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Preliminary Investigation of Damage to Near Fault Buildings of the 1999 Chi-Chi Earthquake

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ABSTRACT

During the 1999 Chi-Chi earthquake, violent shaking was detected and significant vertical surface faulting was observed. Observations of building damage associated with vertical surface faulting were made. Results from the investigation of Chi-Chi near fault ground motion records show that long-period structures are more vulnerable to ground shaking than short-period structures, and the corresponding strength reduction factors are very low, especially for large ductility ratio cases. Building damage rate distribution of the Fengyuan Township confirmed that long-period structures are more vulnerable to near fault ground shaking than short- period structures. It is also noted that the destructiveness of ground motion declined for high-rise buildings that were located more than 1,200m away from the fault line. Damage rate distribution also suggests that the ground shaking of the hanging-wall area was more destructive than that in the foot-wall area.

INTRODUCTION

At 1:47a.m., September 21, 1999, an earthquake of magnitude 7.3 rocked central Taiwan and resulted in more than 2,600 deaths and 8,000 injuries. The epicenter was located in the Chichi Township of Nantou County, and the earthquake is referred to as the Chi-Chi earthquake. Violent ground shaking and significant surface faulting destroyed or damaged more than 8,700 buildings. Rupture of the Chelungpu and Shungtung faults, as shown in Fig. 1, is believed the cause of the earthquake. The Shungtung fault runs through a mountainous and sparsely populated area. The Chelungpu fault ruptured for more than 70km with horizontal offsets of about 1 to 2m and vertical offsets of about 2 to 5m, and passed through some highly populated areas such as Fengyuan, Wufeng, Taiping, and Tsaotun.

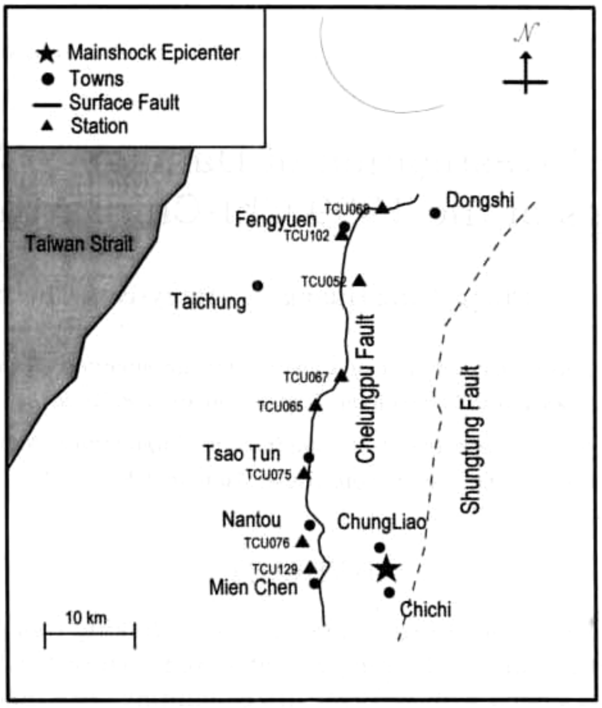

Fig. 1 Map of fault lines and selected storng ground motion stations

There are more than 1,200 strong-motion stations in Taiwan, and about 600 of them successfully recorded the vibration associated with the earthquake. Among the 600, 8 free field stations were within 2km of the Chelungpu fault. The strong ground motion from these 8 stations was regarded as near fault ground motion, and the characteristics of these ground motions were investigated.

The vertical offset of Chelungpu surface faulting was extraordinary. Building damage associated with surface faulting was observed and discussed. In addition, a damage survey of buildings in Fengyuan was conducted. Damage distribution of buildings was investigated with special focus on the buildings within 100m of the Chelungpu fault and on buildings that were 12 stories or higher. Also, the correlation between damage rate distribution and response spectra is investigated.

NEAR FAULT GROUND MOTION AND THE CORRESPONDING RESPONSE SPECTRA

Near fault ground motions are characterized by single or multiple long-period pulses in velocity time histories. Tall building structures are particularly vulnerable when subjected to such ground velocity pulses. In the Chi-Chi event, numerous strong ground motion stations operated by the Central Weather Bureau (CWB) have recorded invaluable near fault ground motion. The available near fault records provide an opportunity to further investigate the destructive nature of ground motions of this type.

Eight Chi-Chi near fault records, as listed in Table 1, are investigated. All 8 stations are within 2km of the rupture trace of the Chelungpu fault (Fig. 1). The corresponding peak ground acceleration (PGA), peak ground velocity (PGV), and an approximated distance to the Chelungpu fault line are also provided. The PGV values range from 88cm/sec to 383cm/sec. TCU068 and TCU052 stations, the only two hanging-wall stations, recorded unprecedentedly large PGVs of 383cm/sec and 254cm/sec respectively. All 8 records show pulse-like ground velocity motion with varied pulse-duration, but mostly at a 3 to 6 seconds long-period range. The ground motion time histories for station TCU052 (hanging-wall station, located at Takun) and station TCU102 (foot-wall station, located at Fengyuen) are respectively shown in Fig. 2 and Fig. 3. It is clear that both records exhibit distinct velocity pulses but the pulse-shapes differ slightly.

Table 1 List of investigated ground motion records

Station	Component	Distance to fault (km)	PGA (cm/sec^2)	PGV (cm/sec)
TCU068	N42W	0.2	459	383
TCU052	N39W	1.5	497	254
TCU067	S63E	0.5	555	108
TCU065	S58E	0.4	767	145
TCU075	S87E	0.3	324	117
TCU076	S52E	2.0	417	88
TCU102	S50W	0.8	251	112
TCU129	S45E	2.0	833	79

Five percent damped elastic response spectra of the 8 records are computed to provide a gross engineering implication of these records. For each record, the computed response spectrum is normalized with its PGA, and a statistical average is then performed on the normalized spectra. The statistical results along with a set of smoothed mean response spectra representing an average for traditional far-field earthquakes [1,2] are shown in Fig. 4. The labels S_1, S_2 and S_3 in Fig. 4 represent different site conditions respectively for rock, stiff clay, and soft clay soil profiles.

The averaged Chi-Chi near fault spectrum deviates significantly from the far-field spectrum regardless of soil type chosen for comparison. The mean Chi-Chi spectrum shows relatively low spectral intensity at short periods and relatively high spectral intensity at long periods. It also shows a nearly constant spectral acceleration for periods ranging from 1.5 to 2.5sec and a very slow decay trend for periods longer than 2.5sec. These analyses indicate that the Chi-Chi near fault spectra are strongly dominated by the source rupture process. Consequently, the traditional far-field spectral approach fails to predict the Chi-Chi near fault spectral shape to a very large extent. The standard deviation of the 8 response spectra is roughly 0.5 over the long period range, an indication of a very large variation in the spectral acceleration as the shape of ground velocity pulse varies.

Inelastic response spectral analyses based on single-degree-of-freedom models with idealized bilinear hysteresis are also performed for the 8 Chi-Chi near fault records. A post-yielding to initial stiffness ratio of 10% is used for the bilinear hysteresis model. The inelastic spectral characteristics are investigated for the strength reduction factor (SRF) defined as the elastic to inelastic strength demand ratio under a prescribed ductility level. The calculated SRF for the 8 Chi-Chi near fault records are statistically averaged. Figure 5 gives the mean SRF plotted as a function of structural period for four different ductility levels, μ = 2, 4, 6 and 8. Shown also in Fig. 5 is a set of

SRF curves resulting from far-field earthquake analyses [3].

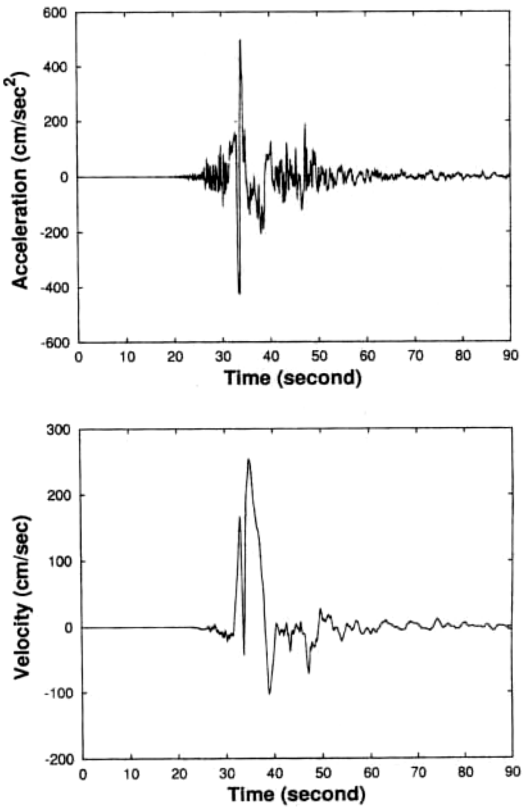

Fig. 2 Acceleration and velocity time histories for station TCU052 (N39W)

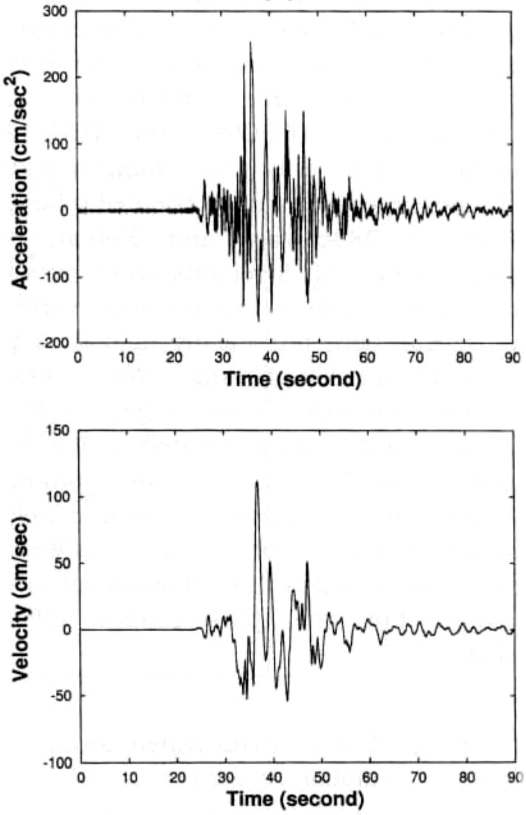

Fig. 3 Acceleration and velocity time histories for station TCU102 (S50W)

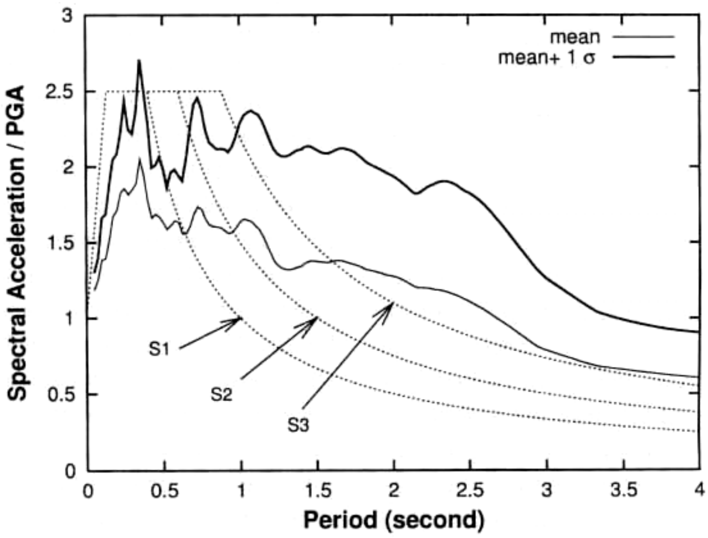

Fig. 4 Chi-Chi near-field spectra and traditional far-field spectra

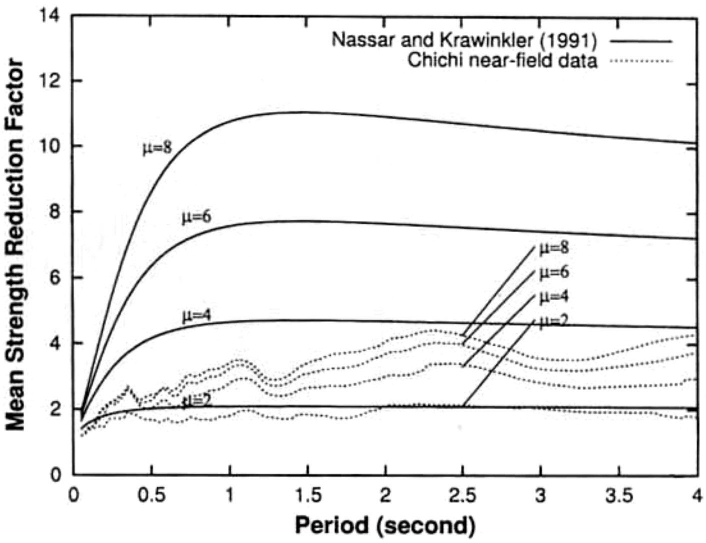

Fig. 5 Strength reduction factors for Chi-Chi near-field records and representative far-field earthquake records

The mean SRFs of Chi-Chi near fault records are lower than the far-field earthquake records for entire periods in cases where the ductility level is $\mu > 2$. The difference is more distinct as the prescribed ductility level increases. At the level of $\mu = 8$, the mean SRF of far-field earthquakes reaches beyond 10 for periods longer than 0.8sec, but the mean SRFs of the Chi-Chi near fault records for $\mu = 8$ are mostly below 4. The closely spaced SRF curves indicate that the ductility demand of the Chi-Chi records is highly sensitive to a decrease in strength. And, the structural inelastic deformation increases dramatically upon yielding. Consequently, the structural strength capacity is more of a concern than the ductility capacity for the case of Chi-Chi near fault ground motions.

BUILDING FAILURE ASSOCIATED WITH SURFACE FAULTING

Tremendous ground movement and surface fault of the Chelungpu fault severely damaged streets, building foundations, electric poles, and even vehicles parked on the street, as shown in Fig. 6. The vertical offset of the Chelungpu surface faulting can be as high as 5m (Fig. 7). As surface faulting passed through multi-house buildings, enormous ground settlement severely damaged the structures, as shown in Fig. 8. As surface faulting cut through the edge of a multi-house building (Fig. 9), the edge house did not deform as intensely as the building shown in Fig. 8 due to the constraint provided by the neighboring houses. However, the ground floor pavement of the edge house (the one marked with an arrow in Fig. 9) was pushed up and squeezed all objects in the first story against the second floor slab, and consequently, caused casualties in the first story. Figure 10 shows a multi-house building sitting on the fault line with its larger plane dimension parallel to the fault line. Although the building also underwent foundation damage, structural damage, and ground floor pavement breakage, surface faulting did not cause excessive and life-threatening uplifting of the ground floor pavement.

Fig. 6 Damage caused by ground movement and breakage

Fig. 7 Vertical offset of Chelyngpu surface faulting

Fig. 8 Multi-house building damaged due to surface faulting

Fig. 9 Multi-house building damaged due to surface faulting and up-lifting of ground floor paverment

Fig. 10 Damage to multi-house building with larger plane dimension parallel to fault line

Unreinforced brick buildings and clay block buildings (Fig. 11), which are susceptible to tensile stress, collapsed as surface faulting passed through or passed by. Low-rise light-gage steel buildings (Fig. 12) were too flexible to cope with the severe ground settlement as well as breakage, and collapsed as surface faulting passed through.

The observations described suggest that: (1) buildings extending across fault lines are prone to severe damage; (2) the larger the plane dimension of a building that is perpendicular to a fault line, the more vulnerable the building; (3) a slab capable of resisting uplifting soil pressure, instead of pavement, helps to reduce hazards caused by vertical surface faulting; (4) strength and stiffness are essential for buildings to cope with vertical surface faulting.

Fig. 11 Collapse of clay-block building

Fig. 12 Collapse of light-gage steel building

BUILDING DAMAGE DISTRIBUTION IN FENGYUAN

Fengyuan is located approximately 45km north of the epicenter (Fig. 1). About 6.5km of the Chelungpu fault go through the Fengyuan Township from south to north and divided Fengyuan into west and east parts (Fig. 13). The land in the west part is a foot-wall and is fairly flat. About 80% of the total population of Fengyuan, which was approximately 160,000 lives in this area. The east part is a hanging-wall and is mountainous with scattered flat lands and holds approximately 20% of total population.

Between the fourth and seventh of October, a team composed of graduate students and faculty members from the Department of Construction Engineering of National Taiwan University of Science and Technology carried out a building damage survey in the Fengyuan. Damaged buildings were categorized into severe damage, moderate damage, and minor damage. Adopted damage criteria were: (1) severe damage — total collapse, partial collapse or significant nonstructural element damage with structural member failure; (2) moderate damage — moderate nonstructural element damage with distinct structural member cracking; (3) minor damage — apparent nonstructural element cracking with or without fine structural member cracking. The damage survey was based on visual inspection, and the categorization of damage levels somewhat depended on the judgment of the individuals conducting the inspection.

All buildings, including those undamaged, located within 100m of the Chelungpu fault (this area is designated as the fault area) were surveyed. In addition, all 12-story or higher buildings were surveyed. The rest of the buildings, except school buildings, were surveyed based on information that was reported by building owners to the township administration.

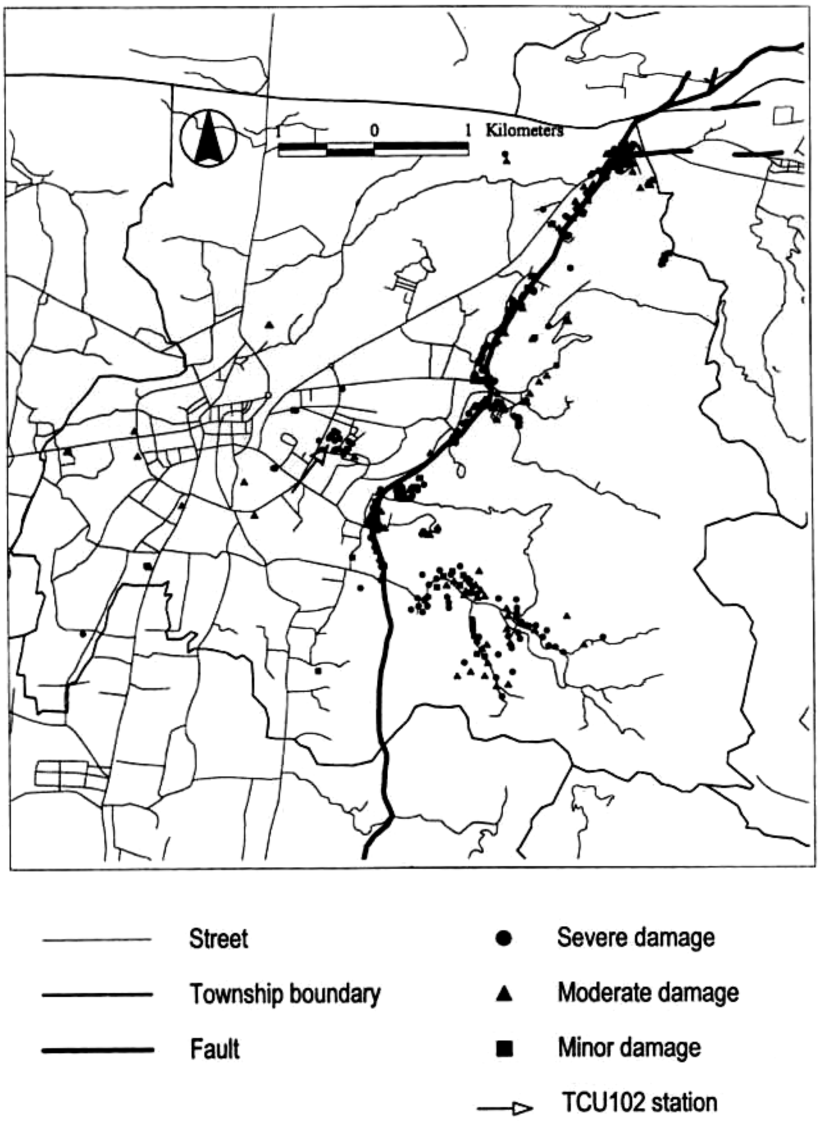

Fig. 13 Damage distribution to buildings in Fengyuan (prepared by the architecture and building reaearch institute)

A total of 552 buildings were evaluated as damaged, as shown in Fig. 13. Sixty three percent of the damaged buildings were reinforced concrete (RC) buildings, as listed in Table 2. The vast majorities of RC buildings in Fengyuan use moment-resisting frames as lateral-force-resisting systems. For RC buildings that were 5 stories or lower, brick walls are used as exterior walls and interior partitions. For those that are 6 stories or higher, 15cm thick RC walls are used as exterior walls, and brick walls or brick walls along with 12cm thick RC walls are used as interior partitions.

Seventeen percent of the damaged buildings were brick buildings (Table 2). Most of those brick buildings have unreinforced brick walls and are no more than 2 stories. A small number of brick buildings were reinforced brick buildings with brick walls reinforced by small and lightly reinforced RC members.

Nineteen percent of the damaged buildings were classified as “Others” (Table 2). Most buildings in this category are buildings with walls built from brick-like clay blocks (Fig. 11). Only 2.5% of the damaged buildings were steel or steel reinforced concrete (SRC) buildings of 2 stories or lower and used light-gage steel members.

Among the 552 damaged buildings, 348 buildings were located in the fault area, and 204 buildings were located in the non-fault area. The total number of structurally independent buildings in Fengyuan is estimated to be 13,000 based on the assumption that 3.5 persons compose a family and 3.5 families occupy a structurally independent building. The total number of buildings in the fault area was 536. Table 3 shows the damage rates in Fengyan, the fault area, and the non-fault area. The overall damage rate of Fengyuan was 4.2%, the damage rate for the fault area was as high as 65%, and the damage rate for the non-fault area was 1.6%. Among the 204 buildings located in the non-fault area, more than half were in the east part of Fengyuan, where only 20% of the total population resided. This would result in a damage rate for the east non-fault area much higher than that of west non-fault area. This seems to indicate that the ground motion in the east part was more destructive than in the west part.

Table 2 Damage distribution to buildings with respect to structural type

Structural type	RC	Steel & SRC	Brick	Wood	Others	Total
Severe damage	165	8	48	3	69	293
Moderate damage	52	1	11	0	16	80
Minor damage	124	5	32	0	18	179
Total	341	14	91	3	103	552

Table 3 Damage rates to buildings in Fengyuan

Area	No. of damaged buildings	Total no. of buildings	Damage rate
Entire Fengyuan	552	13,000	4.2%
Fault area	347	536	64.7%

Non-fault area	204	12,500	1.6%

Table 4 lists the distribution of building damage with respect to story height.

A total of 509 buildings were 1 to 3 stories, however, the total number of buildings from 1 to 3 stories is also very large. For the non-fault area, it is estimated that the damage rate of buildings between 1 to 3 stories was at the same order of the average damage rate (1.6%).

Table 5 lists story height, damage level, and the distance to the fault line of all buildings that were 12 stories or higher.

Table 4 Distribution of damaged buildings with respect to building height

Building height (story)	Number of buildings damaged	Percentage
1	195	35.3
2	174	31.5
3	137	24.8
4 ~ 7	19	3.4
8 ~ 11	4	0.7
12	7	1.3
14	3	0.5
16	7	1.3
20	3	0.5
22	3	0.5
Total	552	100

Table 5 List of buildings that are 12 stories or higher

Name	No. of stories	Damage level	Distance to fault (m)
Hsiangyangyungchao-ABC	12	Severe (total collapse)	750
Hsiangyangyungchao-DE	12	Severe	750
Hsiangyangyungchao-FG	12	Severe	750
Fengtien	14	Severe	1,200
Fengyuantsunlung-A	22	Severe	600
Fengyuantsunlung-B	22	Severe	600
Fengyuantsunlung-C	22	Severe	600
Techuanchiakang-A	16	Severe	1,200
Techuanchiakang-B	16	Severe	1,200
Chingfengnien	12	Moderate	1,000
Yungfu	12	Minor	2,600
Yente	12	Minor	1,200
Fengchenshihchia	14	Minor	1,200
Fengyuantiichia-A	16	Minor	3,100
Fengyuantiichia-B	16	Minor	3,100
Fengyuantiichia-C	16	Minor	3,100
Fengyuantiichia-D	16	Minor	3,100
Fengyuantiichia-E	16	Minor	3,100
Yataiihsin	12	Minor	2,600
Tuhuichiachi-A	20	Minor	2,200
Tuhuichiachi-B	20	Minor	2,200
Tuhuichiachi-C	20	Minor	2,200
Fengyuanhuangchia	14	Minor	2,000
Mingjentienhsia	12	No	1,800
Fengyuanhsinsu	12	No	1,700
Fengyuanhuangchia-A	12	No	1,900
Fengyuanhuangchia-B	15	No	1,900

Tsungtutienyingcheng	14	No	1,700
Wenhuakuangchang	12	No	1,000

All these buildings were on the west side of the Chelungpu fault, and the distance from the buildings to the Chelungpu fault ranged from 750m to 3,100m. 9 out of 29 of these buildings were evaluated as severe damage, yielding a damage rate of 31% for this damage level. It also shows that 23 (79%) of these buildings were evaluated as at least minor damage. The damage rate of the buildings in this range, either 31% or 79%, was more than 15 times higher than the average damage rate in the non-fault area which had only 1.6%. Although improper design and poor construction quality were responsible for some of the damage to these buildings, ground motion is considered to have played a major role.

TCU102 station is the only strong motion station in Fengyuan and is about 0.8km away from the fault line (Fig. 13). Between ground surface and bedrock is a 15m-thick formation of gravel, and the soil condition is classified as type I. The ground motion and the corresponding spectral acceleration of the TCU102 record are shown in Fig. 3 and Fig. 14, respectively. In addition, the code (1997 Taiwan Code) specifications pertaining to design spectral acceleration for soils type I and soil type II are shown in Fig. 14. The PGA of TCU102 (S50W) is 251 gal, which is very close to the code specified acceleration of 0.28g. However, the spectral acceleration curves of the TCU102 record dramatically deviate from code specified curves. For periods shorter than 0.3sec, the TCU102 curves are much lower than code specified curves. However, for periods between 1.0 and 1.5sec, the TCU102 curves are much higher than code specified curves. In addition, the effect of ductility in reducing strength demand is much lower than expected for periods between 1.0 and 1.5sec, as shown by the dotted lines in Fig. 5. It is shown that the strength demand is higher than expected and the effect of ductility is lower than expected for buildings with periods falling between 1.0 and 1.5sec. Therefore, buildings that are 12 stories or higher suffered violent vibrations and were more vulnerable to the earthquake. However, it is

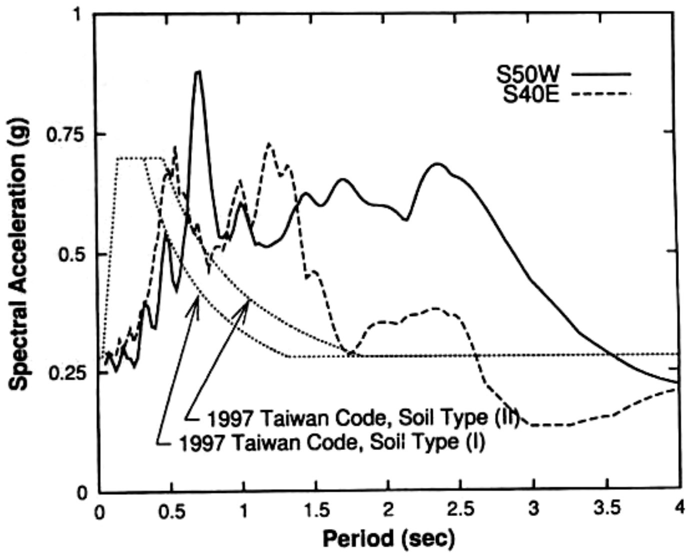

Fig. 14 Spectral acceleration record for TCU102 station

noted that all the buildings located beyond 1,200m away from the fault line were evaluated as either minor damage or no damage. This tends to suggest that the destructiveness of the ground motion declined for high-rise buildings that were 1,200m away from the fault line.

DAMAGE DISTRIBUTION TO BUILDINGS ALONG THE FAULT IN FENGYUAN

Among the 288 buildings classified as severe damage (Table 2), 198 (69%) were located within 100m of the Chelungpu fault. It is evident that the damage to buildings was concentrated heavily in the fault area. The total number of buildings, including those not damaged, in the fault area was 536, and all buildings in the fault area were 1 to 3 stories. The width of surface faulting ranged between 2m and 50m with an average width of 15m. The definition of the fault line is shown in Fig. 15. The distance of a building to the fault line, which is defined as the shortest distance from any point of the building to the fault line, for all buildings in the fault area was recorded.

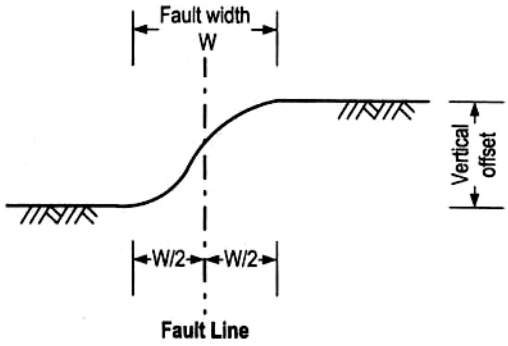

Fig. 15 Definition of fault line

Table 6 lists damage distribution to the buildings in the west and east fault areas. The total number of buildings in west and east fault areas was 293 and 243, respectively. The average damage rate in the east fault area was 91%, which was much higher than the 43% for the west fault area.

Table 6 Damage distribution to buildings in fault area

Distance from fault line (m)	0 ~ 25		25 ~ 50		50 ~ 75		75 ~ 100		0 ~ 100	
	West	East	West	East	West	East	West	East	West	East
Severe damage	62	91	2	20	2	17	2	2	68	130
Moderate damage	15	7	3	10	0	6	1	3	19	26
Minor damage	17	30	14	19	3	10	5	6	39	65
No damage	54	10	50	10	24	1	39	1	167	22
Total	148	138	69	59	29	34	47	12	293	243

Figure 16 shows the damage rate distribution to buildings in the fault area. Most of the building damage in the first 25m was associated with surface faulting, whereas the damage to buildings within 25 to 100m was primarily due to ground shaking. The damage rate associated with ground shaking was considerably higher in the east fault area than the west fault area. Both the average damage rate and the damage rate distribution in the fault area indicate that the ground shaking on the hanging-wall was much more destructive than that on the foot-wall.

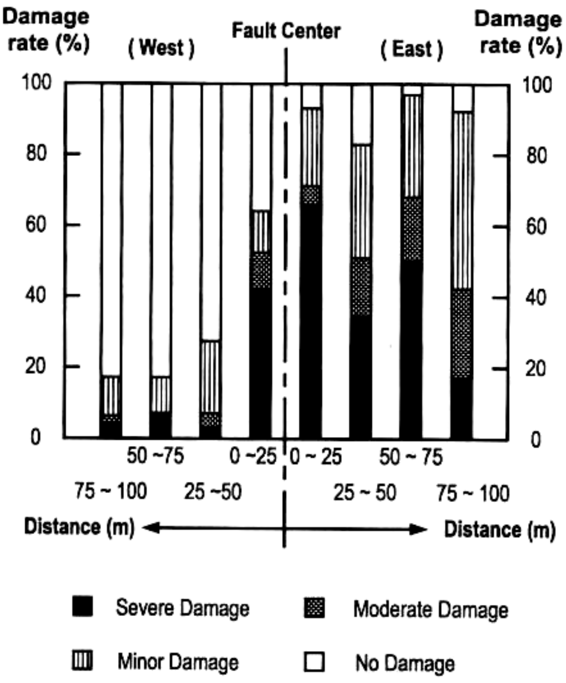

Fig. 16 Damage rate distribution to buildings in fault area

CONCLUSIONS

The violent ground shaking and significant surface faulting of the September 21, 1999 Chi-Chi earthquake has provid- ed an opportunity to expand our understanding of near-fault building responses and building damages associated with surface faulting. Based on the preliminary investigation reported herein, the following conclusions can be drawn.

1. The Chi-Chi near fault records show the characteristics of very long-period pulses in ground velocity time histories. The corresponding response spectra indicate that long-period structures are more vulnerable to long-period velocity pulses than short-period structures. Results from inelastic spectral analyses show that the strength reduction factors for Chi-Chi near fault records are very low, especially for large ductility ratio cases.
2. Buildings with large plane dimensions suffered severe structural damage from ground settlement and casualties from excessive uplifting of ground floor pavement caused by vertical surface faulting. Possible measures for reducing the hazards caused by vertical surface faulting in- clude limiting plane dimensions of buildings and providing ground floor slab with resistance to soil pressure.
3. Spectral acceleration curves based on ground motion from Fengyuan, which deviate significantly with those specified by design code, show that high- rise buildings are more vulnerable to this particular ground motion. Re- sults from damage surveys also show a high damage

rate for high-rise buildings in Fengyuan. However, it is also noted that the destructiveness of the ground motion declined for high-rise buildings located more than 1,200m away from the fault line.

4. Results from the damage survey show that the building damage rate in the hanging-wall area was much higher than that in the foot-wall area. These survey results suggest that ground shaking in the hanging-wall area was more destructive than that in the foot-wall area.

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