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Near-Field Characteristics and Engineering Implications of the 1999 Chi-Chi Earthquake

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ABSTRACT

This paper presents an observation of near-field ground motion characteristics and the patterns of velocity waveforms in relation to the Chelungpu rupture surface of the 1999 Chi-Chi earthquake. Ground motion data integrated from accelerograms measured at close-distances to the surface rupture exhibit pulse-like time histories with very large ground velocities and ground displacements. Two strong motion stations located at the northern portion of the Chelungpu fault measured peak ground velocities (PGV) of up to 380 and 250cm/sec. These measurements far exceed any other PGV records to date. Engineering implications of these important ground motion data are interpreted through response spectra and drift spectra analyses.

INTRODUCTION

On September 21, 1999, 1:47a.m. local time, a powerful earthquake measuring M_L 7.3 or M_s 7.6 struck a heavily populated region in the central part of Taiwan. The epicenter was located near a small town Chichi and the quake is called the Chi-Chi earthquake. Two major faults near Chichi, the Chelungpu fault and the Shungtung fault, are the possible sources of this event. After the quake, an over 80km surface rupture was identified along the Chelungpu fault line (Fig. 1). The surface rupture indicates an east-dipping thrust mechanism that produced a vertical differential ground movement of about 2 ~ 3 meters on average. Left-lateral horizontal ground movement of around 1 ~ 2 meters is also evident along the rupture surface. The Chi-Chi earthquake caused more than 2,300 deaths and wide-spreading damage to building and bridge structures. Intensive building damage was roughly distributed within a 5km band along the Chelungpu fault line.

Ground motion of the Chi-Chi event was well monitored through over 500 strong ground motion stations operated

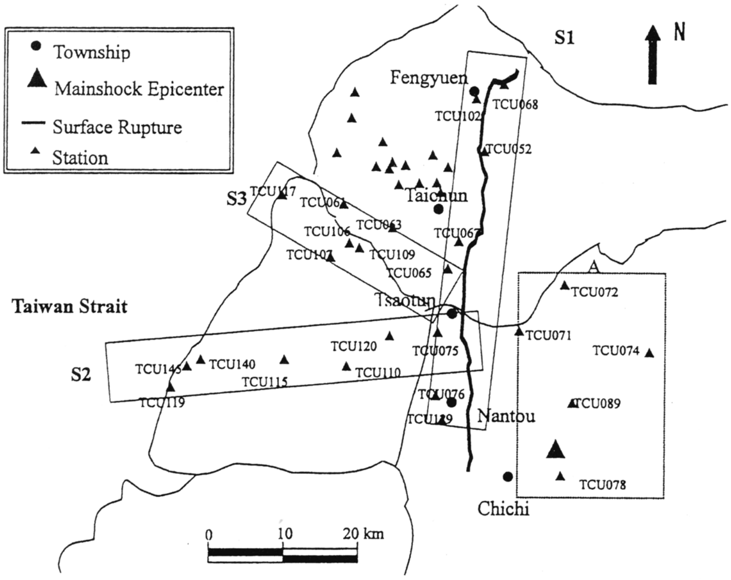

Fig. 1 Map view of the Chelungpu rupture surface and strong ground motion stations

by the Central Weather Bureau (CWB). Arguably one of the most intensive sets of near-field data was also collected from many free-field stations located at very close distances to the rupture trace of the Chelungpu fault (Fig. 1). Two close-to-epicenter stations, the TCU129 station and TCU084 station, both measured maximum horizontal acceleration of over the *g* level. These unparalleled readings indicate a violent ground shaking intensity in the near-field region.

Near-field ground motions observed from recent significant events such as the 1994 Northridge earthquake, USA and the 1995 Hyogoken-Nanbu (Kobe) earthquake, Japan have drawn much attention to both researchers and engineers [1~6]. The Northridge and Kobe near-field ground motions show distinct high velocity long-period ground velocity or displacement pulses that are extremely destructive to tall building structures. The collection of Chi-Chi near-field records provides an opportunity to further investigate the near-field effects in-depth. This paper presents an overview of the near-field ground motion characteristics of the Chi-Chi earthquake. Emphasis is given to ground velocities measured at close distances to the Chelungpu fault line.

GROUND MOTIONS

Near-field ground motion is characterized by its long-period velocity or displacement pulse-like time histories. The indicated long-period contents may artificially be removed when inappropriate base-line correction schemes are used in the data correction process. To preserve these important near-field characteristics, special caution has been taken in treating the uncorrected acceleration data provided by the CWB. This study adopts the segmented low-order polynomial base-line correction scheme [7], which is considered to be more appropriate in dealing with near-field data than other traditional baseline correction schemes. Specifically, a baseline consisting of three polynomial segments is best-fitted to velocity time histories integrated from the uncorrected acceleration. The corrected velocity is then obtained by subtracting the base- line velocity from the uncorrected velocity. The corrected displacement and acceleration are obtained by further integrating and differentiating the resulting velocity with respect to time.

This study considers three spatial profiles and one region, labeled S1, S2, S3 and A respectively, to present the ground velocity time histories. The profile S1 is aligned with the Chelungpu fault line, thus nearly all stations within 5km from the rupture trace are included in S1. The orientations for profiles S2 and S3 are arbitrarily selected, but both profiles share one common station with S1. The profiles S2 and S3 are used to investigate variations in ground motion away from the fault line. Only foot-wall stations are included in S2 and S3 due to the sparseness of the hanging-wall stations along S2 and S3. The ground motion characteristics for the hanging wall are investigated for those stations enclosed by region A. Both the E-W and N-S components of the velocity time histories are presented.

Ground Motions of Profile S1

In this station group, the stations TCU068 and TCU052 are located at the hanging wall, and the other 6 stations are located at the foot wall. The E-W and N-S velocity time histories are shown in Fig. 2. It is noted that the absolute initial time for these records is not precisely known. The presented time scales are based on those of the original CWB data.

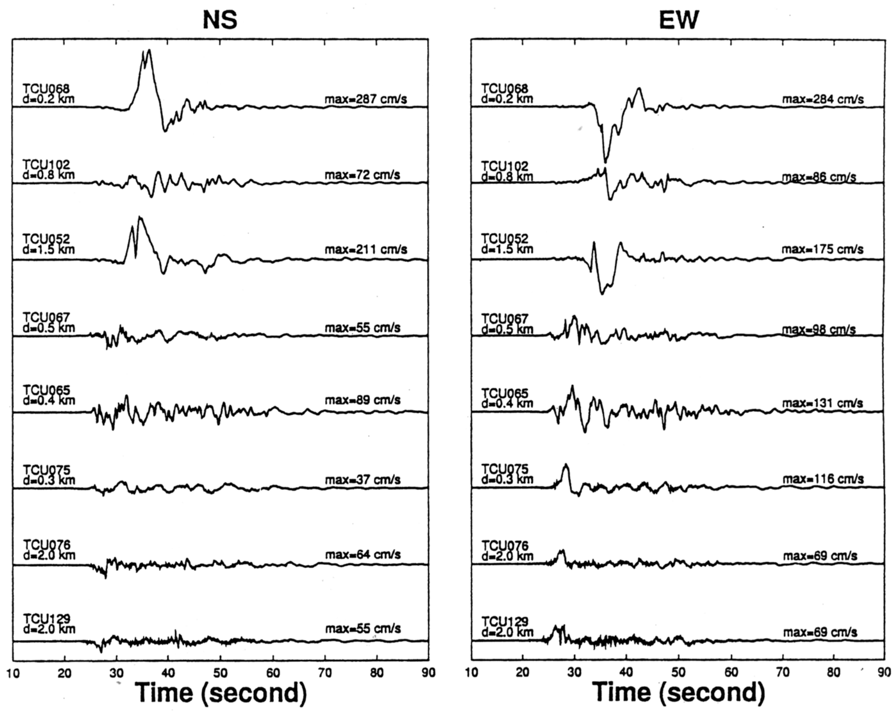

Fig. 2 E-W and N-S components of velocity time histories for stations in S1

For each station in S1, the velocity time history is also rotated into its maximum velocity direction in Fig. 3 to highlight its engineering significance. In Fig. 3, the maximum horizontal velocity of each station is shown by the size of a circle centered at the corresponding station. In addition, a closed curve inside each circle is used to indicate the peak ground velocity (PGV) in all directions. Thus, the maximum velocity direction is oriented from the center of each circle to the only intersection of the closed curve and the circle.

Foot-wall Stations

In Fig. 2, the 6 foot-wall stations in general show long-period ground velocity pulses in the initial E-W ground motion records. The TCU075 record exhibits a single clean pulse while the TCU065 and TCU067 records show higher-frequency contents embedded in a long-period ground pulse. The TCU065 has the highest PGV of 131cm/sec in this station group. It is noted that the E-W component of the TCU129 station has a PGA of around 1 *g*; however, it gives the smallest PGV of 69cm/sec in this station group.

For these 6 stations, the PGV in the E-W direction are larger than that in the N-S direction. However, the difference in PGV is not significant except for the TCU075 record. Since the rupture surface is roughly oriented in an N-S direction, the fault-normal direction appears to experience stronger ground velocity than the fault-parallel direction

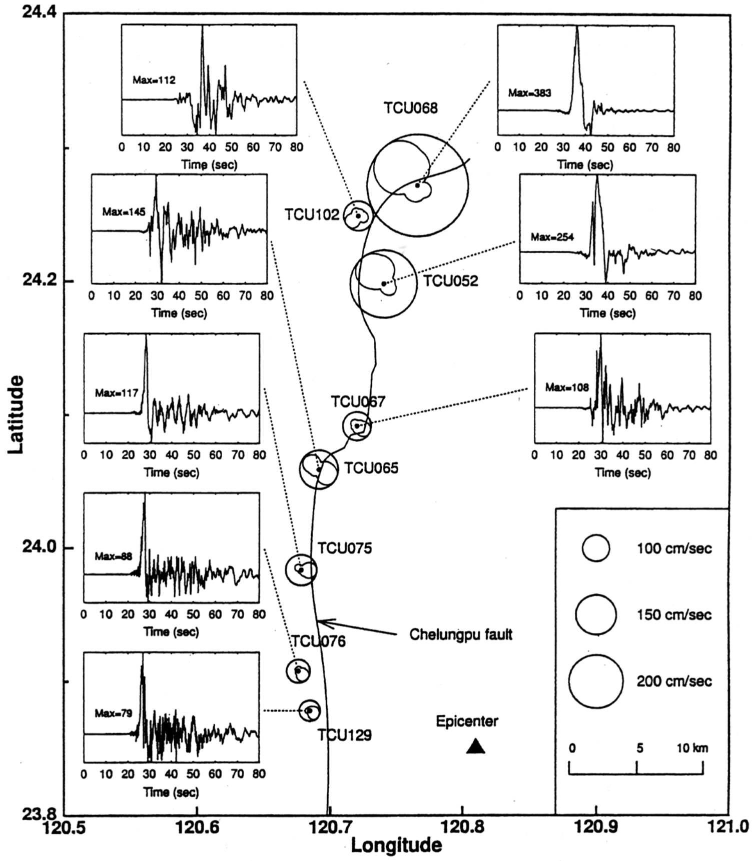

Fig. 3 Velocity time histories in maximum velocity direction for stations in S1

for these stations. Nevertheless, the fault-normal direction does not necessarily coincide with the maximum velocity direction as illustrated in Fig. 3. For example, the maximum velocity direction of the TCU102 station is roughly in the fault-parallel direction, and the maximum velocity direction of the TCU076 station is roughly at a 45° angle from the fault- normal direction.

<u>Hanging-wall Stations</u>

In Fig. 2, the TCU068 and TCU052 records demonstrate exceptional long-duration velocity pulses with clean velocity waveforms in both the E-W and N-S directions. The N-S components of TCU068 and TCU052 records show positive velocity time histories sustained for over 6 seconds between the time frame 30 < t < 40 seconds, an indication of one-sided ground movement for a long duration without reversing. A similar feature is also observed for both records in the E-W direction. The PGV for both records all occur during the one-sided ground movement for both components. The PGV are very high, ranging from 175cm/sec to 287cm/sec, and are at the same level in both the N-S and E-W directions.

Since the PGV of the TCU052 and TCU068 data are exceptionally large, it is necessary to further investigate both records in great detail. Therefore, the ground particle trajectories as well as 3-component acceleration, velocity and displacement time histories associated with the maximum velocity direction are given in Fig. 4 to Fig. 11.

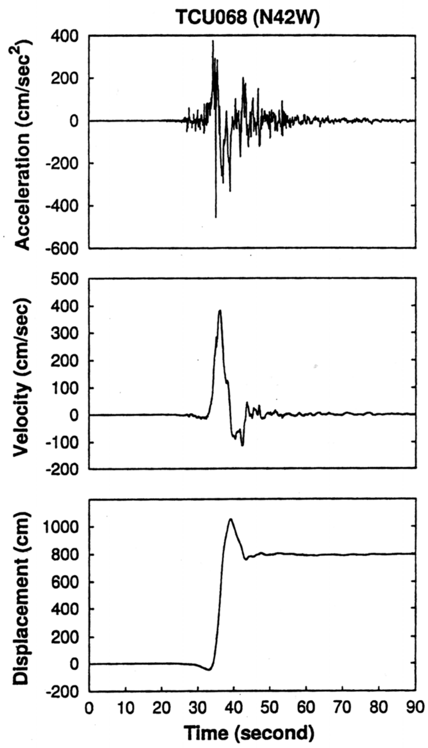

Fig. 4 Acceleration, velocity and displacement time histories for station TCU068 in N42W direction

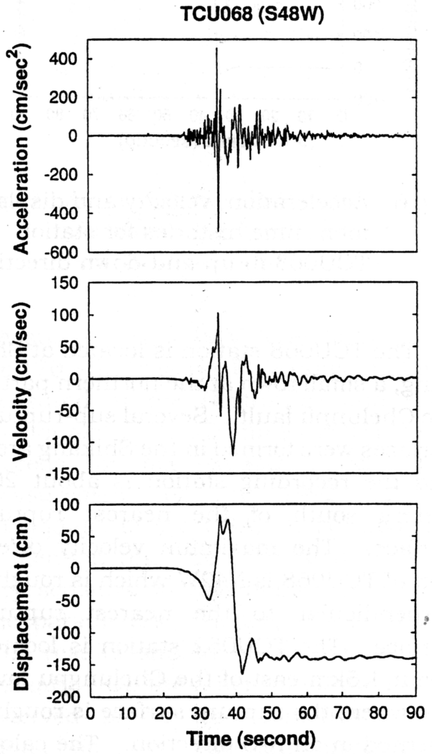

Fig. 5 Acceleration, velocity and displacement time histories for station TCU068 in S48W direction

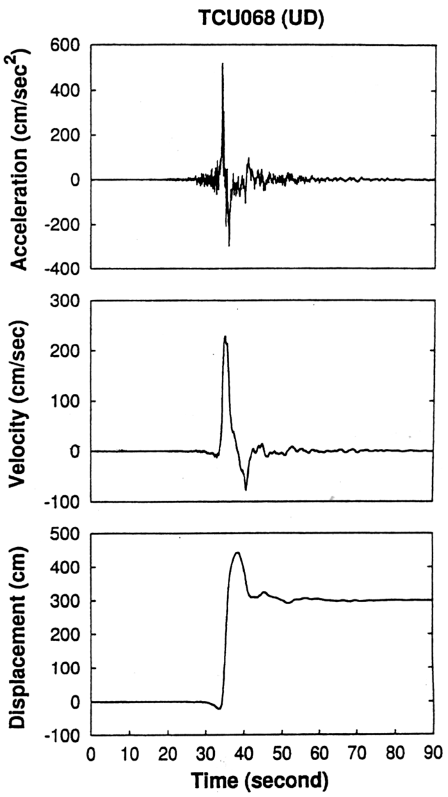

Fig. 6 Acceleration, velocity and displacement time histories for station TCU068 in up-and-down direction

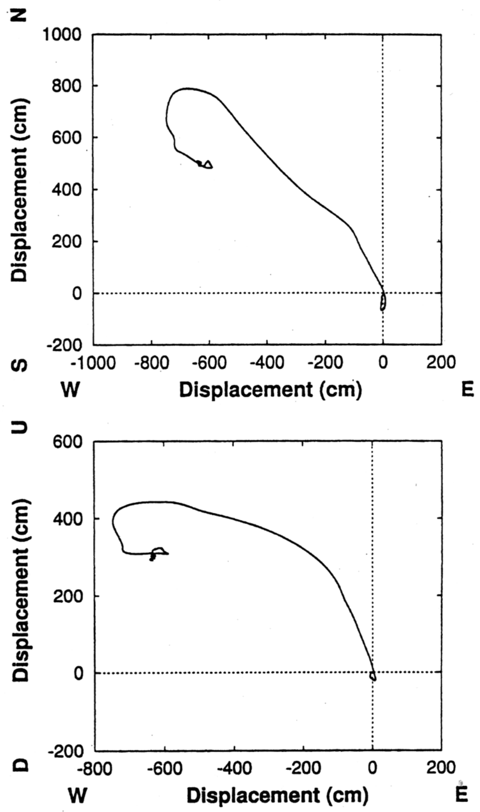

Fig. 7 Trajectories of ground displacement for station TCU068

The TCU068 station is located at Shikang, a small town at the northern part of the Chelunpu fault. Several sub-rupture surfaces were formed in the Shikang area, and the recording station is about 200 meters south of the nearest rupture surface. The maximum velocity direction of TCU068 is N42W which is roughly perpendicular to the nearest rupture surface. The TCU052 station is located about 1.5km east of the Chelungpu fault line where the rupture surface is roughly oriented in an N-S direction. The calculated TCU052 maximum velocity direction is N39W, deviating from the fault-normal direction at about 50°.

The ground moving patterns are very similar for both records. For the maximum velocity direction, the TCU068 shows a clean velocity pulse with a peak of as high as 383cm/sec. The TCU052 record also has a very high peak velocity of 254cm/sec. Both displacement time histories exhibit simple north-westerly ground movement for an over 6-second duration. The dynamic horizontal ground movement of TCU068 reaches 10 meters in PGD and leaves an approximate 8-meter permanent displacement offset. The TCU052 has a PGD of around 8 meters and a permanent displacement offsect of over 5 meters.

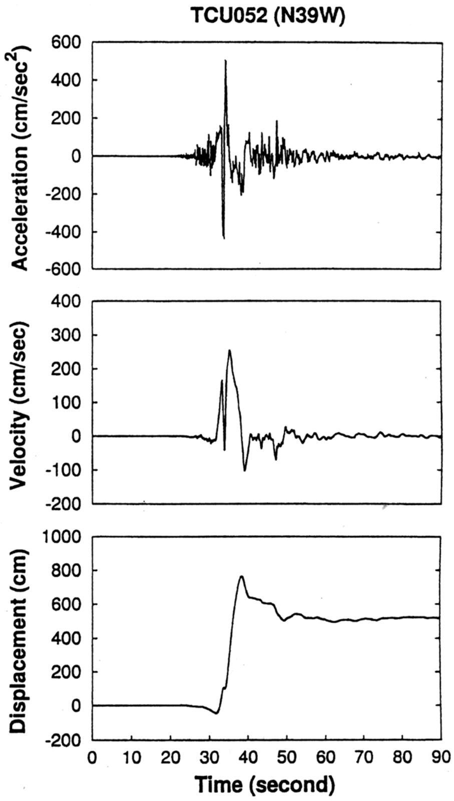

Fig. 8 Acceleration, velocity and displacement time histories for station TCU052 in N39W direction

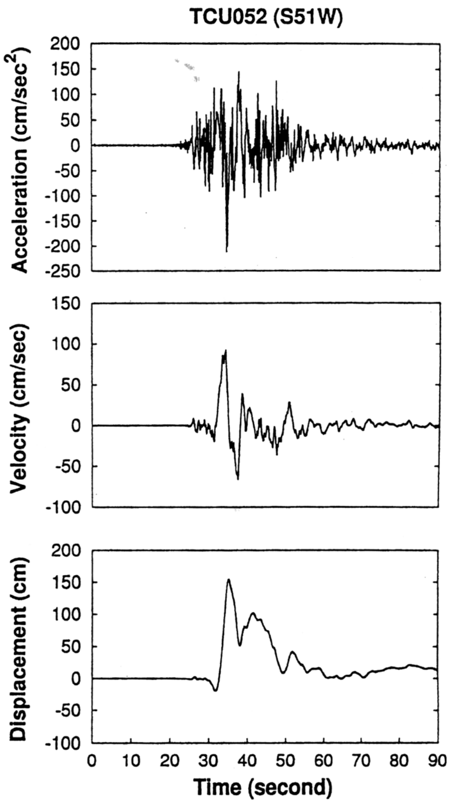

Fig. 9 Acceleration, velocity and displacement time histories for station TCU052 in S51W direction

Both records also show an over 100cm/sec in PGV in the normal to maximum velocity direction. The up-and-down component indicates an uplifted ground motion in a very simple manner and the final permanent displacement offset is about 3 meters in both records. Another distinct feature of these two records is that their peak horizontal acceleration levels are both only about 0.4 *g*, a relatively low value as compared to their exceptionally high velocity.

The 383cm/sec in PGV and around 10 meters in PGD of the TCU068 record are very likely the highest PGV and PGD ever measured. This PGV level far exceeds the 170 ~ 185cm/sec PGV range that was measured in the Northridge and Kobe earthquakes. The 10-meter PGD also far exceeds the approximate 250cm PGD measurement of the 1992 Landers earthquake in the USA. It is important to mention that the calculated PGD are very sensitive to variations of the base-line parameters. Hence, the presented PGD results should be considered preliminary. On the other hand, the PGV is observed to be less sensitive to the adjustments of base-line parameters. The engineering implications of these unusual records are addressed later in this paper.

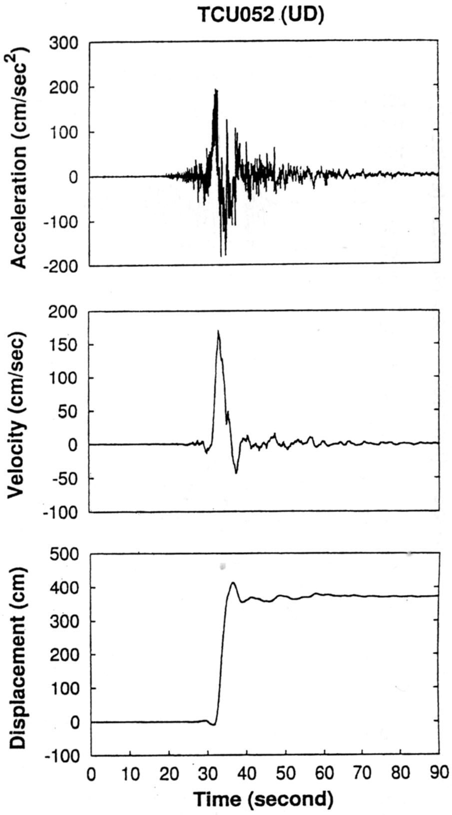

Fig. 10 Acceleration, velocity and displacement time histories for station TCU052 in up-and-down direction

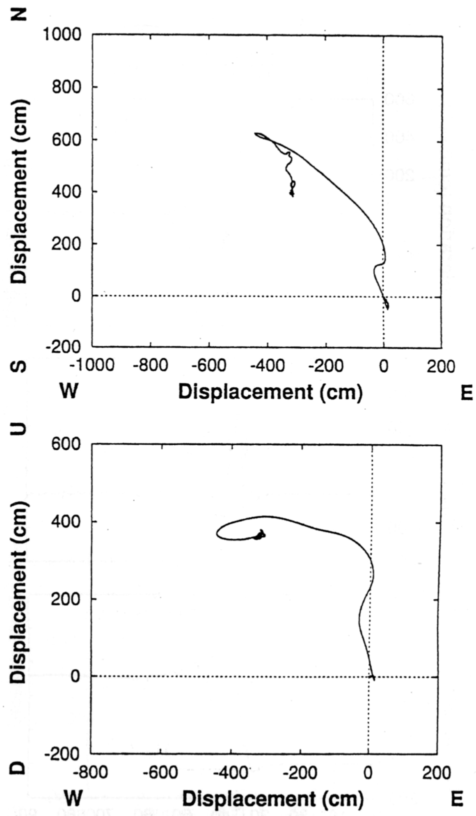

Fig. 11 Trajectories of ground displacement for station TCU052

Ground Motions of Profile S2 and S3

The velocity time histories for S2 are shown in Fig. 12. TCU075 is the closest station to the fault line, followed by TCU120, TCU110, TCU115, TCU140, TCU145 and TCU119, respectively. In the E-W direction, a good coherence is found in the early velocity waveforms for the TCU075, TCU120 and TCU110 data. The TCU075 station is only 0.3km from the fault and its record shows a well-defined initial velocity pulse peaked at 116cm/sec. The TCU120 station is located further away from the fault line at a distance of 6km. The shape of the initial velocity pulse in the TCU075 record seems to be preserved at the TCU120 record. However, the PGV of the TCU120 record is reduced to 61cm/sec, only about half of the 116cm/sec of the TCU075 record. In the TCU110 record, the initial velocity pulse becomes unidentifiable. These three records suggest that the pulse velocities decay rapidly as the site-to-fault distance increases. As the distances reach beyond 12km, no initial velocity pulse is observed and only long-period waveforms appear at later time.

The velocity time histories for the S3 profile are shown in Fig. 13. In this station group, TCU065 is the closest station to the fault and its E-W velocity

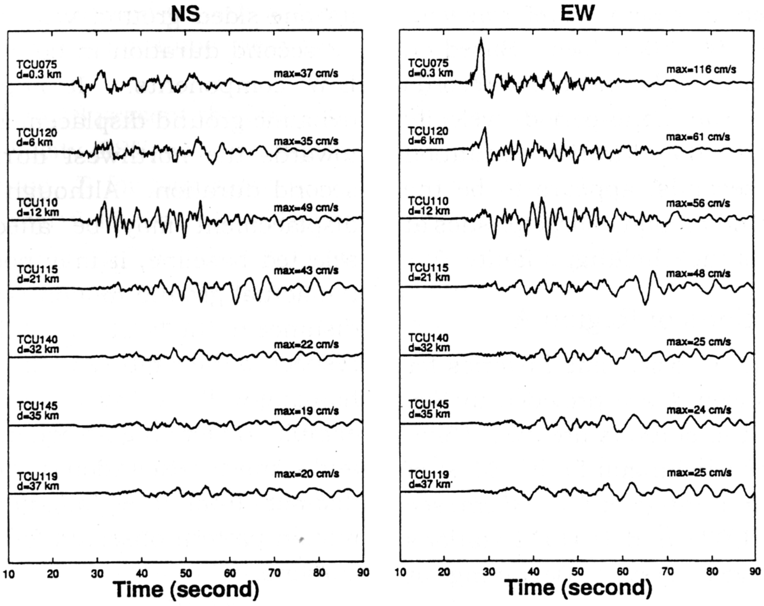

Fig. 12 E-W and N-S components of velocity time histories for stations in S2

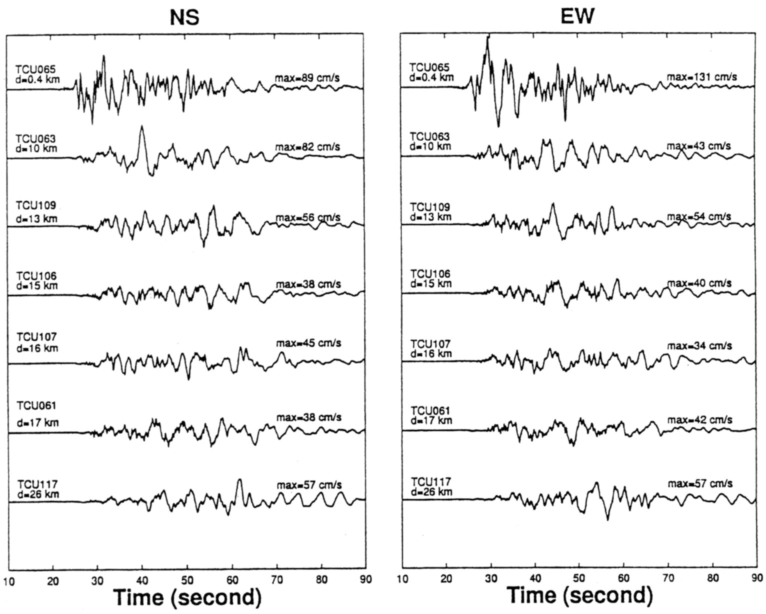

Fig. 13 E-W and N-S components of velocity time histories for stations in S3

component contains multiple ground pulses. This pulse shape can no longer be identified from the TCU063 record due to the fact that two stations are approximately 10 kilometers apart. However, the subsequent stations from TCU063 to TCU061 show an excellent coherence in velocity time histories for both the N-S and E-W components. These stations show long-period velocity waveforms with PGV of about 40 ~ 60cm/sec. Based on the presented records and other records not shown, the long-period velocity waveform with long-duration excitation (roughly 50 seconds) appears to be the common ground motion characteristics at the foot wall of the Chelungpu fault.

Ground Motions of Region A

The ground velocity time histories for stations in region A are provided in Fig. 14. Most of the stations are over 15km away from the Chelungpu fault. Most of the PGV are in a range of 40 ~ 85cm/sec where the TCU071 and TCU072 stations have the largest PGV. Beginning at $t \approx 25$ seconds, the TCU071 record exhibits one-sided ground velocity for over a 10-second duration in both the N-S and E-W components. It implies a large dynamic ground displacement movement towards the northwest during this 10- second duration. Although this ground displacement may be affected by the selected baseline, it may possibly reflect the actual ground motion considering its distance to the fault and its location with respect to the rupture path. The general hanging-wall velocity time histories exhibit richer high-frequency contents and a shorter excitation duration that are distinct from the long-period ground motion pattern observed for the foot-wall stations.

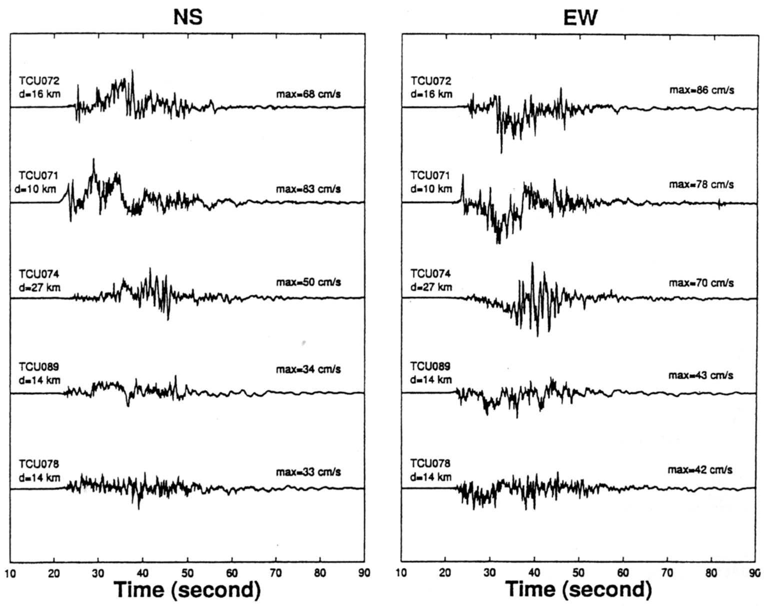

Fig. 14 E-W and N-S components of velocity time histories for stations in region A

CHARACTERISTICS OF RESPONSE SPECTRA

The observed pulse-like ground velocity time histories in S1 stations show typical near-field ground motion experiencing forward rupture directivity effects. Similar types of ground motion were also observed in the Northridge and Kobe near-field records. To compare the spectral contents of these important ground motion records, the standard tripartite response spectra are provided for the Chi-Chi near-field records as well as the Northridge and Kobe near-field records.

Figures 15 to 18 present the 5% damped pseudo-velocity (PSV) as a function of structural period, *T*, for four representative Chi-Chi near-field records, TCU068, TCU052, TCU067 and TCU065. In these plots, the solid lines and dashed lines respectively represent the spectra computed for the maximum velocity directions and the normal to maximum velocity directions. Each plot also provides two other response spectra for the Rinaldi Receiving Station (RRS) record of the Northridge earthquake (dash-dotted line) and the Takatori Station (TAK) record of the Kobe earthquake (dotted line). The maximum velocity direction is considered for both the RRS and TAK records.

A notable difference is observed in the overall spectra shape between the Chi-Chi spectra and the RRS and TAK spectra. For the maximum velocity directions, the overall shape of Chi-Chi near-field spectra appears to have a wider velocity-controlled PSV platform extending towards long periods. The velocity platforms of the Chi-Chi records all extend beyond a period of 5 seconds without apparent decay. By contrast, the RRS and TAK spectra start to approach their asymptotic PGD at $T \approx$ 2sec. As a consequence, the TCU068, TCU052 and TCU065 records all show larger PSV than the RRS and TAK records for T > 3sec. The PSV of TCU067 record exceeds that of the RRS and TAK records at $T \approx$ 5sec due to its relatively low PSV platform.

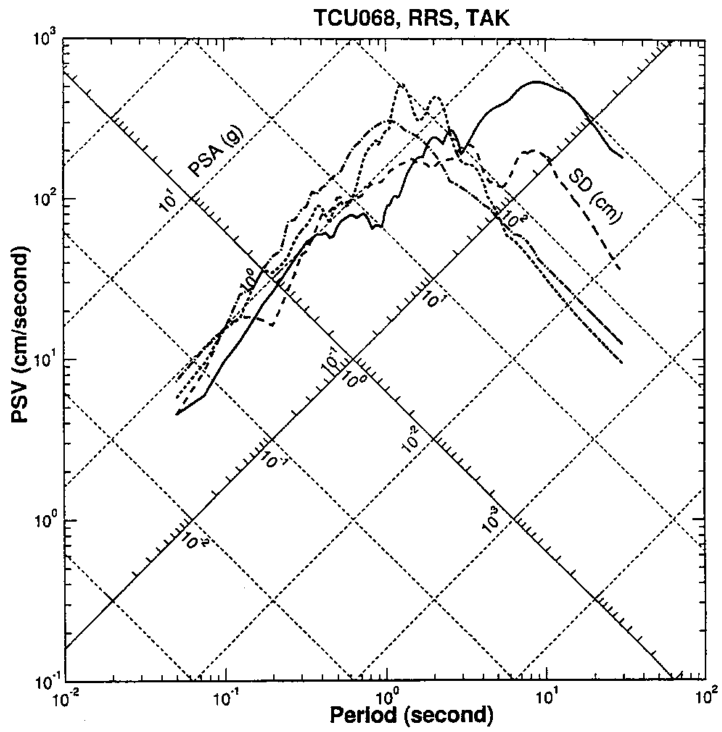

Fig. 15 Comparison of response spectra for stations TCU068, RRS and TAK

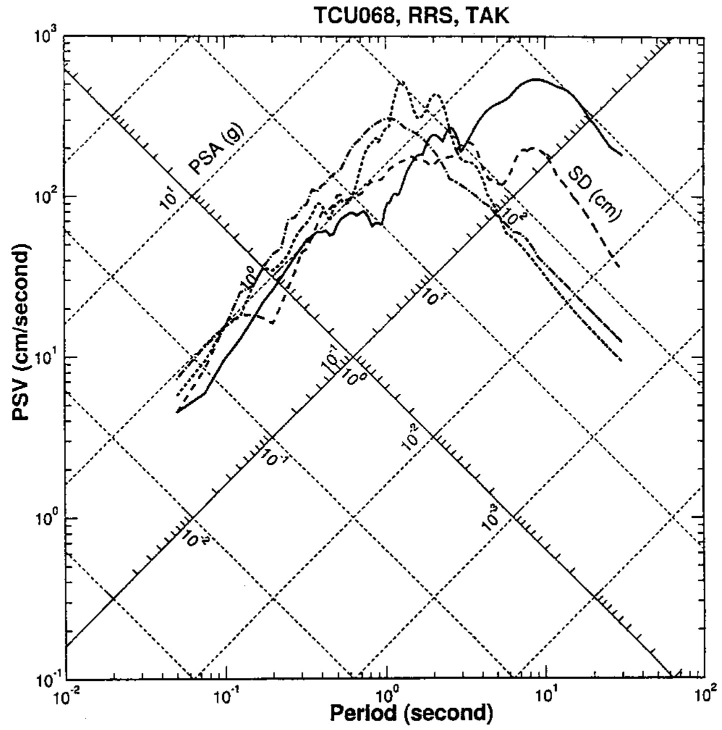

Fig. 16 Comparison of response spectra for stations TCU052, RRS and TAK

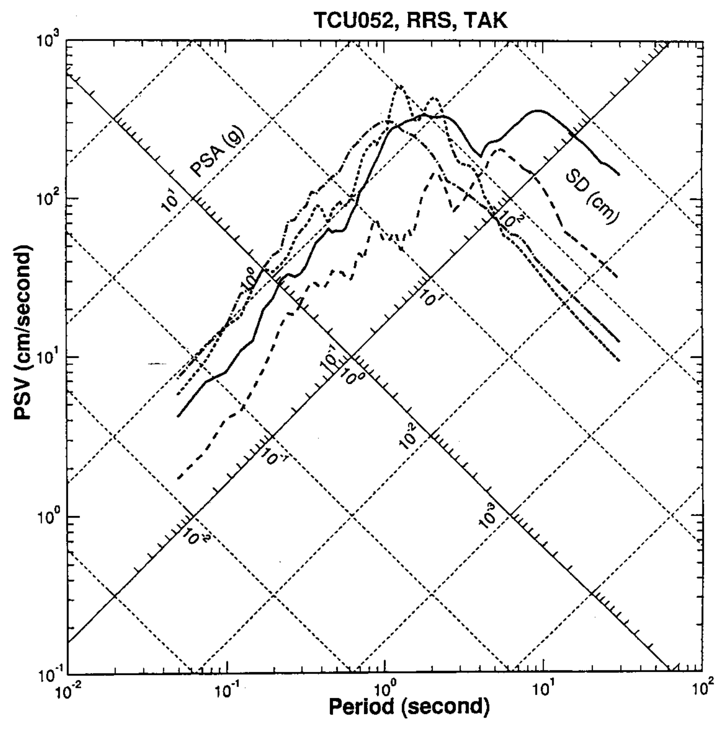

Fig. 17 Comparison of response spectra for stations TCU067, RRS and TAK

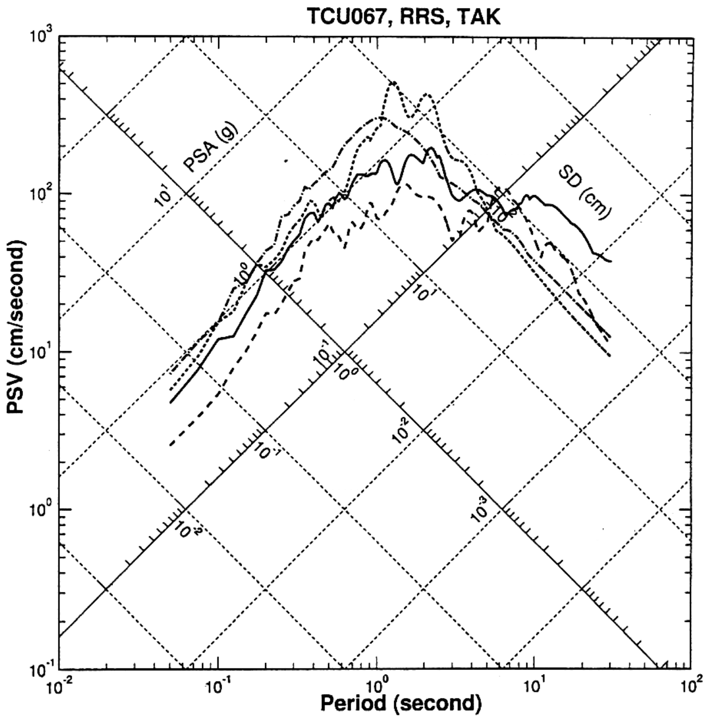

Fig. 18 Comparison of response spectra for stations TCU065, RRS and TAK

The major causes for the wider PSV platform with a large response are related to two important Chi-Chi near-field ground motion characteristics. The first characteristic is the high velocity ground pulse, a common feature shared by the RRS, TAK and the Chi-Chi records. The high velocity ground pulse generally results in large PSV response extended over a wider period range than most far-field earthquake spectra. The second important characteristic is the much larger PGD or, equivalently, the much longer pulse-duration of the Chi-Chi near-field records as compared to the RRS and TAK records. The PGD for RRS and TAK are within a level of 80cm, but the PGD for TCU052 and TCU068 records are around 7 meters and 10 meters respectively. The large PGD effect significantly raises the spectral shape at very long periods where the spectral values are governed by the asymptotic spectral displacement. Since the corrected PGD is very sensitive to the baseline selected, the resulting spectral displacement asymptote is thus inherent with certain degrees of uncertainty for the TCU052 and TCU068 records. However, such an uncertainty would mostly occur at very long periods that are beyond the period range of general engineering interests.

Also in the maximum velocity directions, the Chi-Chi near-field records have generally lower PSV than the RRS and TAK records at short periods. Except for the TCU065 record, the PSV responses of Chi-Chi near-field records are all lower than the TAK and RRS records for $T < 1$sec. In particular, the TCU068 spectrum shows relatively low PSV at short periods and high PSV at long periods. The peak of the TCU068 PSV curve occurs at $T \approx 8$sec, and the peaks of the RRS and TAK curves both occur at $T \approx 2$sec. Thus, the spectral shape of the TCU068 record appears to have a PSV platform right- shifted towards long periods. A similar right-shifted trend in spectral shape is also observed in other Chi-Chi near-field records. This unusual spectral shape not only significantly differs from most spectral shapes of far-field earthquakes, but also substantially deviates from the near-field spectral shape inferred from the RRS and TAK records.

Velocity-to-Acceleration Ratio

The right-shifted spectral shape may be explained by unusual velocity-to-acceleration ratios in many Chi-Chi near-field records. This ratio parameter has long been used to estimate the starting period of a velocity-controlled region in response spectra. An appropriate approach in presenting this ratio is to divide the PGV by normalized maximum ground acceleration, PGA/g, where g is the acceleration of gravity. Figure 19 presents the velocity-to-acceleration ratios of the 8 Chi-Chi near-field records ordered in their longitudinal coordinates. Calculations for these ratios are given in Table 1. Figure 19 also illustrates a ratio range evaluated from 6 near-field records of the Northridge and Kobe earthquakes. These 6 stations and the corresponding ground motion data are listed in Table 2.

For typical far-field earthquakes in the U.S., statistical studies suggest that the velocity-to-acceleration ratios roughly range from 50cm/sec to 120cm/sec depending on the local site conditions [8]. A similar ratio range is also reported from a recent statistical study based on 168 Taiwan far-field earthquake records [9]. As indicated in Fig. 19, the Northridge and Kobe near-fields records have a ratio range of 125 ~ 210cm/sec which is beyond the 50 ~ 120cm/sec range of the far-field earthquakes. It indicates that the near-field effects can highly amplify the ground velocity. Such an increase in ground velocity is not in proportion to an increase in ground acceleration.

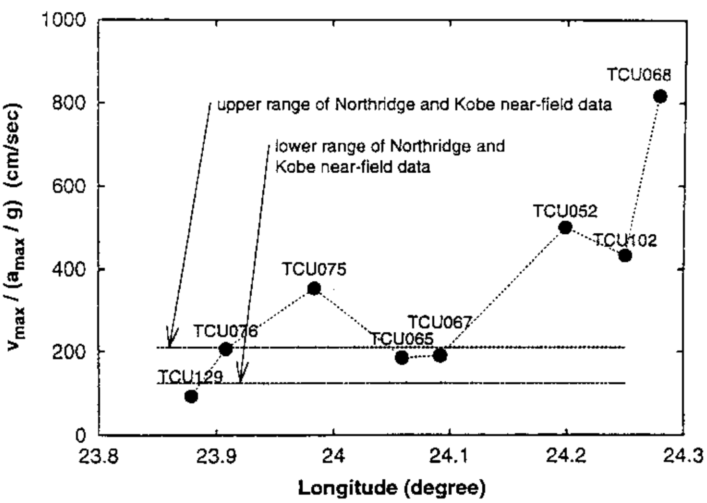

Fig. 19 Velocity to acceleration ratios of Chi-Chi near-field earthquake data, v_{max} and a_{max} are respectively the peak ground velocity and peak ground acceleration in the maximum velocity direction

Table 1 List of Chi-Chi near-field earthquake data

Station	Comp.	a_{max} (cm/s^2)	v_{max} (cm/s)	Comp.	a_p (cm/s^2)	v_p (cm/s)	$v_{max}/(a_{max}/g)$ (cm/s)	v_{max}/v_p	a_{max}/a_p
TCU068	N42W	459	383	S48W	497	120	818	3.19	0.92
TCU102	S50W	251	112	S40E	269	64	433	1.73	0.93
TCU052	N39W	496	254	S51W	212	92	502	2.76	2.34
TCU067	S63E	555	108	N27E	278	51	191	2.12	2.00
TCU065	S58E	766	145	N32E	440	69	186	2.10	1.74
TCU075	S87E	324	117	N03E	264	35	354	3.34	1.23
TCU076	S52E	417	88	N38E	345	31	207	2.61	1.21
TCU129	S45E	833	79	N45E	723	45	93	1.76	1.15

Table 2 List of Northridge and Kobe near-field earthquake data

Earthquake	Station	StationCode	Comp.	v_{max} (cm/sec)	a_{max} (cm/s^2)	$v_{max}/(a_{max}/g)$ (cm/sec)
Northridge (USA)	Rinaldi Receiving Station	RRS	S33W	186	873	209
	Sylmar County Hospital	SCH	S10W	138	848	159
	Sylmar Convertion Station	SCS	S16W	138	690	196
	Newhall Fire Station	NHL	S37W	120	720	163
Hyogoken-Nanbu (Japan)	Takatori	TAK	N49W	155	721	210
	Kobe	KOB	N35W	107	838	125

The velocity-to-acceleration ratio pattern of the Chi-Chi near-field data shows a great variability along the longitudinal coordinate. The TCU129, TCU076, TCU065 and TCU067 records roughly fall within the ratio range of the Northridge and Kobe records. However, a significant difference exists for the TCU068, TCU102 and TCU052 stations. The TCU068 record has the highest ratio reaching as high as 800cm/sec. As a direct consequence, that unexpected large ratio substantially causes the TCU068 overall spectral shape to significantly right-shift towards large periods. The cause for these unexpected large ratios may be associated with strong forward rupture directivity effects at those station locations, but this preliminary assertion demands further investigation.

Bias in Spectral Response

From Figs. 15 ~ 18, one observes significant bias in spectral response between the maximum velocity direction and its normal direction for the presented Chi- Chi near-field data. The difference in PSV becomes more distinct as the structural period increases. To

better quantify this difference, a spectral acceleration ratio is plotted as a function of structural period *T* in Fig. 20 where the ratio is defined as the spectral acceleration (SA) in the maximum velocity direction divided by the SA in its normal direction. The spectral acceleration ratios show great variability. The TCU052 record has the largest spectral ratio of over 6 around $T \approx 1.3$sec. The spectral ratios for other stations are
roughly in a range of 1 ~ 2 for $T < 4$sec. The TCU068 and TCU065 spectral ratio curves show an increasing trend for $T >$ 4sec. Both curves reach over 3 at $T =$ 5sec.

The bias in spectral response can be partially interpreted from the bias PGA and PGV exhibited in the Chi-Chi near-field records (Table 1). Figure 21 illustrates the velocity ratios and acceleration ratios for the 8 Chi-Chi near-field records ordered in the longitudinal coordinate. It is observed that the PGV in the maximum velocity direction are about 2 to 3 times larger than the PGV in its normal counterpart. The acceleration ratios are observed to be about 1 to 2.

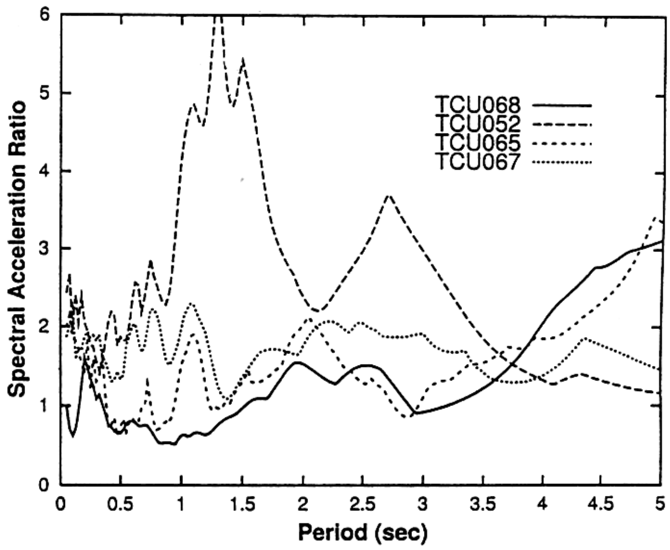

Fig. 20 Comparison spectral acceleration ratios of Chi-Chi near-field records

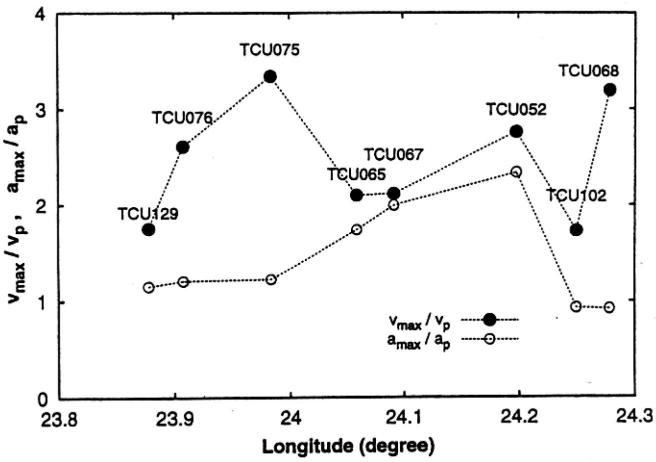

Fig. 21 Velocity ratios and acceleration ratios of Chi-Chi near-field earthquake data, v_p and a_p are respectively the peak ground velocity and peak ground acceleration in the normal to maximum velocity direction

DRIFT SPECTRA

It is a well-known fact that flexible tall buildings subjected to long-period pulse-like ground motion will exhibit wave-like deformation responses. The wave-like response is capable of producing large local structural deformation that may not be approximated well by a response spectrum analysis using the fundamental mode assumption. To take into account the higher-modal contributions, the drift spectral technique [2] based on a continuous shear beam model is employed herein to estimate the drift response of tall buildings subjected to the Chi-Chi near-field earthquakes. Drift spectra are computed for four Chi-Chi near-field records, TCU068, TCU052, TCU129 and TCU065 in Fig. 22. The drift spectra for the RRS and TAK are also provided for comparison. In calculating the inter- story drift ratio, the building height, H, is related to the structural period, T, by $T = 0.0853\ H^{3/4}$ based on the Uniform Building Code formula for steel structures [10].

Nearly all near-field records show over a 1% drift response for all periods. For the presented Chi-Chi data and plotted periods, the TCU052 record gives the highest drift response of 3.6% at $T \approx 1.3$sec. This 3.6% drift level is less than the maximum drift ratios calculated for the RRS and TAK records. However, the drift responses for the TCU052 record are uniformly larger than the RRS drift responses for $1.2 < T < 5$sec.

For the range $0.5 < T < 1.2$sec, the drift responses of the Chi-Chi records are all less than those of the RRS and TAK records. Except for the TCU052 record, the Chi-Chi drift responses are only equal to or less than the RRS and TAK drift responses for the range $1.2 < T < 3.5$sec. The above observation is also applicable to the TCU068 record in spite of its having the largest PGV of 383cm/sec. This indicates that most Chi-Chi near-field records do not yield a larger inter-story drift response for short buildings or mid-rise structures as compared to the Northridge and Kobe near-field records.

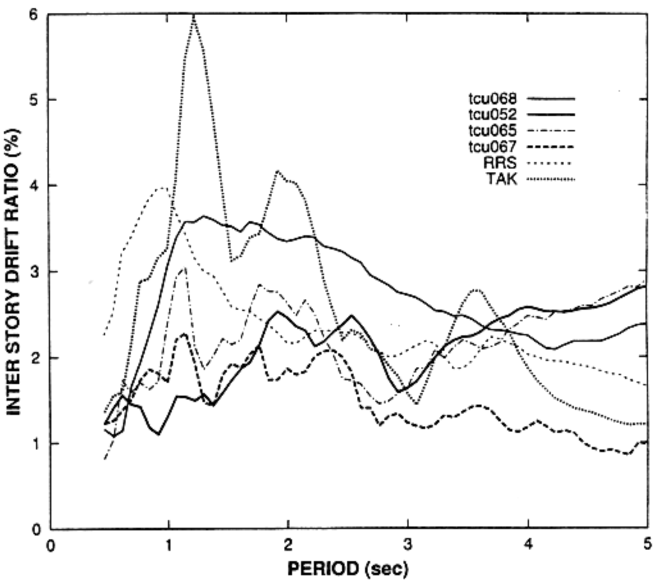

Fig. 22 Comparison of drift spectra for RRS, TAK and Chi-Chi near-field data

The relatively small drift response of Chi-Chi near-field records may be attributed to the very long-duration of velocity pulses.

Most Chi-Chi records show an increasing trend in drift response for $T >$ 3.5sec. The drift responses for TCU068 and TCU065 almost reach 3% at T = 5sec. The TCU052 data also reaches around 2.5%. This demonstrates that the Chi-Chi near-field records are very destructive for high-rise building structures. The cause for these large drift responses for tall buildings with $T >$ 3.5sec is directly related to the presence of long-duration high velocity pulses in the Chi-Chi near-field records. For such tall buildings, a deformation wave induced by a long-duration positive velocity pulse is allowed to complete an upward-and-downward traveling cycle within the buildings to meet a negative ground velocity pulse at the base. The downward deformation wave (produced by the positive ground velocity) and the upward deformation wave (produced by the negative ground velocity) can then add up in-phase to produce a very large drift response around the base level.

CONCLUDING REMARKS

1. Near-field effects manifested by long-period ground velocity pulses are evident in earthquake data of nearly all stations located within 5km of the Chelungpu fault line. It is plausible that the region experiencing the near-field effects covers a widely extended area of approximately 50km by10km along the Chelungpu fault line which is considerably larger than that of the Northridge and Kobe earthquakes.
2. The Chi-Chi near-field data show similar velocity pulse shapes to many previously recorded near-field data, but exhibit much longer pulse duration. The TCU068 and TCU052

stations respectively measured unprecedented PGV levels of 380cm/sec and 250cm/sec, respectively. However, both records predict a drift response level only comparable to or slightly less than the Northridge and Kobe earthquake data for structural periods of $0.5 < T < 3.5$sec. The TCU068 and TCU052 records show greater damage potential for tall building structures with $T > 3.5$sec.

3. Bias in peak ground velocity and acceleration is evident in the Chi-Chi near-field data. Some of the Chi-Chi near-field data demonstrate unusual peak velocity-to-acceleration ratios of 400 ~ 800cm/sec that differ significantly from the ratio range of 125 ~ 210cm/sec in the Northridge and Ko- be near-field data. Consequently, the Chi-Chi spectral shapes substantially differ from those inferred from both traditional far-field earthquake records and recent near-field earthquake records such as the RRS and TAK records.

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