Ground rotational motions of the 1999 Chi-Chi, Taiwan earthquake as inferred from dense array observations

Bor-Shouh Huang
Institute of Earth Sciences, Academia Sinica, Taipei, Taiwan

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1. Introduction

Large rotational motions excited by the 1999 Chi-Chi, Taiwan earthquake are inferred from a dense acceleration array near the northern end of the rupture fault where large surface slips along the fault are observed. The estimated major frequency content is from 0.1 to 1.0 Hz with a peak near 0.2 Hz. It is found that in the footwall region the observed strong rotational ground motions were most probably excited by the slip of the northern rupture ending segment of the Chi-Chi earthquake fault and that its thrust slips induced a major rock motion in the radial component. The analysis here indicates that during the Chi-Chi earthquake significant rotation seismic energy was radiated from the bent northern end of the earthquake fault. Further analysis of rotational ground motions may provide useful constraints for its rupture mechanisms.


2. Data

The 1999 Chi-Chi, Taiwan earthquake (Mw = 7.6) rupture initiated near the town of Chi-Chi in Nantou County, central Taiwan, and resulted in a final surface rupture amounting to about 100 km in the north-south direction. The largest inland earthquake in the past 100 years in Taiwan, its mechanism was a thrust fault with a strike of nearly N20°E and a dip of about 25° to 30°. The largest displacements were concentrated near its northern end of the earthquake fault. This disastrous earthquake was well recorded by both free-field digital accelerometers, operated by the Central Weather Bureau (CWB) [Shin, 1993], and some research-oriented strong motion stations, operated by the Institute of Earth Sciences, Academia Sinica (IESAS). It has, therefore, been the subject of numerous detailed studies of source rupture processes [Ma et al., 2001; Huang, 2001] and wave propagation [Huang, 2000]. However, ground rotation motions have never been estimated using those records because all of the recorded strong motion seismograms, unfortunately, lost their absolute times due to the week number roll over of GPS clocks. In this study, some strong motion records with absolute timing from a dense acceleration array on the Li-Yu-Tan Dam, located 6 km north of the Chi-Chi earthquake fault trace (Figure 1a), are analyzed for the purpose of estimating ground rotational motions in the near-source region of this large earthquake. The aim of this study is to report the characteristics of the near source rotational ground motions excited by a large thrust event and to uncover some implicit rupture characteristics of the Chi-Chi earthquake in its northern ending of the rupture fault.

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the Li-Yu-Tan Dam has been carefully calibrated just after the Chi-Chi earthquake. However, due to unrecoverable errors on the horizontal components of T4, the recorded ground motions there were not used in the further analysis to determine rotational motions. The recording systems were equipped with GPS clocks and run in a common trigger mode. The software for the GPS clocks had previously been upgraded to overcome the problem of the week number roll over of those stations; thus, they worked well during the Chi-Chi earthquake, with this instrumentation system providing overall accurate absolute timing among stations and as such can be considered a dense array. After the amplification correction of each record, all data show highly correlated ground motions over all seismograms (Figure 2a). It is reasonable then that this study analyzes the recorded translational accelerograms to infer differential ground motions with which to study the near source rotational characteristics. Comparing the dense array seismograms to the recorded ground motions of the CWB strong motion network, which were recorded near the northern end of the Chi-Chi earthquake fault, it is found that the ground motions show strong spatial variations (Figure 2b).

3. Analysis and Results

Rotational ground motions are usually derived from spatial gradients of translational ground motions, and these
motions can be considered as being comprised of acceleration, velocity and displacement. Hence, the rotation rates of the torsion component, \( W_z \), around the vertical axis and the rocking components, \( W_x \) and \( W_y \), around the horizontal axes were computed from the translational velocities, \( U_x \), \( U_y \) and \( U_z \), as follows:

\[
W_z = \frac{1}{2}(\partial U_y/\partial x - \partial U_x/\partial y),
\]

(1)

and

\[
W_x = (\partial U_z/\partial y), \quad W_y = (\partial U_z/\partial x)
\]

(2).

Here, the tangential strains are taken as zero at the free surface. In this study, based on finite difference approximation, the rotational ground motions were estimated from station pairs and averaged over the array using a stacking technique. The same procedure has been previously employed by Oliveira and Bolt [1989] to analyze SMART-1 array data to determine rotational ground motions.

Figure 4a shows the computed time histories for three component ground rotation rates across the Li-Yu-Tan seismic array based on the translational ground velocities which are obtained by numerically integrating the accelerograms. To avoid high frequency errors induced by the finite difference approximation, the translational ground accelerations had previously been filtered to remove signals with frequencies higher than 5 Hz. The signal to noise ratio from those three traces are estimated to be greater than 100. Here, the noise level of the rotation rates is measured using the pre-event portion of the seismograms. To study the variability among station pairs, the computations were represented by the average (blue line) plus one standard deviation in the upper and lower portions of its mean (red lines). It is noted that the torsion component is slightly larger than the rocking components along the Y-component and more than twice as large along the X-component. However, the standard deviation of rotational ground motion along the Y-axis is smaller than that in other components. It is found that rotation rates around the \( W_z \) and \( W_x \) axes seem to include relatively high frequency signals compared with that around the \( W_y \) axis. Figure 4b shows the ground rotations determined using the translational displacements double integrating from the same filtered acceleration records. Those three traces show very high signal to noise ratios. Unlike the rotation rates, the computed rotations for the rocking motion in the Y-component are greater than those of other components, and the rotation around the Y-axis has a similar waveform to the ground translational velocity in the vertical component (Figure 3b).

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[9] On the basis of the measured Fourier amplitude spectra of these rotation rates, it is evident that there are dominant peak amplitudes around 0.2 Hz for both torsion and rocking motions and that another peak is found around 0.7 Hz around the torsion motion (Figure 5). Dynamic analysis of the Li-Yu-Tan Dam show that the natural period of the dam is near 2.2 Hz and the major seismic amplification during earthquakes is around 0.55 Hz [http://kbteq.ascrc.net/archive/nse/eidc/1/19.html]. Both observed peaks do not correlate to resonance of the dam, however, the high frequency pulse (0.7 Hz) could be associated with the
seismic amplification of dam and considered as its structure response of ground rotations. It is found that the uppermost shear-wave velocity of the Tertiary sedimentary rock in this area is near 2.2 km/sec, thus, the 0.2 Hz seismic waves have wavelength greater than the size of the dam (235 meters). Furthermore, the low frequency peak is consistent with the peaks of the free-field translational motions recorded by nearby CWB stations (Figure 2a). Hence, it is reasonable to consider the low frequency ground rotation (0.2 Hz) as a result of the source rupture of the Chi-Chi earthquake.

4. Discussion and Conclusions

In this study, some ground rotation features determined here are distinctly different from those previously reported for rotational ground motions recorded by relatively large epicentral distance events or seismic explosions. The rotational components of seismic waves estimated from major events recorded by the SMART-I array show that the highest values have occurred on torsions while the strongest peaks have been observed on the onset of S wave arrivals and/or throughout the surface wave train [Oliveira and Bolt, 1989]. Near source rotational ground motions (about 3.3 km away) from an event with a magnitude of 5.7 analyzed by Takeo [1998] showed that the recorded high frequency rotational motions around the vertical axis is up to $3.3 \times 10^{-3}$ rad/sec, and the observed values are several times larger than the simulation results of Bouchon and Aki [1982] based on dislocation theory. However, the estimated rotations from both observations are very small because their velocity peaks are dominated at high frequencies. A unique case similar to this study for near-field rotational ground motions from a large earthquake was reported by Niazi [1986] to analyze the El Centro Differential Array data of the 1979 Imperial Valley earthquake (Ms = 6.9). Those observations were within 5 km of a 40-km right-lateral faulting. The observed peak rotation amplitude is approximately $1 \times 10^{-3}$ rad and has similar values for rocking and torsion motions. However, these estimations were based on an inaccurate time base of those records, and the determined ground rotation rates included large high frequency noises (see Figure 7 of Niazi [1986]). Furthermore, the source mechanism of this event is a typical strike-slip fault that is different from that of the thrust-type faulting of the Chi-Chi earthquake.

The rotational ground motions of the Chi-Chi earthquake reported in this study are close to the surface rupture traces with distance about 6 km (Figure 1a). Here, the observed rocking motions along the Y-axis of Figure 1b are greater than torsions and rocking motions along the X-axis, and dominated by a low frequency pulse (Figure 4). This low frequency feature is the same as that from theoretical simulated ground rocking for a thrust fault on the footwall side [Bouchon and Aki, 1982]. According to theoretical modeling, rocking motions decay quickly with respect to epicentral distances [Bouchon and Aki, 1982; Takeo and Ito, 1997]. This indicates that low frequency ground rotation motions in the case of the Chi-Chi event may be induced by the nearest fault segment, namely at the northern end of the Chi-Chi earthquake (Figure 1). This suggests that the significant contribution of seismic energy radiation from the bent northern end of the Chi-Chi earthquake fault (Figure 1a) and the fault ruptures in the southern part of the fault do not contribute significant rotation motions at the Li-Yutan site. Although qualitative discussions concerning the depth extension of the northern end of the fault segment are still unavailable, the suggested fault rupture in the bent northern end of the Chi-Chi earthquake fault provides a useful constraint for further studies of its rupture mechanism. In future a detailed analysis of the characteristics of rotational motions may provide independent information to verify the rupture processes of the Chi-Chi earthquake.

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