there was not the sufficient knowledge related to earthquake hazard researches of active faults. In this research, it has achieved as a pioneer of earthquake researches in which the large-scale investigations of finishing the overall positioning of the victims were using by the GPS tool. Simultaneously, building-up the database of victims' attributes is provided to explore the major factor of human fatalities caused by the Chi-Chi earthquake. Through this research, the major conclusions are summarized below.

1.The tendency of relations between the mortality and distance to the fault is quite clear that the shorter distance to the Chelungpu fault the higher mortality is observed, and vice versa. There were 65 victims lived in regions that were 15 m from both sides of the Chelungpu fault (2.6%) among the total of 2492 victims. As far as the ratio 2.6 % is concerned the number is low. So to reduce human fatalities through proposing of building sites that were at least 15 m from an identified region of the Chelungpu fault based on the fault zoning for prohibiting buildings construction regulations by The Executive Yuan is not effective.

2. Based on the statistics of victims in various building types, the results explicitly show that the collapse of mud-brick residences and masonry buildings was the major cause of great loss of lives in the near fault areas; but the number of victims stayed in RC and reinforced masonry buildings was relative low. The distance to the Chelungpu fault is closely related to the human fatalities in the Chi-Chi earthquake. Moreover, the enhancement of design of earthquake-resistant buildings will be the effective way of decreasing the mortality.
3. According to our research results, the mortality for the residents lived in hanging-wall block is significantly higher than that in footwall block especially in areas of 1 km from both sides of the Chelungpu fault. There were 1348 victims in hanging-wall block and 557 victims in footwall block. The ratio of hanging-wall and footwall block is approximately 2.4:1.
4. PGA data of 63 ground-motion stations in adjacent areas from both sides of the Chelungpu fault were gathered in this research. According to the characteristics of ground motions, mortality of victims and the closest distances to the Chelungpu fault, it shows the fragility curve of the MPI and mortality resulted from the Chi-Chi earthquake as functions of the closest distance to the Chelungpu fault of every ground-motion station. We clearly find that the mortality is nearly zero in the areas experienced the MPI below 220 gals. But on the other hand, the mortality increases dramatically from 0.2% up to 2% when the MPI value exceeds 400 gals.

ACKNOWLEDGMENTS

This research was supported by the National Science Council under Contract No. NSC 90-2211-E-008-068. We sincerely thank the Central Weather Bureau and the Architecture and Building Research Institute for providing the ground-motion data and 1:25,000 scale Taiwan digital geologic maps. We especially appreciate Yi-Ben Tsai professor for his valuable comments. Finally, we dedicate this achievement in memory of the victims in the Chi-Chi earthquake.

REFERENCES

1. Chang, C. H., Wu, Y.M., Shin, T. C., and Wang, C. Y. "Relocation of the 1999 Chi-Chi earthquake in Taiwan." TAO 2000; 11(3): 581-590
2. Hsiao, C. P., Tien, Y. M., Chen, J. C., Juang, D. S., and Pai, C. H. "Investigation and statistical analyses of the characteristics of buildings in which victims stayed in the 1999 Chi-Chi earthquake (Ⅰ)&(Ⅱ)." Report for the Architecture & Building Research Institute, Ministry of the Interior, Taipei, Taiwan. 2001 (in Chinese)
3. Hsiao, C. P., Lee, B. J., and Chou, T. Y. "Analyses and statistics of the characteristics of buildings damage in the 1999 Chi-Chi earthquake." Report for the Architecture & Building Research Institute, Ministry of the Interior, Taipei, Taiwan. 2001 (in Chinese)
4. Tien, Y. M., Juang, D. S., Pai, C. H., Hisao, C. P., and Chen, C. J. "Statistical Analyses of Relation Between Mortality and Building Type in the 1999 Chi-Chi Earthquake." Journal of the Chinese Institute of Engineers 2002; 25(5): 577-590
5. Executive Yuan of the Republic China, "The limitations of Fault zoning for prohibiting buildings construction." Special Publication, 1999 (in Chinese)

6. Taiwan Building Code and Regulations, "The building construction regulations for slope sites." Publication, 1994 (in Chinese)
7. Lee, C. T., Kang, K. H., Cheng, C. T., and Liao, C.W. "Surface rupture and ground deformation associated with the Chi-Chi, Taiwan earthquake." SINO-GEOTECHNICS 2000; 81: 5-16 (in Chinese)
8. California Department of Conservation, Division of Mines and Geology, “Report Fault-rupture Hazard Zones in California,” Special Publication, 1997: 42,38
9. Architecture and Building Research Institute, Ministry of Interior, "Investigation of building damage in the 921Chi-Chi earthquake." 1999 (in Chinese)
10. Wang, G.-Q., Zhou, X.-Y., Zhang, P.-Z., Igel, H. "Characteristics of amplitude and duration for near fault strong ground motion from the 1999 Chi-Chi, Taiwan earthquake." Soil Dynamics and Earthquake Engineering 2002; 22(1): 73-96
11. Central Geological Survey, "Report on geological investigations of the 921 earthquake." 1999 (in Chinese)
12. Ma, K.F., Lee, C. T., Tsai, Y.B., Shin, T.C., and Mori, J. "The Chi-Chi, Taiwan earthquake: large surface displacements on inland thrust fault." EOS 1999; 80: 605-611
13. Tsai, Y.-B., Yu, T.-M., Chao, H.-L., and Lee, C.-P. "Spatial distribution and age dependence of human-fatality rates from the Ch-Chi, Taiwan, earthquake of 21human-fatality rates from the Chi-Chi, Taiwan, earthquake of 21 September 1999." Bulletin of the Seismological Society of America 2001; 91(5): 1298-1309
14. Central Weather Bureau, "PGA data of Chi-Chi earthquake." Website address, http://www.cwb.gov.tw/V4/index.htm, 2004