Article

Exploring the Rheology of a Seismogenic Zone by Applying Seismic Variation

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Featured Application: A 4D tomographic technique is utilized to investigate the variation of rheology around the fault zone.

Abstract: Although the study of spatiotemporal variation of a subsurface velocity structure is a challenging task, it can provide a description of the fault geometry as well as important information on the rheological changes caused by fault rupture. Our main objective is to investigate whether rheological changes of faults can be associated with the seismogenic process before a strong earthquake. For this purpose, a 3D tomographic technique is applied to obtain P- and S-wave velocity structures in central Taiwan using travel time data. The results show that temporal variations in the Vs structure in the source area demonstrate significant spatiotemporal variation before and after the Chi-Chi earthquake. We infer that, before the mainshock, Vs began to decrease (and Vp/Vs increased) at the hanging wall of the Chelungpu fault, which may be induced by the increasing density of microcracks and fluid. However, in the vicinity of the Chi-Chi earthquake's source area, Vs increased (and Vp/Vs decreased), which may be attributed to the closing of cracks or migration of fluid. The different physical characteristics at the junctional zone may easily generate strong earthquakes. Therefore, seismic velocity changes are found to be associated with a subsurface evolution around the source area in Taiwan. Our findings suggest that monitoring the Vp and Vs (or Vp/Vs) structures in high seismic potential zones is an important ongoing task, which may minimize the damage caused by future large earthquakes.

Keywords: temporal velocity variation; subsurface velocity structure; seismogenic process; crustal rock characteristics; 4D tomographic technique

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1. Introduction

Changes in the physical properties of a fault zone before an earthquake rupture have become an important issue that scientists attempt to explore. Generally, the most popular methods for the topic of earthquake precursors are ionospheric anomalies [1–3] and seismic activity [4,5]. They can include variations in rock properties or pore pressures during the inter-seismic period, but these characteristics still cannot be directly observed around the seismogenic zone. Results of seismic velocity measurements reveal some information about the potential role of crustal rock strength and pore pressure in crustal dynamics. From a wave propagation simulation, it is known that Vp is inversely proportional to the crack density and Vs is proportional to the fractional volume of the fluid content in fractured rock [6]. In addition, for the velocity structures of Vp and Vs, the Vp/Vs ratio is correlated to Poisson's ratio; therefore, they are regarded as important parameters in research into crustal rock characteristics [6,7]. Poisson's ratio reflects the porosity, degree of crushing, and hydraulic pressure of rock formation.

Many factors such as the composition of rock, orientation of cracks, pore pressure, temperature, and fluid saturation would affect the Vp/Vs ratio. Since most seismic events occur in active fault zones, the Vp/Vs ratio can be used to determine if pressure changes

will cause cracks to affect the velocity structure, which may result in gas or fluid migration and further large changes in pore pressure [8,9]. Therefore, the relationship between the characteristics of a fault zone and the distribution of the V_p/V_s ratio can be explored through three-dimensional (3D) tomography inversion. Furthermore, velocity structures can also be utilized to detect the attitude of subsurface formation and a brief overview of interface properties and features. Based on the above advantages, the results obtained in this study can be used to further understand the spatiotemporal evolution of fault materials.

Recently, some studies about seismic velocity variation have been conducted on the basis of the rupture of rocks caused by faulting [10], migration of magmatic fluids accompanying volcanic activity [11,12], and dilatancy and fluid migration before earthquakes [13], among others. The authors of [6] also described the variations in V_p before and after the 1999 Chi-Chi earthquake and the corresponding variations in V_p/V_s . Although there were no significant changes in V_p , after the occurrence of the Chi-Chi earthquake, deeper regions of the low-velocity anomaly appeared to have further expanded. The V_p/V_s model showed a substantial change reflecting an outward shift of the fluid-filled fractured source region. These changes are attributed to a localized stress change caused by the slip of the Chi-Chi rupture. The authors of [14] stated that the relationship between the velocity structure and time can be applied in earthquake forecasting and prediction, volcano warning systems, geothermal exploration, oil and gas reservoir assessment, and carbon dioxide capture and storage. However, the study of spatiotemporal variations of subsurface velocity structures is still a challenging work.

For the Taiwan region, from studies using 3D velocity models, similar results were discovered [15–18]; however, temporal variation was not considered in these 3D models. In 1999, the disastrous Chi-Chi earthquake M_L 7.3 occurred in central Taiwan and greatly affected Taiwanese society. In addition, although considerable research has been conducted to better understand the changes in the velocity structure in response to seismic events in central Taiwan, few studies have emphasized the significance of the velocity structure in relation to time. Therefore, this study aims to determine the impact of the Chi-Chi earthquake in central Taiwan before and after the event in order to understand the behavior of subsurface velocity structures. The main objectives of this research can be divided into three parts. First verifying the resolution of the model in each period. Next, detecting the uncertainty of the difference in different periods. Finally, the time evolution of the imaging velocity structure.

2. Geological Setting

Taiwan is situated on the collision boundary between the Eurasian and Philippine Sea Plates. Since the late Miocene, the southeast of the rifted continental margin, which was part of the Eurasian Plate, has been colliding with the Philippine Sea Plate, leading to the Taiwan orogeny [19]. The Philippine Sea Plate moves in a NW direction with a convergence rate of 8.2 cm/year [20]. The ongoing orogenic process causes a series of imbricate fold–thrust belts in the Western Foothills of Taiwan. Therefore, central Taiwan is composed of a complex system of belts, including the Changhua Fault (CHF), Chelungpu Fault (CLF), Shuangtung Fault (STF), Shuilikeng Fault (SKF), Lishan Fault (LF), and Longitudinal Valley Fault (LVF) (see Figure 1).

The great 1999 Chi-Chi earthquake ($M_L = 7.3$; depth = 8 km) that occurred at the CLF has received the most attention. The SKF is on the east of the foreland basin, and to its west are the STF, CLF, and CHF. They represent the major geological structures of central Taiwan. In addition, the continental margin of the Eurasian Plate contains several Eocene rift basins [21–23], of which the Hsuehshan Basin holds an important part of the Taiwan orogenic belt [21]. The sedimentary stratum beneath the foreland basin can reach more than 6 km in thickness, and the deformation front is also included [24].

The Eocene rocks of the Hsuehshan Basin now topographically occupy the higher ground and structurally overlie Pleistocene rocks of the foreland basin along the SKF [25,26]. Among them, the Peikang Basement High is located in western Taiwan, which impedes the

orogenic process. Moreover, central Taiwan is the transition zone of the Peikang Basement High and the Central Range.

Figure 1. (a) Fault setting in central Taiwan and seismic stations used in this study. The black arrows indicate the near-field GPS horizontal coseismic displacement. (b) Seismic distributions at different time periods. In the period I, there were 6075 events and 93,870 ray paths within the study area. In the period II, there were 5970 events and 96,862 ray paths within the study area. In the period II, there were 8234 events and 135,391 ray paths within the study area. EP: Eurasian Plate; PP: Philippine Sea Plate; WF: Western Foothills; HR: Hsuehshan Range; CR: Central Range; CHF: Changhua Fault; CLF: Chelungpu Fault; STF: Shuangtung Fault; SKF: Shuilikeng Fault; LF: Lishan Fault; LVF: Longitudinal Valley Fault.

According to thin-skinned thrust theory [27], a basal detachment, composed of brittle structures, may exist beneath the fold thrust belts in the Western Foothills of Taiwan. During the collision of plates, structures above the basal detachment form a series of imbricate fold–thrust belts in the shallow layer. However, when the rift-related basin bounding faults were reactivated as a result of the collision process, the crust deformation proceeded toward the deeper parts and caused the underlying basement to be uplifted and exhumed [28,29]. This orogenic process can lead to destructive deformity on the surface, which leads to heavy casualties and property losses. In addition, the seismicity can occur along the reactivating rift-related faults, and steeply inclined seismic clusters extending into the lower crust are exhibited [28,30,31].

3. Data and Methods

In this research, we utilized the massive volume of the seismic events compiled by the Central Weather Bureau Seismic Network (CWBSN) from January 1991 to December 2003. We divided this time span into three segments to investigate velocity structures in different time periods, namely, 1 January 1991–31 December 1995; 1 January 1996–19 September 1999; 1 January 2001–31 December 2003 (hereinafter, period I, period II, and period III, respectively) (see Figure 1b). We excluded the days immediately before and after the Chi-Chi earthquake because of complicated source effects that make some seismic events unsuitable to be adopted as a point source; therefore, these data could not be used for tomography [32]. This study suggests that a large earthquake caused by stress

adjustment makes the subsurface structure unstable, so the data for the year after the Chi-Chi earthquake was eliminated.

In this study, we used the travel times of P- and S-waves from earthquakes located inside the study area. Our study area stretched from 120.0° E to 122.0° E in longitude and from 23.5° N to 24.5° N in latitude. Earthquakes with magnitudes equal to or greater than 1.0 were considered, and data with poor location quality were excluded. Twenty-five stations were chosen in the study area, and at least 10 readings of each earthquake event were recorded, as the amount of observation of the matched earthquake event arrival affects the quality of the location of the earthquake; fewer observations result in poor location quality.

We applied seismic travel time data for tomography inversion by local tomography software [33]. The local tomography software was modified according to the bending-ray tracing algorithm by [34]. First, we utilized the Goal function [35] to detect the initial locations of the earthquakes. A straight path was drawn from the hypocenter to the station to locate the turning point at the midpoint and create a new path in sequence. Then, the corresponding travel time residue was calculated and the one with the minimum value was set as the ray path [28]. Finally, travel-time inversion was performed using the LSQR algorithm [36,37] to measure the P- and S-wave velocity anomalies and for obtaining the source parameters (four parameters for each seismic event). Furthermore, these results are fed back on a 3D grid for performing iterative inversion calculations until the iteration number or the travel-time residual value was less than the threshold value.

The study area was divided into numerous grids to invert the velocity variation. The grid was centered (121° E, 24° N) on the positive and negative sides of the x-, y-, and z-axes to 200 km and had dimensions of $5 \times 5 \times 5 \text{ km}^3$. As a single-grid azimuth may cause artifacts [38], this study averaged the results from four angles—0°, 22°, 45°, and 67°—to reduce any grid dependency. We integrated different combinations of Vp and Vs damping values to obtain the optimal model through the trial and error process. Finally, we selected the appropriate Vp and Vs damping parameters that would give results with the stable travel-time residual (RMS). The different combinations of the Vp and Vs damping parameters for each stage are 15 and 15, respectively. In addition, the initial velocity model often plays a decisive role in the problem of velocity inversion. Therefore, for the selection of the velocity structure in this study area, we chose the one that closely approximates the real velocity structure model to facilitate the inversion. We applied the one-dimensional (1D) velocity model adopted by [17] as the initial 1D velocity structure in this study.

This formula refers to the method of [32], and the description is simplified. In the subsequent study, the following formula was applied on the temporal variation in the velocity structure:

$$\left[\frac{(V_n^{i+1} - V_n^i)}{V_n^i} \right] \times 100\% \quad (1)$$

where V is the velocity, i is the number of periods, and n is the number of grids. Finally, the velocity perturbation model was obtained to explore the temporal variations in the velocity structure in central Taiwan.

4. Model Examination

An important objective of this study was to investigate the local velocity structural changes before and after the occurrence of strong earthquakes in central Taiwan. The evolution of velocity models in different time periods before and after the Chi-Chi earthquake is discussed. Through this analysis, we can further understand the seismogenic process before the earthquake, which is of great importance for future strong earthquake monitoring in central Taiwan.

In this study, the travel time data of the earthquake events compiled by the CWBSN were used, and the whole study time interval was divided into three periods for the inversion of 3D temporal velocity models for central Taiwan. To understand the reliability of the inversion results, a checkerboard test was used to verify the resolution at different depths.

We utilized the 1D velocity model adopted by [17] and added a $\pm 8\%$ perturbation to V_p and V_s to generate a new 3D velocity model in the form of a checkerboard (grid dimensions: $10 \times 10 \text{ km}^2$ in horizontal space). Utilizing this 3D velocity model, the assumed travel times of P- and S-waves are calculated. The results yielded by the checkerboard test for each period are shown in Figures 2–4.

Figure 2. Perturbations of $\pm 8\%$ of V_p and V_s were added to generate a new 3D velocity model in the form of a checkerboard (grid distance: $10 \times 10 \text{ km}^2$). Yellow triangles represent the stations. (a) Period I checkerboard of V_p . (b) Period I checkerboard of V_s .

The checkerboard test reflected the density of the ray paths at different depths, which could explain the resolution at different depths and confirm the reliability of the velocity model. The results show that both V_p and V_s have poor resolution at shallow depths of 0–5 km; this is because, near the surface, the ray path is nearly perpendicular to the station, resulting in an incomplete reflection of the lateral variation in the velocity structure. At depths of 10–25 km, excellent resolution was obtained because of a high ray density. These results suggest that the 3D velocity model of this area has a very high level of reliability for different time periods. The 3D velocity models of each period are shown in the Appendix A.

To verify the impact of artifacts, this study designed another test [32] restoration by identical synthetic models using two data subsets corresponding to different periods (Figures 5–7).

The test results using data of periods I and II in the proposed model with the variation in the synthetic manner are shown in Figure 8.

Figure 3. Perturbations of $\pm 8\%$ of V_p and V_s were added to generate a new 3D velocity model in the form of a checkerboard (grid distance: $10 \times 10 \text{ km}^2$). Yellow triangles represent the stations. (a) Period II checkerboard of V_p . (b) Period II checkerboard of V_s .

Figure 4. Perturbations of $\pm 8\%$ of V_p and V_s were added to generate a new 3D velocity model in the form of a checkerboard (grid distance: $10 \times 10 \text{ km}^2$). Yellow triangles represent the stations. (a) Period III checkerboard of V_p . (b) Period III checkerboard of V_s .

Figure 5. (a) A synthetic model with realistic configurations of anomalies. (b) Period I synthetic model of V_p . (c) Period I synthetic model of V_s . See the detail description in the text.

Figure 6. (a) A synthetic model with realistic configurations of anomalies. (b) Period II synthetic model of V_p . (c) Period II synthetic model of V_s . See the detail description in the text.

Figure 7. (a) A synthetic model with realistic configurations of anomalies. (b) Period III synthetic model of Vp. (c) Period III synthetic model of Vs. See the detail description in the text.

Synthetic difference in the periods I and II

Figure 8. The synthetic difference model with unchanged synthetic model recovered using two data subsets. Yellow triangles represent the stations. (a) Synthetic difference of Vp in the periods I and II. (b) Synthetic difference of Vs in the periods I and II.

The grid settings for the two cases were the same. After restoring models in these two time periods, we computed the differences between the recovered models, representing the Vp and Vs variations, at different depths. First, Figure 8a,b, respectively, show that the Vp and Vs results are similar, except for the border area, where the variation was 4%. In other areas, the variations were less than 0.40% and 0.54% on average. Next, Figure 9a,b, respectively, show that the Vp and Vs results are similar, except for the border area, where the variation was 4%. In other areas, the variations were less than 0.54% and 0.64% on average.

Synthetic difference in the periods II and III

Figure 9. The synthetic difference model with unchanged synthetic model recovered using two data subsets. Yellow triangles represent the stations. (a) Synthetic difference of Vp in the periods II and III. (b) Synthetic difference of Vs in the periods II and III.

We set the white area as resolvable, where the average variation was less than the actual temporal evolution of the velocity structure. These results revealed that the change over time was reliable. The blue and red areas represented greater variation, which implies greater effect of artifacts. In contrast, no temporal resolution capability could be shown in the black area. Furthermore, the variation in the synthetic models in periods II and III (Figure 9) was similar to that in periods I and II (Figure 8). However, the variations in Vp and Vs increase, which is attributed to the aftershocks of the Chi-Chi earthquake. Therefore, special attention must be given to the subsequent interpretation of the results.

As will be explained in the following section, the seismic velocity variations obtained by the model were less than those obtained from actual observation in the data analysis. This implies that the temporal variation in our model is not significantly affected by the artifacts associated with changes in the ray configuration for the selected data subset. However, a much wider range of artifact effects must be considered when exploring local changes in the study area. The presented test results demonstrate that, for the study region,

the proposed model robustly revealed the variations in the crust with a scale of more than 2%. The results of the experimental data analysis for stronger variations, presented in the next section, thus represent variations that occur in the crust as a result of tectonic processes.

5. Results and Discussion

5.1. Temporal Evolution of a Velocity Structure

The pore pressure is inversely proportional to the seismic wave velocity, evidenced by oil field detection and laboratory experiments [39]. Moreover, many experiments have examined the effects of fluid-filled cracks on seismic velocity [40–43]. Therefore, it is generally accepted that V_p is inversely proportional to the crack density and that V_p/V_s is proportional to the fluid saturation in the crack. In addition, its correlation with the rock crack and pore pressure was discussed. Fortunately, there have been studies using more realistic observational data to build fracture models [44] and there are detailed discussions on the differences between various fracture models.

First, variations in V_p , V_s , and V_p/V_s in the α zone (source area, see Figure 10b) before the occurrence of the Chi-Chi earthquake sequence in periods I and II are discussed and are shown in Figure 10.

Figure 10. (a) Temporal variation in V_p in the periods I and II. (b) Temporal variation in V_s in the periods I and II. (c) Temporal variation in V_p/V_s in the periods I and II. See the detail description in the text.

The results indicate that V_p decreased by approximately 2%, V_s decreased by approximately 4%, and V_p/V_s increased by approximately 4%. In the β zone (around the source area, see Figure 10b), V_p increased by approximately 4%, V_s increased by approximately 10%, and V_p/V_s decreased by approximately 6%. The results demonstrate that the

subsurface structure had already changed before the impending Chi-Chi earthquake, and the reason for the significant decrease in V_s in the α zone compared with V_p is possibly the proliferation of cracks and fluid intrusion. The authors of [45] also speculated using a magnetotelluric technique that the seismogenic mechanism of the Chi-Chi earthquake may be associated with fluid intrusion. The velocity structure variation in the β zone was opposite to that in the α zone, presumably due to the closure of the crack, resulting in an increase in V_s . Figure 10b,c clearly show that, at depths of 5–10 km, the hypocenter of the Chi-Chi earthquake occurred in the boundaries of the areas of high and low V_p/V_s . However, no significant difference was noticed at depths greater than 15 km.

From periods II and III, the variations in V_p , V_s , and V_p/V_s after the earthquake sequence are shown in Figure 11.

Figure 11. (a) Temporal variation in V_p in the periods II and III. (b) Temporal variation in V_s in the periods II and III. (c) Temporal variation in V_p/V_s in the periods II and III. See the detail description in the text.

The results demonstrate that V_p and V_s varied within $\pm 10\%$ in the vicinity of the CLF. These variations were more complicated in the shallow crust (equal to or less than 15 km). Note that in Figure 11a, the result shows a significant decrease in V_p at a depth of 5–15 km in the northern segment of the CLF. The distribution of the low V_p anomaly is in good agreement with the result of maximum slip distribution in the GPS calculation [46,47], because the slip vector in the GPS calculation is the combined effect from the surface observation. However, from the temporal variations in the velocity structure, we can estimate the possible slip pattern beneath the subsurface. When the depth was less than 15 km, the lateral variation in V_p was more prominent than in the lower crust, which reflected changes in rock cracks after the earthquake occurred. No more lateral change was noted for depths greater than 25 km, which indicated that the lower crust was less

affected by the Chi-Chi earthquake. At a depth of more than 15 km, the variations in Vs and Vp/Vs near the hypocenter reduced after the earthquake, and the area with obvious velocity variation was located in the area north of the CLF to LF.

5.2. Tectonic Implications

In this study, we discussed the relationship between the velocity structures of Vs and Vp/Vs over time and the geometry of faults in order to determine the variations in Vs and Vp/Vs before and after the occurrence of the Chi-Chi earthquake sequences along the velocity profiles. Figure 12 shows the time-dependent perturbation profile in periods I and II. It can be seen from the section of CC*–EE* connection that in the α area (hypocenter) during the Chi-Chi earthquake, Vp/Vs increased by approximately 4% and Vs decreased by approximately 4%.

(a) Temporal variations profile of Vs in the periods I and II

(b) Temporal variations profile of Vp/Vs in the periods I and II

Figure 12. The AA* to EE* profiles analyzed in this study are displayed in the left panel. The profile across the Chi-Chi earthquake uses gray dotted line and red star to indicate the location of the CLF and the mainshock, respectively. The right panel shows the location of the AA* to EE* profiles. The profile CC* across the Chi-Chi earthquake are depicted with the thick red line. (a) Temporal variation profile of Vs in the periods I and II. (b) Temporal variation profile of Vp/Vs in the periods I and II.

In the β area (near the hypocenter), V_p/V_s decreased by approximately 6% and V_s increased by approximately 10%. The fluid-filled fractured region at the α area (hypocenter) was assumed to lead to fissure expansion; therefore, the decline of V_s was greater than V_p . Furthermore, in the south to north sections of V_s , V_s changed along an eastward-tilted inclined plane. Moreover, V_s changed more significantly south of the hypocenter compared with the north. This phenomenon occurred before the Chi-Chi earthquake and was concentrated south of the CLF. However, the variations in the β area were opposite to those in the α area.

In contrast, in this study, we discuss the velocity variation over a long time scale before the occurrence of the earthquake sequence; we found remarkable changes in periods I and II, such as the decrease in V_s in the α region and the increase in V_s in the β region, while the hypocenter was located at the junction of the α and β areas. This phenomenon indicated that the direction of the tectonic stress was from the south-east (approximately 100° , [48]), resulting in the closure of the pores in the β area, which may allow the fluid to migrate toward the α area. The decrease in the frictional strength of the fault in this area might be attributed to the vicinity of the α area to the hypocenter, the increase in the pore density, and the possibility of fluid intrusion. These factors may have led to the occurrence of the Chi-Chi earthquake, suggesting it is a precursor phenomenon.

From periods II and III, the time-dependent perturbation profile of V_s is shown in Figure 13; it can be seen from the section of AA*–EE* connection in the low anomalous regions that V_s significantly expanded from south to north, revealing that the northern section of the CLF has a larger slip displacement after the rupture, which leads to an east-dipping, low- V_s anomalous region.

Furthermore, the slip displacement of the southern section was smaller than that of the northern section, and V_p/V_s exhibited fewer anomalies compared with those in the northern section. This anomalous region is speculated to be the Chi-Chi earthquake rupture zone, which is consistent with the location of the CLF. Further analysis is required to explore the spatial variation of the earthquake rupture, the results of which would also be valuable for confirming the larger rupture zone in the northern section of the CLF compared to the southern section.

(a) Temporal variations profile of V_s in the periods II and III

Figure 13. Cont.

Figure 13. The AA* to EE* profiles analyzed in this study are displayed in the left panel. The profile across the Chi-Chi earthquake uses gray dotted line and red star to indicate the location of the CLF and the mainshock, respectively. The right panel shows the location of the AA* to EE* profiles. The profile CC* across the Chi-Chi earthquake are depicted with the thick red line. (a) Temporal variation profile of V_s in the periods II and III. (b) Temporal variation profile of V_p/V_s in the periods II and III.

In addition, the authors of [49] independently analyzed the Qs of earthquakes and found that Qs changed with time. Among them, the region where Qs is higher before the Chi-Chi earthquake corresponds to the β region where V_s is increased in Figure 12a of the present study. The lower area of Qs after the Chi-Chi earthquake is corresponding to the V_s falling area in Figure 13a of this study. They speculate that the decrease in Qs (increased S-wave attenuation) may indicate an increase in fluid content in the ruptured area after the Chi-Chi earthquake which resulting in increased pore fluid saturation.

6. Conclusions

This research used travel time data for earthquake events compiled by the Central Weather Bureau Seismic Network (CWBSN). Using these data, tomography inversion was conducted for different periods of structures in central Taiwan. The results were utilized to deduce the relationship between seismicity and fault structure with spatiotemporal evolution. Based on the aforementioned information, the following conclusions can be drawn.

1. The results showed that the temporal variations of V_p were less than those of V_s , and V_p was not affected significantly before the occurrence of the Chi-Chi earthquake.
2. The velocity profile indicates that the temporal variation of the subsurface velocity structure may have been affected before the occurrence of the Chi-Chi earthquake sequences. In the α area, the decreased V_s and increased pore pressure are attributed to the increasing density of microcracks and the possibility of fluid or gas intrusion. Moreover, we observed increasing V_s in the β area; this was because the β area was located on the eastern side of the α area. It was presumed that the direction of the tectonic stress was from the southeast, resulting in the closure of the pores and fluid migration in the β area. This phenomenon may be attributed to the different mechanism of action in the α and β areas.

3. Based on the present results, the temporal variations reflect precursory phenomena in the source area before the Chi-Chi earthquake and the range of the CLF affected by the Chi-Chi earthquake.

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Appendix A

Results of velocity structure model

In general, the seismic velocity is affected by several geological factors, including lithology, fluid saturation, pore density, geometry of the crack, and the degree and type of rock cementation [50]. The effect of shallow layer is the most prominent; the pressure increases with depth due to the weight of the rocks above the layer, which subsequently leads to the closure of the majority of the pores [51].

This study was divided into three time periods to explore the variations in V_p , V_s , and V_p/V_s in the study area; the results are shown in Figures A1–A3. We divided the time period 1 January 1991–31 December 2003 into three periods to study the change in the velocity structure before and after the Chi-Chi earthquake that occurred on 21 September 1999 (UTC+8). Each period is discussed in the following paragraphs.

In the period I (1 January 1991–31 December 1995), the lateral variations in V_p (Figure A1a), V_s (Figure A1b), and V_p/V_s (Figure A1c) in the study area were not significantly different from those at depth. However, at a depth of 10–45 km, especially at a depth of 15 km or less, the Hsuehshan Range presented a significantly low V_p and V_s zone, which may be related to the plastic deformation caused by the plate extrusion (plate collision); these findings were consistent with the previous studies [15–18]. In addition, there was a higher in V_s and a lower in V_p/V_s at depths of 5–20 km in the LF and LVF.

In the period II (1 January 1996–19 September 1999), which was before the occurrence of the Chi-Chi earthquake sequence, V_p (Figure A2a) showed no significant variation compared to that in the first period. However, V_s (Figure A2b) began to change significantly before the earthquake. We found that there was lower V_s value in the source area, resulting in a higher V_p/V_s ; this may be due to the cracks generated in this area and the intrusion of the fluid causing pore expansion. Instead, V_s was higher around the source area, which led to a lower V_p/V_s . This may be attributed to the closure of the pores in this region. At depths of 15–35 km, the low- V_s zone in the WF was still visible.

In the period III (1 January 2001–31 December 2003), V_p (Figure A3a), V_s (Figure A3b), and V_p/V_s (Figure A3c) were recorded after the episode of the Chi-Chi earthquake sequence. The results showed significant lateral variations at depths less than 15 km, and the tectonic stress was assumed to be readjusted after the large earthquake. One interesting phenomenon at depths of 5–25 km was the lower V_p anomaly in the northern and WF and HR compared to that in the first and second periods. Furthermore, the abnormal range of V_p was larger than the range in V_s . At a depth of 5 km, relatively low V_p/V_s

was concentrated in the CLF. A high V_p/V_s mainly concentrated in the south and north sides. At a depth of 10 km, relatively low V_p/V_s was observed westward and concentrated between the CHF and SKF; moreover, the range of the low V_p/V_s tended to expand. The low V_p/V_s was located further to the central of the LF at depths of 5–20 km. The high V_p/V_s was located further to the south side of the CLF and north side of the LVF at depths of 5–35 km.

Figure A1. This study is divided into three periods to explore the V_p , V_s , and V_p/V_s in the study area. Yellow triangle represents the station. The results of Figure A1 represent the first period. (a) V_p at different depths. (b) V_s at different depths. (c) V_p/V_s at different depths.

Figure A2. This study is divided into three periods to explore the V_p , V_s , and V_p/V_s in the study area. Yellow triangle represents the station. The results of Figure A2 represent the second period. (a) V_p at different depths. (b) V_s at different depths. (c) V_p/V_s at different depths.

Figure A3. This study is divided into three periods to explore the V_p , V_s , and V_p/V_s in the study area. Yellow triangle represents the station. The results of Figure A3 represent the third period. (a) V_p at different depths. (b) V_s at different depths. (c) V_p/V_s at different depths.

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