Large Effects of Moho Reflections (SmS) on Peak Ground Motion in Northwestern Taiwan

by Kun-Sung Liu and Yi-Ben Tsai

Abstract A total of 336 three-component strong-motion recordings from the $M_w$ 6.35 Niu Dou earthquake of 25 June 1995 at a focal depth of 39.9 km in northern Taiwan are used to study the effects on strong ground motion due to Moho reflection of $S$ waves. The residuals of both horizontal peak ground acceleration (PGA) and peak ground velocity (PGV) recorded from the earthquake are analyzed. The results confirm that many Class $E$ soft soil stations in the Taipei Basin and the Ilan Plain had the expected large amplification of about 1.7 and 1.5 times, respectively, the predicted median PGA values. Surprisingly, a large group of Class $C$ or $D$ dense and stiff soil sites in Taoyuan (TCU007), Lungtan (TCU013), Guanshi (TCU021), Hsinchu (TCU095), and Miaoli (TCU047) areas in northwestern Taiwan had unusually large amplification of about 3.4–8.1 and 1.7–3.3 times the predicted median PGA and PGV values, respectively. They are interpreted in terms of focusing and interference between $SmS$ waves reflected from the horizontal and inclined portions of an east-dipping Moho discontinuity in this area. This interpretation is supported by the close agreement between the expected amplitudes and arrival times of the largest shear waves with the observed data. Our results suggest that when a damaging earthquake occurs near an inclined Moho boundary, the reflected $SmS$ waves can result in significantly amplified ground motions at distances beginning about 50 km. The exact distance range will depend on the thickness of the crust and the dip angle of the Moho boundary.

Introduction

Ground-motion characteristics are known to depend on the properties of seismic source, wave propagation, and site response. The most commonly used method for characterizing ground motion is through attenuation relations, in which the effects of earthquake source, wave propagation, and site response are typically parameterized by the earthquake magnitude, fault type, source-to-site distance, and site condition. Conversely, we can study the contribution of source, path, and site effects by examining the residuals of observed ground-motion data at individual sites with reference to the values predicted by the empirical attenuation relations.

The path effects on strong ground motion due to crustal structures have been known for some time. Burger et al. (1987) investigated the attenuation relations of eastern North America, which show amplitudes in the distance range of 60–150 km to be higher than that at smaller and greater distances. They showed that the observed interval of relatively high amplitudes can be attributed to postcritically reflected $S$ waves from the Moho discontinuity. The presence and location of the interval of relatively high amplitudes is highly dependent on the crustal velocity structures and may therefore be expected to show regional variations.

Somerville et al. (1990) found significant influence of critical reflections from the lower crust on ground-motion attenuation from the large set of strong-motion recordings of the Saguenay, Quebec, earthquake of 25 October 1988. At distances beyond 64 km, the peak ground motions occurred at times corresponding not to the direct $S$ wave but to strong critical reflections from the lower crust. The amplitude of recorded ground motions did not significantly decrease between 50 and 120 km, but it abruptly decreased beyond 120 km.

In central California, Bakun and Joyner (1984) suggested that the large positive residuals in $M_L$ at distances between 75 and 125 km could be due to Moho reflections. Large-amplitude reflections from the Moho ($PmP$) were also observed in seismic refraction data near the source region of the Loma Prieta earthquake (Walter and Mooney, 1982). Somerville and Yoshimura (1990) presented evidence of enhanced amplitudes of strong ground motion from the Loma Prieta earthquake recorded in the San Francisco and Oakland areas, which were found to exceed the levels predicted by standard empirical attenuation relations. Their analysis of accelerograms with known trigger times strongly suggests that
enhancement of ground-motion amplitudes in the distance range of approximately 40–100 km was due to critical reflections from the base of the crust. The effect of critical reflections in amplifying peak accelerations of the Loma Prieta earthquake in the San Francisco and Oakland regions was as large as the amplification effect of soft soil site conditions.

McGarr et al. (1991) presented observations in the epicentral distance range of 59–95 km, including the San Francisco International Airport, of the Moho-reflected phases \( PmP \) and \( SmS \) from the aftershocks of the Loma Prieta earthquake to support the hypothesis that the phase \( SmS \) accounted much of the enhanced peak ground motion experienced from the mainshock throughout most of the San Francisco Bay area.

Mori and Helmberger (1996) used closely spaced aftershock data from the 28 June 1992 Landers earthquake to create event record sections that showed clear examples of varying amplitudes of \( SmS \). Some of the data showed strong \( SmS \) phases to be two to five times larger than the direct \( S \) waves. They interpreted the amplitude variations in terms of the local crustal and Moho structures in southern California.

Yeh et al. (1988) demonstrated, on the basis of an assumed velocity structure, that focusing of seismic-wave energy in the Taipei Basin can occur for some earthquakes under favorable conditions. The wave focusing phenomena were also supported by other strong-motion data collected by the accelerograph network in Taiwan.

Several later studies have shown additional evidence that reflected seismic energy can significantly intensify the ground shaking at an appreciable distance from the epicenter of an earthquake (Atkinson and Boore, 1995; Catchings and Kohler, 1996; Atkinson and Boore, 1997; Somerville et al., 1997; Toro et al., 1997; Chen, 2003). Thus, focusing of seismic-wave energy can play an important role in enhancing seismic intensity even in regions some distance away from the epicentral zone. It follows that it may be important to consider such path effects in engineering practice. The objective of this article is to analyze large effects of the Moho reflection on the amplification of peak ground motion (peak ground acceleration [PGA] and peak ground velocity [PGV]) observed at several sites located in northwestern Taiwan during the 1995 Niu Dou earthquake.

### Strong-Motion Data

The Central Weather Bureau has undertaken the Taiwan Strong-Motion Instrumentation Program (TSMIP) since July 1991 to collect high-quality instrumental recordings of strong earthquake shaking. Thus far, more than 640 free-field accelerograph stations have been deployed in populated areas of Taiwan. This network has provided large numbers of recordings to form an excellent database for studying strong-motion characteristics and for developing attenuation relations. Each operating free-field station includes triaxial accelerometers, a digital recording subunit, a power supply, and a timing system. The transducers for the accelerograph must respond accurately in the frequency range from d.c. to 50 Hz in order to faithfully record the near-source ground motion caused by large earthquakes. In order to record a wide range of earthquakes on scale, it is required that the complete system be digital and have at least a 16-bit resolution and a 96 dB dynamic range (Liu et al., 1993). The full scale of the recording system is \( \pm 2g \) at a sample rate of 200 samples/sec. Each recording system is operated in trigger mode with a 20 sec pre-event memory and is set to record an additional 10 sec of data after the signal dropped below a preset threshold (Liu et al., 1999).

In this study, we use the TSMIP strong-motion data of the \( M_w \) 6.35 Niu Dou earthquake of 25 June 1995 at a focal depth of 39.9 km in northern Taiwan (Central Weather Bureau, 1995). A total of 336 three-component accelerograms were recorded at epicentral distances ranging from 4.9 to 244.7 km. We have analyzed these data to study the dependence of PGA on the seismic-wave propagation path, especially to examine the effects of Moho reflection. Figure 1 shows a contour map of the mean PGA of two horizontal components, together with the epicenter location (24.606° N, 121.669° E) of the Niu Dou earthquake. The largest PGA of all of the records is 259 gal (gal = cm/sec²). The heavy lines in the map represent the PGA value of 80 gal. Similarly, Figure 2 plots a contour map of the mean PGV of two horizon-

![Figure 1. Horizontal PGA contour map with the epicenter of the 25 June 1995 Niu Dou earthquake. Nine stations with large amplitude located at Class C or D dense and stiff soil sites are also shown.](image-url)
tal components. The largest PGV of all of the records is 10.8 cm/sec. The heavy lines in the map represent the PGV value of 6 cm/sec. From these PGA and PGV contour maps, a surprising feature is noticed: unusually large PGA and PGV anomalies were observed at several soft-rock and dense soil sites (Lee et al., 2001) in the Taoyuan, Lungtan, Guanshi, Hsinchu, and Miaoli areas in northwestern Taiwan (see Fig. 1 for the location of the cities).

It is well known that ground-motion characteristics can be affected by local site response. According to the site classification criteria of Table 1 (Lee et al., 2001), each recording station in Taiwan can be classified as a Class B, C, D, or E site. Examination of the records with different site classifications confirmed that many Class E soft soil stations in the Taipei Basin and the Ilan Plain had large PGA values. However, many Class C and D stiff soil sites, especially those located in the Taoyuan, Lungtan, Guanshi, Hsinchu, and Miaoli areas, also had unusually large PGA and PGV values during the 1995 Niu Dou earthquake. As shown in the following, this unusual PGA and PGV amplification can be explained by large effects of Moho reflection.

### Attenuation Model and Residual Analysis

A strong-motion attenuation relationship expresses an earthquake ground-motion parameter as a function of simple parameters characterizing the earthquake source, the propagation path between the earthquake source and the site, and the geologic conditions beneath the site. The following equation form is used in this study:

\[
\ln Y = a \ln(X + h) + bX + cM + d \pm \sigma. \tag{1}
\]

### Table 1

Comparison between the 1997 UBC Provisions and the Simplified Site Classification Used in This Study (after Lee et al. [2001])

<table>
<thead>
<tr>
<th>Site Class</th>
<th>Site Class Description of 1997 UBC Provisions</th>
<th>Site Class Description of Lee et al. [2001]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Hard rock, eastern United States sites only, (V_s &gt; 1500 \text{ (m/sec).})</td>
<td>(not used) Miocene and older strata, along with limestone, igneous rocks, metamorphic rocks, etc.</td>
</tr>
<tr>
<td>B</td>
<td>Rock, (V_s ) is 760–1500 (m/sec)</td>
<td>Pliocene and Pleistocene strata, along with conglomerates, pyroclastic rocks, etc. and geomorphologic lateritic terraces</td>
</tr>
<tr>
<td>C</td>
<td>Very dense soil and soft rock, (V_s ) is 360–760 (m/sec), undrained shear strength (u_s \geq 2000 \text{ psf} ) or (N \geq 50 \text{ blows/ft})</td>
<td>Late Pleistocene and Holocene strata, geomorphologic fluvial terrace, along with stiff clays and sandy soils with average SPTN (\geq 15) in the upper 30 m</td>
</tr>
<tr>
<td>D</td>
<td>Stiff soils, (V_s ) is 180–360 (m/sec), stiff soil with undrained shear strength (1000 \text{ psf} \leq u_s \leq 2000 \text{ psf} ) or (15 \leq N \leq 50 \text{ blows/ft})</td>
<td>Holocene deposits and fills, etc. with average SPT (N &lt; 15) in the upper 30 m</td>
</tr>
<tr>
<td>E</td>
<td>Soft soils, profile with more than 10 ft (3 m) of soft clay defined as soil with plasticity index (PI &gt; 20), moisture content (w &gt; 40%), and undrained shear strength (u_s &lt; 1000 \text{ psf} ) or (N &lt; 15 \text{ blows/ft})</td>
<td>(not classified in the present study and will be studied in the future)</td>
</tr>
<tr>
<td>F</td>
<td>Soils requiring site specific evaluations: (1) soil is vulnerable to potential failure or collapses under seismic loading; for example, liquefiable soils, quick and highly sensitive clays, collapsible weakly cemented soils; (2) peats and/or highly organic clays (10 ft [3 m] or thicker layer); (3) very high plasticity clays; (25 ft [8 m] or thicker layer with plasticity index &gt; 75); (4) very thick soft/medium stiff clays: (120 ft [36 m] or thicker layer)</td>
<td></td>
</tr>
</tbody>
</table>

Note: the provisions of 1997 NEHRP and 1997 UBC are similar.
where $Y$ is the ground-motion parameter, $X$ is the hypocentral distance, $M_w$ is the moment magnitude, $a$ is the geometrical spreading coefficient, $b$ is the anelastic attenuation coefficient, $c$ is the magnitude coefficient, $d$ is a constant, $h$ is the close-in distance saturation coefficient, and $\sigma$ is the standard deviation. The coefficients $a$, $b$, $c$, $d$, and $h$ are to be determined by regression from the data (Liu and Tsai, 2005). This equation form is similar to the one used by Joyner and Boore (1981), except for the difference in distance definitions.

Regressions on the TSMIP data set without differentiating site conditions have resulted in the coefficients of the attenuation relationships, as given in Table 2, for the horizontal ($H$) components of PGA and PGV for the whole of Taiwan (Liu and Tsai, 2005). In Table 2, $\sigma$ refers to the standard deviation of $\ln(Y)$. Assuming a log-normal distribution, this value can be used to obtain the value of the parameter $Y$ corresponding to different probability levels. Specifically, $\ln(Y)$ at 84% probability (median plus one sigma) may be obtained by multiplying the predicted median value by $e^\sigma$.

Figures 3 and 4 compare the observed data from the 1995 Niu Dou earthquake ($M_w$ 6.35) with the PGA and PGV attenuation relations, respectively, for the Taiwan area. It can be seen in these figures that most observed data are distributed within the range between ±1 standard deviation of the median attenuation curve. We can also find a cluster of very high-valued data at a hypocentral distance 66–84 km from TCU007, TCU013, and TCU021 stations and so on, which are located in Taoyuan, Lungtan, and Guanshi areas in northwestern Taiwan, located in Figures 3 and 4.

Examination of the PGA residuals (i.e., the difference between logarithms of the observed and predicted PGA) for sites with different soil categories is a useful method for sets of records where site information is not complete and hence cannot be included explicitly within the equation (Abrahamson and Litehiser, 1989). Liu and Tsai (2005) analyzed both the PGA and PGV residuals to study their variations with respect to site conditions. The results showed that

![Figure 3](image1.png)

**Figure 3.** Comparison of the horizontal PGA data for the $M_w$ 6.35 Niu Dou earthquake with the corresponding median and median ± $\sigma$ values derived from the attenuation relationships of Liu and Tsai et al. (2005).

![Figure 4](image2.png)

**Figure 4.** Comparison of the horizontal PGV data for the $M_w$ 6.35 Niu Dou earthquake with the corresponding median and median ± $\sigma$ values derived from the attenuation relationships of Liu and Tsai et al. (2005).
the residual contour maps have high consistency with both regional geology and topography of Taiwan. For example, positive residuals are expected in areas like the Taipei Basin and the Ilan Plain that will experience amplification of ground motion due to soft soil site conditions.

In order to understand the relation between both PGA and PGV residuals and local sites as well as propagation path effects, we plot the residual of horizontal PGA versus epicentral distance in Figure 5 and the residual of horizontal PGV versus station azimuth in Figure 6. The results confirm that many Class E soft soil stations in the Taipei Basin and the Ilan Plain have, as expected, large positive PGA residuals of about 0.53 and 0.40, corresponding to an amplification factor of 1.7 and 1.5, respectively, relative to the predicted median values.

Surprisingly, residuals at a group of Class C or D dense and stiff soil sites, especially those in Taoyuan (TCU007), Lungtan (TCU013), Guanshi (TCU021), Hsinchu (TCU095), and Miaoli (TCU047) areas, have even larger PGA and PGV residuals corresponding to an amplification factor of 3.36–8.13 and 1.73–3.30, respectively, relative to the predicted median values. As shown in Figures 5 and 6, this group of unusually large PGA and PGV sites is distributed in a narrow range of epicentral distances (i.e., 50–75 km) and azimuths (i.e., 270°–331°). Figures 1 and 2 clearly show that these sites form a northeast–southwest-trending narrow band of anomalously large PGA and PGV in northwestern Taiwan.

Why did these stiff soil sites in northwestern Taiwan, which were previously shown to have normal local site response (Liu and Tsai, 2005), have such large amplifications during this earthquake? A plausible answer to this question is presented in the following section.

Crustal Velocity Structures

We first analyze the path effects, especially regarding the role of crustal structure in affecting strong ground motion. In order to pick seismic phases and calculate the theoretical travel times of direct and reflected waves from the hypocenter, an appropriate crustal model for the Taiwan area is needed. Some attempts to determine the crustal structure of Taiwan were made in the past. Yeh and Tsai (1981) used an iterative damped least-squares inversion procedure to find P-wave velocities of a horizontally layered model for the crust of central Taiwan. Their crustal velocity model has an upper crust of two sublayers whose thickness and velocity are 9 km and $5.8 \text{ km/sec}$ for the upper layer and 8 km and $6.7 \text{ km/sec}$ for the lower layer, respectively. The thickness and velocity of the upper crust are 19 km and $6.7 \text{ km/sec}$, respectively. The velocity of the upper mantle is $7.8 \text{ km/sec}$.

Thus, the overall thickness of the crust in the Central Range
The results showed that $Pn$ velocity under the CR is about 8.52 km/sec, which is about 5%–8% higher than the other two provinces: 7.79 km/sec under the Coastal Plain (CP) and 8.04 km/sec under the WF, respectively. The Moho depths are about 31, 34.5, and 43 km, respectively, for the CP, WF, and CR.

Kim et al. (2004, 2005) used the receiver function method (RFM) and tomographic inversion method (TIM) to investigate the complex crustal structures in the Taiwan region. The depths of Moho discontinuity were determined as follows: a trend of crustal thinning starting from the east (at 50–52 km and 55 km by RFM and TIM, respectively) toward the west (at 28–32 km and 35 km by RFM and TIM, respectively). This is in good agreement with the results from two east–west-trending deep seismic profiles previously obtained using airgun sources (Shin et al., 1998; Yeh et al., 1998). In summary, the depth of Moho under Taiwan varies significantly, especially in the east–west direction. In the western CP and WF, it is about 28–35 km, deepening gradually eastward to reach a maximum depth of 50–55 km beneath the eastern CR.

Moho Reflection

In this study, we first considered the one-dimensional (1D) velocity model of Chen (1995), which is used for rou-
Large Effects of Moho Reflections (SmS) on Peak Ground Motion in Northwestern Taiwan

Because the hypocenter of the Niu Dou earthquake was located in northern Taiwan, the crustal velocity structures under northern Taiwan are discussed in more detail. Shen (2000) used an iterative damped least-squares inversion procedure to find a P-wave velocity model for the crust of northern Taiwan. This crustal velocity model consists of four sublayers. The total thickness of the crust varies significantly from 35 to 43 km, especially along the southwest–northeast direction. In the western CP and WF, it is about 35 km. It gradually deepens northeastward to reach a maximum depth of 43 km beneath the Ilan Plain. Lin (2001) and Lin et al. (2004) used a tomographic inversion method to determine the three-dimensional \( V_P \) and \( V_S \) velocity structures and to outline the Moho depth under northern Taiwan. They found a Moho depth of about 42 km in the area around the Niu Dou earthquake. Similar results were found by Song (1997) and Liao (2005). Based on these studies, a velocity model is constructed, incorporating the following features (1) the crustal thickness for Taiwan as a whole is about 33 km and (2) a crustal velocity model, as given in Table 3, we conclude that the hypocenter of the Niu Dou earthquake is indeed located within the crust (C.-H. Chang, personal comm., 2006).

In order to exclude the strong-motion records in the Taipei Basin, which are known to be subjected to large site amplification due to soft soils, a profile of recorded time histories, as shown in Figure 8, is compiled by selecting 53 velocity seismograms restricted in the azimuth range of 245°–335° and epicenter distance range of 5–100 km. The recordings are from a variety of site conditions. The calculated travel-time curves and the range of distances for the direct \( P \), \( S \), \( PmP \), and \( SmS \) waves are also shown in Figure 8. The calculated travel-time curves and the range of distances for the direct \( P \), \( S \) waves and the reflected \( PmP \), \( SmS \) waves that represent the waves reflected from the horizontal and inclined portions of Moho discontinuity, respectively, are also shown in Figure 8. These curves were computed using the 2D crustal velocity model whose original model was given in Table 3; the modified model is shown in Figure 9.

The source-time function of the Niu Dou earthquake as teleseismically determined has a pulse with a duration of about 3 sec (Lin and Ma, 1996). Accordingly, the \( SmS \) arrival-time curves in Figure 8 reappear at a delay of 3 sec to represent the duration of the strong source pulse teleseismically seen. In Figure 8, the onset of the largest waves at most stations coincided with the arrival time of the Moho reflection \( SmS \) at distances beyond 50 km. The move-out of this onset with distance clearly follows the \( SmS \) arrival-time curve and not that of direct \( S \). The observed duration of strong motion following the \( SmS \) arrival-time curves is about 3 sec, which is compatible with the 3 sec duration of strong source pulse, as determined by Lin and Ma (1996).

Focusing Effects of an Inclined Moho

In the previous record profile, the Moho reflection from the base of layer 8 is a strong arrival at the epicentral distance between 50 and 75 km. It is visible on most of the stations in this distance range. In the following analysis, we will focus on the effects of \( S \)-wave reflection from the base of an-

<table>
<thead>
<tr>
<th>Thickness (km)</th>
<th>Depth (km)</th>
<th>( V_P ) (km/sec)</th>
<th>( V_S ) (km/sec)</th>
<th>Density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0–2</td>
<td>3.48</td>
<td>1.96</td>
<td>2.1</td>
</tr>
<tr>
<td>2</td>
<td>2–4</td>
<td>4.48</td>
<td>2.62</td>
<td>2.5</td>
</tr>
<tr>
<td>5</td>
<td>4–9</td>
<td>5.25</td>
<td>3.03</td>
<td>2.6</td>
</tr>
<tr>
<td>4</td>
<td>9–13</td>
<td>5.83</td>
<td>3.35</td>
<td>2.6</td>
</tr>
<tr>
<td>4</td>
<td>13–17</td>
<td>6.21</td>
<td>3.61</td>
<td>2.8</td>
</tr>
<tr>
<td>8</td>
<td>17–25</td>
<td>6.41</td>
<td>3.71</td>
<td>2.8</td>
</tr>
<tr>
<td>5</td>
<td>25–30</td>
<td>6.83</td>
<td>3.95</td>
<td>2.8</td>
</tr>
<tr>
<td>12</td>
<td>30–42</td>
<td>7.29</td>
<td>4.21</td>
<td>3.0</td>
</tr>
<tr>
<td>8</td>
<td>42–50</td>
<td>7.77</td>
<td>4.49</td>
<td>3.2</td>
</tr>
<tr>
<td>half-space</td>
<td>&gt; 50</td>
<td>8.24</td>
<td>4.76</td>
<td>3.6</td>
</tr>
</tbody>
</table>
clined Moho discontinuity to explain the enhanced PGA and PGV recorded in northwestern Taiwan.

We use a ray-tracing method to calculate the travel time of reflected waves from the Moho discontinuity. As the incident angle increases to 69.7° corresponding to a distance of 76 km, reflection of shear waves from the interface at the lower crust will reach the critical angle and undergo total internal reflection. In order to explain and fit the large amplitudes observed at a distance less than 76 km, a refined two-dimensional (2D) velocity model with inclined Moho discontinuity is developed.

Let us consider that the Moho discontinuity surface is not parallel to the free surface but has a dip angle $\psi$. For up-dip propagation, the surface is inclined upward from east to west. The thickness of the crust is not uniform: it is 42 km beneath the northern Central Mountain Range and 33 km under the western CP and WF. Thus, the final 2D model for the velocity structure along the east–west direction consists of 10 layers, as shown in the upper left part of Figure 9. The Moho discontinuity is at a depth of 42 km beneath the epicenter of the Niu Dou earthquake. It extends horizontally toward the west for 6.8 km. It then turns up-dip at 24.2° with a ratio of 20 km horizontally to 9 km vertically. Beyond that point westward, the Moho discontinuity is kept flat at a constant depth of 33 km.

The curves for the travel time and the incident angle (theta) as a function of epicentral distance for the dipping Moho model are shown in Figure 9. Curves A and B show the relation between incident angle versus the distance for waves reflected from the horizontal and inclined portions of the Moho discontinuity, respectively. Curves C and D show the relation between travel time versus distance for waves reflected from the horizontal and inclined portions of the Moho discontinuity, respectively. It is noted that there exists an overlap distance range from 48 to 86 km over which reflected waves from both discontinuities will simultaneously arrive, when the theta angle increases from 55.6° to 92.1°. In the intervals of theta from 55.6° to 72.9° and from 72.9° to 92.1°, the $S$ waves are reflected from the horizontal and dipping portions of the Moho discontinuity, respectively.

In the overlap distance range from 48 to 86 km, simultaneous arrival of the $SmS$ waves reflected from the horizontal and dipping portions of the Moho discontinuities will cause focusing and interference resulting in enhancement of ground-motion amplitudes. Figure 10 shows a crustal velocity model for northern Taiwan with ray traces for direct $S$ waves (in red) and $SmS$ (in blue) reflected from the Moho discontinuity. We can see that focusing and interference between $SmS$ waves reflected from both the horizontal and inclined portions of the Moho discontinuity in the epicentral distance range of 48 to 76 km. This is taken as the primary cause for significantly enhanced PGA and PGV at a group of stations distributed in this narrow distance range in northwestern Taiwan.

It should be noted that at distances beyond 48 km, the PGA and PGV occurred at times corresponding to strong reflections from the Moho discontinuity, instead of direct $S$ waves. Because of the presence of an inclined Moho discontinuity, the amplitudes of recorded ground motion did not significantly decrease at hypocentral distances between 66 and 84 km, but decreased rapidly beyond 84 ± 2 km, as shown in Figure 3.

**Discussion**

In the preceding analysis, we have demonstrated the focusing and interference effects of reflected $S$ waves from an inclined Moho discontinuity to be the primary cause for significantly enhanced PGA and PGV recorded in northwestern Taiwan during the Niu Dou earthquake. However, ground-motion amplitudes can also be affected by a variety of other factors, such as source or site effects, some of which may contribute together. It is therefore necessary to distinguish

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**Table 4**

Comparison of the Niu Dou Earthquake Location by Using Two Crustal Velocity Models

<table>
<thead>
<tr>
<th>Velocity Model</th>
<th>Latitude (°N)</th>
<th>Longitude (°E)</th>
<th>Focal Depth (km)</th>
<th>Moho Depth (km)</th>
<th>$M_L$</th>
<th>$M_w$</th>
</tr>
</thead>
<tbody>
<tr>
<td>This study</td>
<td>24.603</td>
<td>121.666</td>
<td>39.77</td>
<td>42</td>
<td>6.50</td>
<td>6.35</td>
</tr>
</tbody>
</table>

Figure 7. A crustal velocity model for this study. This crustal velocity model, basically following Chen (1995), consists of 10 layers, except the thicknesses of the eighth and ninth layers are modified. Thus, the total thickness of the crust, to the base of layer 8, is 42 km beneath the epicenter of the Niu Dou earthquake instead of 35 km as proposed by Chen (1995).
the predominant factor that caused the significant enhancement of recorded ground-motion amplitudes.

Seismic radiation patterns can result in geographic asymmetry of ground motion due to the faulting process that is closely related to the focal mechanism of the earthquake. The focal mechanism of the Niu Dou earthquake was determined by Lin and Ma (1996) using teleseismic waveforms. It was an oblique faulting mechanism with the dip at 76.2°, the rake at 34.6°, and the strike at 133.5° (Ma and Mori, 1998). In order to understand the relation between the station residuals of PGV and the seismic radiation patterns, we now refer to Figure 6 where the residuals of the horizontal PGV are plotted as a function of site azimuth, that is, the direction from the seismic source to a recording station. The data confirm that many Class E soil stations in Chianan Plain (CHY area) have large positive PGV residuals, above 0.8, corresponding to an amplification factor of 2.2 relative to the predicted median values. The large residuals of these stations at azimuth ranging from 220° to 240°, which were close to the azimuths perpendicular to the fault plain, were most likely due to seismic radiation effects. In the meantime, some of the stations belong to Class E soft soil sites that might have contributed to part of the large amplification.

Figure 6 also shows that another group of stations at azimuth ranging from 270° to 331°, especially those in Tao-
yuan (TCU007), Lungtan (TCU013), Guanshi (TCU021), Hsinchu (TCU095), and Miaoli (TCU047) areas, had logarithmic residuals of about 0.55–1.19, corresponding to an amplification factor of 1.73–3.30 over the predicted median values. These large PGV sites were not located in azimuths perpendicular to the fault plane. This suggests that the observed large-amplitude late-arrival S waves were unlikely to be caused by seismic radiation effects.

Moreover, site effects can also play an important role in amplifying seismic ground motions. A simple way to estimate site effects is made in terms of soil-type classification (Kawase, 2004). Figures 11 and 12 show a reduced time plot of the north–south-component acceleration and velocity waveforms, respectively, for the nine stations with PGA greater than 100 gal, as extracted from Figure 8. According to Table 5, these nine stations with large PGA and PGV amplitudes are located on Class C or D dense and stiff soils. Obviously, the unusually large amplification phenomenon cannot be explained by site effects, either. This is supported by normal site response at these stations found in our previous studies using a large data set (Liu and Tsai, 2005). In summary, we can discount either seismic radiation or local site response effects as a major cause for unusual amplification observed at these stations.

Furthermore, McGarr et al. (1991) pointed out that if the highest-amplitude portion of the S-wave train is SmS in the horizontal seismogram, then the highest-amplitude portion of the P-wave train should also be found in the PmP phase on the vertical seismogram. Figure 13 plots a profile of recorded time histories of the vertical component, as compiled by selecting 53 velocity seismograms. The ranges of azimuth and epicenter distance of these records are the same as Figure 8. The calculated travel-time curves and the range of distances for the direct P, S, PmP, and SmS phases are also shown in Figure 13. In the figure, the portion of PmP wave trains shows similarly enhanced amplitudes just as the enhanced SmS wave trains shown in Figure 8.
Based on preceding results and discussion, we can summarize as follows:

1. In the present study, we have identified focusing and interference between $SmS$ waves reflected from a horizontal and inclined portions of the Moho discontinuity as the primary cause for unusually large peak ground motion recorded at distances between 50 and 75 km in northwestern Taiwan. This interpretation is supported by constructing an inclined Moho model in which the amplitudes and arrival times of the largest shear waves were in close agreement with the data.

2. The residuals of horizontal PGA and PGV recorded from the Niu Dou earthquake confirmed that many Class E soft soil stations in the Taipei Basin and the Ilan Plain had the expected large amplification of about 1.7 and 1.5 times, respectively, the predicted median values. Surprisingly, residuals at many Class C or D dense and stiff soil sites, especially those in Taoyuan (TCU007), Lugtian (TCU013), Guanshi (TCU021), Hsinchu (TCU095), and Miaoli (TCU047) areas located in northwestern Taiwan, had residuals about 3.4–8.1 times the predicted median values. This is shown primarily due to effects of reflection at the Moho discontinuity.

3. The propagation path effects, especially those due to crustal structures, can play an important role in producing large ground motion while site conditions are clearly not responsible. Our results suggest that when a damaging earthquake occurs at depth near the Moho boundary, the reflected $SmS$ waves can cause significantly amplified ground motions in distances beginning at around 50 km. The exact distance range will depend on the thickness of the crust and the dip angle of an inclined Moho discontinuity.

Data and Resources

Seismograms used in this study were collected as part of the Taiwan Strong-Motion Instrumentation Program (TSMIP) using 16-bit accelerographs. The digital TSMIP strong-motion data can be obtained from the Central Weather Bureau of Taiwan at www.cwb.gov.tw, available at http://e-service.cwb.gov.tw/i-sales-web2/Services%20Application/services_application.htm.

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<table>
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<tr>
<th>Station Number</th>
<th>Station Code</th>
<th>Latitude (°N)</th>
<th>Longitude (°E)</th>
<th>Epicentral Distance (km)</th>
<th>Hypocentral Distance (km)</th>
<th>Azimuth (°)</th>
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<th>NS PGA (cm(\text{sec}^2))</th>
<th>NS PGV (cm/\text{sec})</th>
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Figure 13. A reduced travel-time plot of the vertical velocity seismograms for stations located in the azimuth range of 245°–335° and in the epicenter distance range of 5–100 km. The calculated travel-time curves and the range of distances for the direct $P$, $S$, $PmP$, and $SmS$ waves are also shown. The calculated travel-time curves and the range of distances for the direct $P$, $S$ waves and the reflected $PmP_h$ ($SmS_h$), $PmP_i$ ($SmS_i$) waves that represent the waves reflected from the horizontal and inclined portions of Moho discontinuity, respectively, are also shown.
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Large Effects of Moho Reflections (SmS) on Peak Ground Motion in Northwestern Taiwan


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