

Chapter 2

Assessment of Tomography Models of Taiwan Using First-Arrival Times from the TAIGER Active-Source Experiment

In 2008, the TAIGER project conducted an active-source experiment in which seismic records from 10 explosions were collected at nearly 1400 locations on the island of Taiwan. In this study, we manually pick the first-arrival times from the explosion records to ensure reliable and accurate travel time observations, and use them to examine the complex P-wave structural variations in the crust beneath Taiwan. Aided by numerical simulations, we compare the observed first-arrival times with those predicted from a one-dimensional (1D) model and three three-dimensional (3D) tomography models for Taiwan which portray the underlying variations in seismic wave speeds frequently utilized to decipher the regional tectonic framework in Taiwan. We evaluate the quality of the four models by the goodness of fit between the observed and model-predicted travel times. Statistical distributions of the differential travel time residuals allow us to inspect quantitatively the overall effectiveness of these models in replicating the observed ‘ground-truth’ first-arrival times so as to make an assessment of the strength and deficiency of the resolved velocity structures that agree with or contradict the travel time observations from the explosion experiment.

2.1 Introduction

Taiwan is situated at the boundary zone between the Eurasian Plate (EP) and Philippine Sea Plate (PS). Most of the island is bracketed by two different types of subduction systems. Off the northeast coast of Taiwan the oceanic PS subducts northwestwardly under the continental EP along the Ryukyu Trench, whereas to its south the EP plunges eastward under the PS (Fig. 2.1). The oblique convergence

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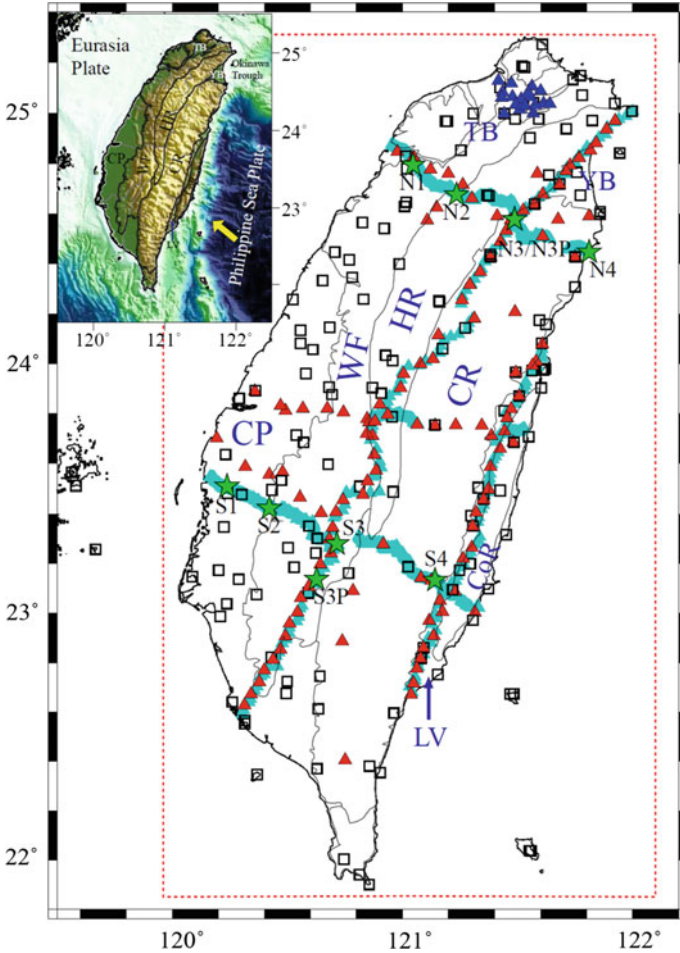


Fig. 2.1 Locations of the TAIGER explosions (stars) and stations. Open squares show the stations of permanent CWBSN and BATS networks. Red and cyan triangles are portable broadband/short-period and TEXAN instruments, respectively, deployed by the TAIGER project. Blue triangles indicate portable array stations in the Taipei Basin. Inset map shows the regional tectonic setting. Tectonic divisions in Taiwan shown in this and subsequent figures are: Central Range (CR), Hsueshan Range (HR), Coastal Range (CoR), Western Foothills (WF), Longitudinal Valley (LV), Coastal Plain (CP), Taipei Basin (TB), and Yilan Basin (YB). Yellow arrow indicates the current movement direction of the Philippine Sea Plate. The red-dashed box indicates the horizontal extent of the finite-difference simulations. Reprinted from Lin et al. (2011) with permission Bulletin of the Seismological Society of America

between these two plates has resulted in the collision of the Luzon Arc with the Chinese continental margin and subsequent orogeny in Taiwan (Teng 1996). Nowadays, the island of Taiwan continuously undergoes a northwest-southeast compression with a convergence rate of about 8 cm/year (Yu et al. 1997; Bird 2003).

The active collision, orogeny, and subduction cause very high rates of deformation (Yu et al. 1997) and seismicity (Wang 1998; Wang and Shin 1998) in the Taiwan region, which provides abundant geological and geophysical observables for studying regional structures and tectonics. Over the past two decades, networks of densely-distributed seismic stations have been deployed across Taiwan and nearby islands as well as offshore on the sea floor. These networks have accumulated a tremendous amount of high-quality seismic data from worldwide earthquakes. Primarily based on P- and S-wave arrival times from local earthquakes, a number of tomography models have been constructed for the seismic velocity structures in the crust and uppermost mantle beneath Taiwan, which are often used to interpret the complex tectonic processes in the region. Rau and Wu (1995) manually picked P-wave arrival times recorded by short-period instruments of the Central Weather Bureau Seismic Network (CWBSN) to image the 3D lithospheric structure beneath Taiwan. Ma et al. (1996) employed the P- and S-wave arrival times reported in the Central Weather Bureau (CWB) earthquake catalog to investigate both the velocity structure and the variation in crustal thickness. Shin and Chen (1998) obtained a layered 1D model suitable for the Taiwan region, which has since been used by the CWB for routine determinations of earthquake hypocenters and origin times. More recently, Kim et al. (2005) combined the augmented dataset from the CWBSN and two temporary seismic arrays in east-central and southern Taiwan to simultaneously determine 3D models of P and S velocities in the crust and uppermost mantle and relocate earthquake hypocenters. Wu et al. (2007) included additional S-P differential arrival times from the Taiwan Strong Motion Instrumentation Program (TSMIP) network and the CWBSN data to construct 3D models of V_p and V_p/V_s ratio beneath Taiwan.

In order to further advance our understanding of regional tectonics, the TAIGER project carried out a series of comprehensive geophysical experiments which collected a large amount of data useful for the accurate determination of earthquake locations and mechanisms as well as the construction of multi-scale images of the crust and upper-mantle structures. One of them was an active-source seismic experiment conducted in the spring of 2008, with a total of 10 controlled-source explosions being shot across the island of Taiwan. The recorded seismic data and scientific outcomes are extraordinary in that the source locations and origin times are exactly known and the observed P-wave arrival times can thus be applied directly to assess the robustness of existing tomography models and alleviate their possible deficiencies. Furthermore, they allow us to explore alternative structural models and geodynamic interpretations consistent with the new data.

In this study, we pick the onset times of the first arrivals from the TAIGER explosion records to examine the crust and uppermost mantle structure beneath Taiwan. We also compare the observed first-arrival times with those predicted by the tomography models in order to evaluate their efficacy in travel time estimation. Although ultimately these active-source first-arrival times can be used as constraints in a future 3D seismic tomography study, their immediate application is in the assessment of currently available tomography results. The rationale for this undertaking is two folds: (1) Coming from controlled experiments almost entirely

free of source uncertainties, these highly accurate first-arrival times provide the “ground truth” that must be satisfied by all structural models, and (2) given the variety of tomography models derived from different datasets and modelling techniques, there is clearly a need for a careful examination of the available models in order to understand their strengths and weaknesses so that these models can be used more effectively and appropriately, and the first-arrival times from active sources provide an accurate and objective ground-truth criterion. Systematic, careful and quantitative assessment of the available regional models is also helpful in selecting the optimal 3D model to serve as the starting model for non-linear iterative full-wave tomography approaches developed in recent years (e.g. Chen et al. 2007; Tape et al. 2009).

For predicting first-arrival times in 3D models, many algorithms based on ray tracing have been developed in the past four decades (e.g. Julian and Gubbins 1977; Červený 1987; Um and Thurber 1987; Vidale 1990; Moser 1991; Podvin and Lecomte 1991). These algorithms provide efficient tools in predicting first-arrival times in 3D structures. However, for the entire Taiwan region we consider in this study, most of the algorithms are either non-parallel thus require expensive shared-memory computers to allow for small spatial grid spacing, or lack the flexibility to switch models easily. Therefore, we adopt the 4th-order staggered-grid finite-difference method (e.g. Olsen 1994; Graves 1996) to compute synthetic seismograms from individual explosive sources. We obtain the first-arrival times from the synthetic seismograms for the 1D model of Shin and Chen (1998) and the 3D models of Rau and Wu (1995), Kim et al. (2005), and Wu et al. (2007), and compare them with the observations to evaluate the reliability of their resolved Vp structures.

2.2 Observations of First-Arrival Times

The first-arrival time data used in our study were measured from the waveform records of the 10 TAIGER explosion shots. Table 2.1 lists the basic information of each explosion source including the GMT time, location, yield, and site condition. Figure 2.1 shows distributions of the stations and explosion sites, among which five shots are located along the Northern Cross-Island Highway and the other five are along the Southern Cross-Island Highway. The recording stations belong to a number of permanent and portable networks which include: (1) the Broadband Array in Taiwan for Seismology (BATS), a permanent network operated by the Institute of Earth Sciences (IES), Academia Sinica; (2) the CWBSN, a permanent network consisting of a real-time monitoring system of short-period, strong-motion and broadband stations; (3) a portable array of broadband seismographs in the Taipei Basin (TBBN) operated by IES; (4) a portable array of 47 IRIS PASSCAL broadband instruments deployed by the TAIGER project along three approximately east-west lines; (5) portable arrays composed of 48 broadband and 20 short-period

Table 2.1 Primary information of the 10 TAIGER explosions

Shot	Yield (kg)	Date mm/dd/year	Time (GMT)	M_L	Longitude (°E)	Latitude (°N)	Elev. (m)	Site class	α (km/s)
S1	1000	02/27/2008	17:01:49	3.02	120.2380	23.50886	6	D1	1.60
S2	750	02/27/2008	17:30:57	2.62	120.4213	23.42339	20	D2	1.67
S3	500	02/26/2008	18:02:46	1.89	120.7147	23.28013	650	B	4.10
S3P	1500	02/26/2008	17:32:43	1.78	120.6267	23.13699	335	B	4.10
S4	750	02/28/2008	17:02:09	2.30	121.1417	23.13288	390	B	4.10
N1	750	03/06/2008	17:03:23	2.56	121.0459	24.79356	55	C2	2.00
N2	750	03/06/2008	17:34:56	1.55	121.2358	24.67563	590	B	4.10
N3	750	03/04/2008	18:01:18	2.10	121.4879	24.57694	405	B	4.63
N3P	3000	03/04/2008	17:01:18	2.67	121.4879	24.57694	405	B	4.63
N4	1000	03/05/2008	17:03:40	2.43	121.8117	24.44690	6	D3	1.74

Note M_L is the magnitude for the explosions determined by the Central Weather Bureau of Taiwan, α is the P-wave speed either given from Vs30 (for Classes C, D and E) or estimated from TAIGER explosion records (for Class B)

instruments deployed by the IES, the National Chung Cheng University, and the National Central University; and (6) an array of TEXAN geophones distributed at a spacing of about 200 m along the Northern and Southern Cross-Island Highways. The geophones were also deployed along the Central Range at a spacing of 2 km in between the portable instruments in (5). The sampling intervals of the records are 0.004 s for the TEXAN instruments and 0.01 s for the rest.

2.2.1 *Picking Onset Times from Waveform Records and Removing Elevation Effect*

We collected the explosion waveforms from a total of about 1400 recording sites. Most of the records are in good quality, as shown in Fig. 2.2. Figure 2.2a, b exhibit a suite of vertical-component records at a number of stations (Fig. 2.2a) along the Central Range from Shot N3P. In the raw waveform records in Fig. 2.2a, the first motions are sharp and their arrival times can be very accurately determined. In Fig. 2.2b, bandpass filtered version of these records around 1 Hz show that coherent converted surface waves from the explosion can be seen even beyond about 80-km epicentral distance. These short-period Rayleigh waves can be used in dispersion and waveform inversions to investigate both P- and S-wave structures at very shallow depth (1–2 km).

We manually picked the onset times of the first-motions in the raw vertical-component explosion records. The procedure for the onset-time picking is illustrated in Fig. 2.2d. We first zoom in around the emergence of the first motion to a duration of only a few sampling intervals of a seismic record. For instance,

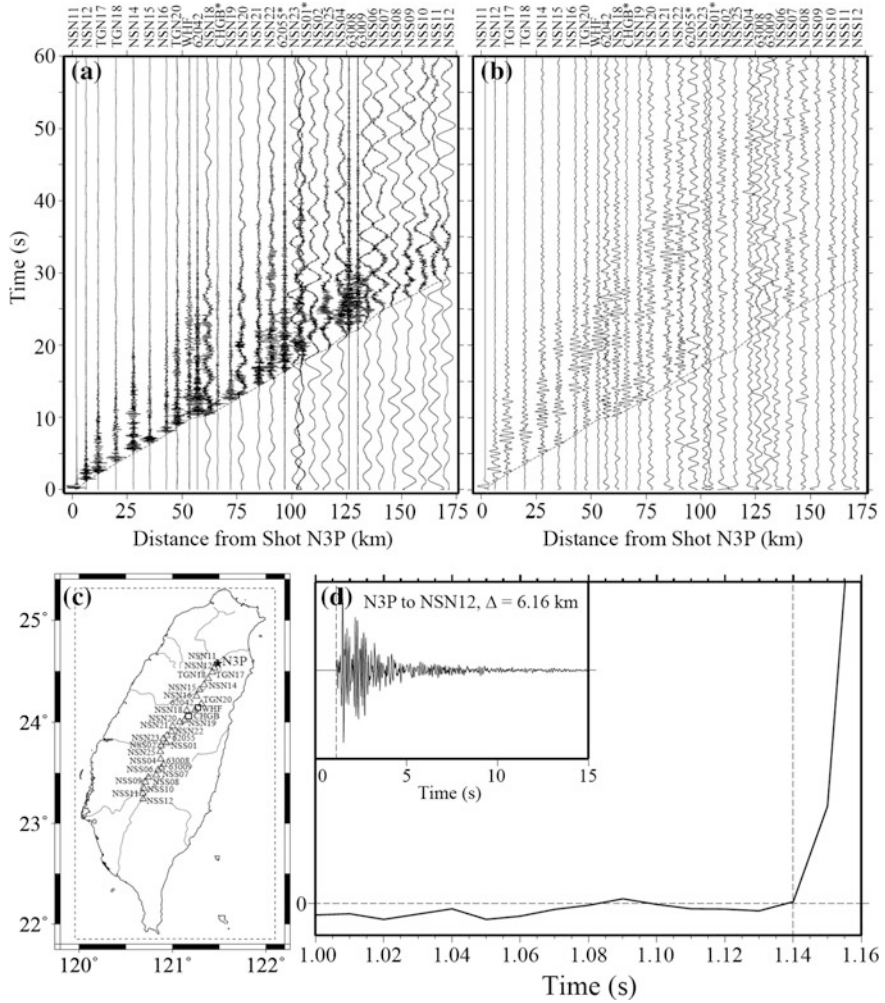


Fig. 2.2 **a** A suite of vertical-component raw seismograms recorded by instruments located along a linear trend from Shot N3P. The dashed line indicates the manually picked first-arrival times. Station names are given at the end of each trace, and stations with no first-arrival time picks are identified by a star. **b** Bandpass filtered versions of the records in **(a)** with cutoff frequencies of 0.8 and 1.5 Hz. **c** Locations of Shot N3P and the instruments whose records are shown in **(a)** and **(b)**. **d** An illustration of picking the first-arrival time shown by the record at station NSN12 from Shot N3P. The dashed line indicates the first-arrival time pick. Reprinted from Lin et al. (2011) with permission Bulletin of the Seismological Society of America

Fig. 2.2d shows the zoom-in record of a 0.16-s long time window equivalent to 16 sampling intervals. Since the first motion from an explosion is always upward, we choose the onset time of the first motion at the instant of a sudden increase in the slope of the waveform (vertical dashed line in Fig. 2.2d). All of our first-arrival

time picks have been obtained following a set of stringent standards to ensure the consistency, reliability and accuracy. In the end a total of 6029 first-arrival times were obtained from fewer than half of all TAIGER explosion records, most of which have picking errors well below 0.1 s.

The observed first-arrival times from the active-source experiment provide a ground-truth dataset of P-wave travel times, which can be applied to evaluate 3D tomography models by comparisons with model predictions. However, before making this comparison careful consideration must be taken to account for the effect of topography and shallow structure on the first-arrival times which are usually poorly modeled in tomography inversions. The effect of topography on first-arrival times is mainly caused by the elevations of shots and stations relative to the sea level. Since the elevations of shots and stations are exactly known, consideration of the topography effect on first-arrival times boils down to the estimation of the near-surface seismic wave speed.

Current tomography models for Taiwan are confined to the structures below sea level and topography of the region is not taken into account. The shots and stations in the TAIGER active-source experiment are all located at different elevations with a variation range of over 3 km. Therefore, the observed first-arrival times reflect shortest travel times not between two points at sea level, but between two points at different altitudes. To compare the observed and model-predicted first-arrival times, we can make adjustment to either observed or model-predicted arrival times to account for the elevation effect.

In travel time tomography, a quantity called ‘station correction’ is often used to account for the travel time anomaly associated with the station elevations, strong, small-scale structural heterogeneity, and sharp, discontinuous velocity changes at shallow depths under the stations. These features are usually considered as nuisance in tomography inversions which implicitly assume that the imaged velocity perturbations are weak and smooth. As a result, it is unreliable to use ‘station corrections’ or near-surface velocities in tomography models to estimate the contributions of the source and station elevations to an observed first-arrival time. Instead, we make use of the results from decades of thorough geological mappings and geophysical surveys in Taiwan (Ho 1988) to determine the near-surface P-wave speed consistent with the geological units at the sites of stations and explosions. Then, for each shot-receiver pair, we estimate the difference in travel time taken along two P-wave ray paths: one being the true ray path from the actual location of the shot to the receiver and the other from the projection of the shot on the sea level to that of the receiver. The geometry is shown by the diagram in Fig. 2.3. The sub-surface portion of the true ray path from S_1 to R_1 has approximately the same length as the portion of the ray path from the sea-level source to the sea-level receiver from S_2 to R_2 . From the geometry we have the relation

$$T_{SR} = T_{SS_1} + T_{S_1R_1} + T_{R_1R}, \quad \text{and} \quad T_{S_0R_0} = T_{S_0S_2} + T_{S_2R_2} + T_{R_2R_0}, \quad (2.1)$$

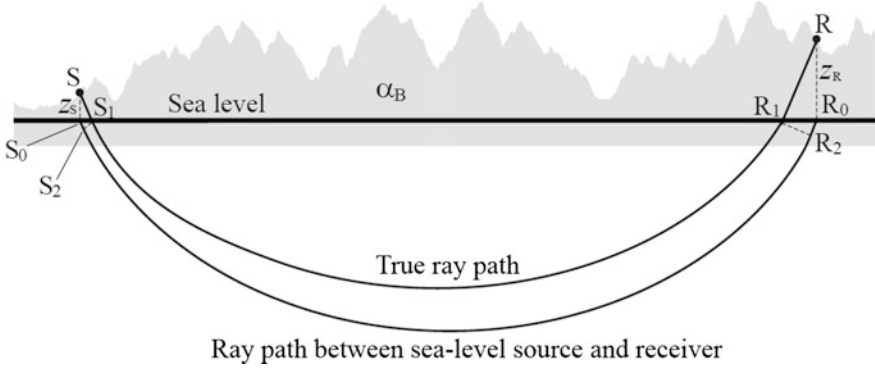


Fig. 2.3 Diagram showing the geometry in making first-arrival time adjustment for elevation travel time. S and R are the actual positions of the shot and receiver, respectively, and S_0 and R_0 are their vertical projections on the sea-level. Solid curves are ray paths from S to R and from S_0 to R_0 . S_1 and R_1 are intersections between the ray path from S to R and the sea-level. α_B is the assumed constant P-wave speed of the Class B material between the topographic surface and the sea level. Reprinted from Lin et al. (2011) with permission Bulletin of the Seismological Society of America

Thus we have

$$T_{S_0R_0} = T_{SR} - (T_{SS_1} - T_{S_0S_2}) - (T_{R_1R} - T_{R_2R_0}). \quad (2.2)$$

From the geometrical relations between the sides of $\triangle SS_0S_1$ and $\triangle S_1S_2S_0$ and between the sides of $\triangle RR_1R_0$ and $\triangle R_1R_0R_2$ shown in Fig. 2.3, we know that

$$T_{SS_1} - T_{S_0S_2} = \frac{z_S}{\alpha_0} \sqrt{1 - p^2 \alpha_0^2}, \quad \text{and} \quad T_{R_1R} - T_{R_2R_0} = \frac{z_R}{\alpha_0} \sqrt{1 - p^2 \alpha_0^2}, \quad (2.3)$$

where z_S and z_R are the elevations of the shot and receiver, respectively, and p is the ray parameter of the first-arriving P wave. For a given shot, the ray parameter varies with the receiver elevation and the shot-receiver distance. Therefore we can write

$$T_{S_0R_0} = T_{SR} - \delta t_{SR}, \quad (2.4)$$

where

$$\delta t_{SR} = (T_{SS_1} - T_{S_0S_2}) + (T_{R_1R} - T_{R_2R_0}) = \frac{z_S + z_R}{\alpha_0} \sqrt{1 - p^2 \alpha_0^2} \quad (2.5)$$

is the difference between the travel time T_{SR} from the actual locations of the shot to receiver and the travel time $T_{S_0R_0}$ between sea-level source and sea-level receiver. Here we assume that the P-wave speed α_0 between the surface and the sea-level is homogeneous.

The source and station elevations z_S and z_R in Eq. (2.5) are known quantities. Therefore, if we also know the topographic surface P-wave speed α_0 and the ray parameter p , we can estimate δt_{SR} , and Eq. (2.4) provides a straightforward means to adjust the travel times T_{SR} from actual locations of the shots to receivers that are manually picked on the records, to $T_{S_0R_0}$, the travel times from sources to receivers on the sea level, which can be compared directly with the model-predicted first-arrival times to assess the validity of the models. After the adjustment to all first-arrival time picks for the elevation-induced time differences, the resulting P-wave travel time anomalies can be used not only for evaluating the quality of the regional tomography models, but also for constraining the heterogeneous structures in the crust and uppermost mantle.

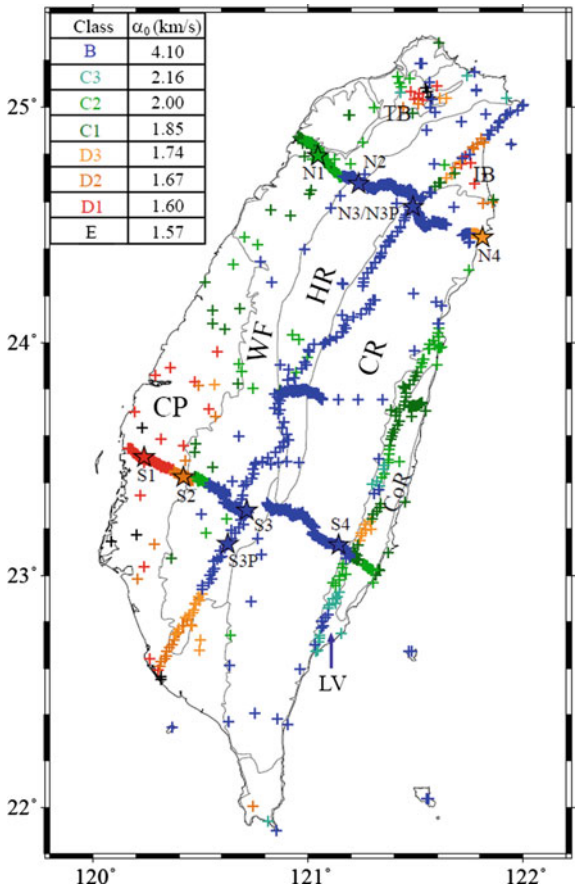
In this study, we estimate the near-surface P-wave speeds by the in situ conditions at the source and station sites. Lee et al. (2001) classified the site conditions in Taiwan into four categories, B, C, D and E, corresponding to Classes S_B , S_C , S_D and S_E , respectively, in the 1997 UBC provisions (ICBO 1997). Lee and Tsai (2008) assigned the site categories of 711 free-field strong-motion stations distributed in Taiwan and estimated the shear velocity values of these four categories. We adopt their classification and determine the site class for each source and station by choosing the same site category as that for the nearest strong-motion station. These four site classes are distinguished by age and rock type (Classes B and C) or engineering soils (Classes D and E). Class B refers to igneous and metamorphic rocks, limestones, and hard volcanic intrusions. Miocene or older rocks may be classified as Class B, with an average shear-wave velocity of 760 m/s to 1500 m/s in the uppermost 30-m layer (V_{s30}). Sandstones, shales and conglomerates in the Pliocene and Pleistocene, and soft rocks or very compact soils are classified as Class C. Class C has a V_{s30} value ranging in 360–760 m/s, and is divided into three subclasses C1, C2 and C3 (Lee and Tsai 2008). Late Quaternary loose sands, silts, clays, gravel deposits or stiff soils like fluvial terrace, and stiff clays are classified as Class D, which is also divided into three subclasses D1, D2, and D3 with V_{s30} values varying in 180–360 m/s (Lee and Tsai 2008). Class E, with $V_{s30} < 180$ m/s, contains Holocene alluvium flood plains and recent fills. The site classes determined for all the sources and stations used in this study are shown in Fig. 2.4.

In the active-source experiment of the TAIGER project, the sources and stations associated with the site classes of C, D and E are all at low altitudes of a few tens of meters or less. Therefore, for all stations of C, D and E classes, we adopt the V_{s30} values in Lee and Tsai (2008) for shear-wave speeds, β , at the sites associated with these three categories, and estimate the corresponding P-wave speed, α , by the so-called Castagna mud-rock equation (Castagna et al. 1985):

$$\alpha = 1.16\beta + 1.36, \quad (2.6)$$

where α and β have the unit of km/s. The estimated P-wave velocities for site classes C, D and E are shown in the inset table in Fig. 2.4.

Fig. 2.4 Site classes of all stations and explosions used in this study. The inset table on the top-left corner lists the P-wave velocities for Classes C, D and E estimated directly from the Vs30 values (see text) and the Castagna mud-rock equation. The P-wave speed for Class B is determined by a linear regression between first-arrival times and travel distances at stations within 6 km from Shots N2, S3 and S3P. Reprinted from Lin et al. (2011) with permission Bulletin of the Seismological Society of America



The sources and stations associated with Class B are all located at higher elevations where the velocities above sea level are no longer available from the local Vs30 model. Shots N2, N3P, S3 and S3P are all classified as Class B, and fortunately each of these shots has a number of stations located within a few kilometers. It is worth mentioning that in addition to the TEXAN geophone records, we incorporate data from 13 and 8 accelerometers deployed by IES (Lin et al. 2009) and located less than 1 km away from Shots N3P (N3) and S3P, respectively. The integrated dataset provides a far more accurate estimate of both the origin times and the P-wave velocities near the explosion sites. Assuming that the structural column above sea level at each shot is relatively homogeneous, we estimate the uniform P-wave speed within the column by the linear relation between the first-arrival times and travel distances from the stations less than 6 km to the shot. Figure 2.5 shows the first-arrival times increasing with distances which give the P-wave speed

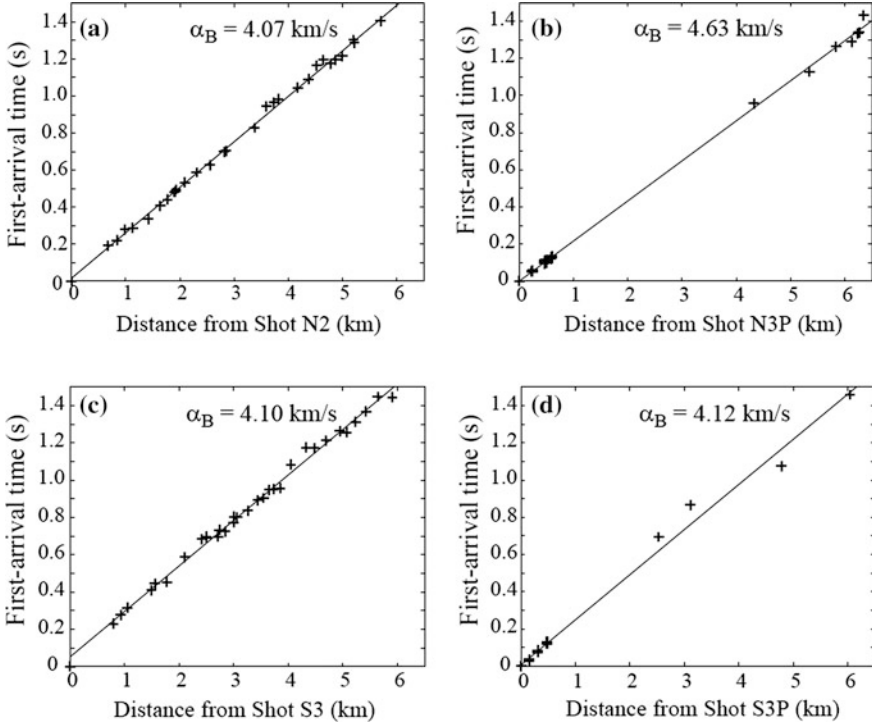


Fig. 2.5 P-wave velocities for Class B estimated directly by least-squares linear regressions between the first-arrival times and distances observed at stations within 6 km from Shots N2, N3P, S3 and S3P. Crosses clustered near the origin in **b** and **d** denote the first-arrival times observed at several accelerometers deployed within 1 km from Shots N3P and S3P, respectively. Reprinted from Lin et al. (2011) with permission Bulletin of the Seismological Society of America

for the metamorphic rock of Class B at each shot by the inverse of the slope of the best-fitting line. The P-wave speeds near Shots N2, S3 and S3P are similar, about 4.1 km/s (Fig. 2.5a, c, d), but is higher near Shot N3P, about 4.63 km/s (Fig. 2.5b), indicating that the material property in the vicinity of Shot N3P significantly differs from that at the other shots. Therefore, we determine the P-wave velocity to be 4.10 km/s for Class B by averaging the estimates at Shots N2, S3 and S3P, and use the value of 4.63 km/s for Shot N3P and the stations within 1 km from the shot. Details of the site classes for the 10 explosions are listed in Table 2.1.

After obtaining the surface P-wave speeds for all site classes for the shots and stations, we use Eq. (2.5) to estimate δt_{SR} , the time differences due to source and station elevations needed to adjust the first-arrival time picks T_{SR} to those between sea-level source and stations $T_{S_0R_0}$ (Fig. 2.3). For stations of site classes C, D and E, they are located above low-velocity sediments with low elevation (a few tens of meters), we thus make the approximations

$$\delta t_{SR} = \frac{z_S + z_R}{\alpha_0} \sqrt{1 - p^2 \alpha_0^2} \approx \frac{z_S}{\alpha_0} + \frac{z_R}{\alpha_0} \sqrt{1 - p^2 \alpha_0^2}, \quad (2.7)$$

for C, D or E class explosion site,

$$\delta t_{SR} = \frac{z_S + z_R}{\alpha_0} \sqrt{1 - p^2 \alpha_0^2} \approx \frac{z_S}{\alpha_0} \sqrt{1 - p^2 \alpha_0^2} + \frac{z_R}{\alpha_0}, \quad \text{for C, D or E class station site,} \quad (2.8)$$

$$\delta t_{SR} = \frac{z_S + z_R}{\alpha_0} \sqrt{1 - p^2 \alpha_0^2} \approx \frac{z_S + z_R}{\alpha_0}, \quad \text{for C, D or E class explosion and station,} \quad (2.9)$$

Ray tracing tests using realistic structures show that Eqs. (2.7)–(2.9) are very good approximations with only a maximum error of ~ 0.025 s. For stations in class B, the elevations may be too high and we must estimate the ray parameter p more accurately. The first-arrival time picks from the nearly linear array of stations along the five southern shots enable us to derive an average 1D model which can be considered as a representative of the average 1D structure of class B, and then we determine the ray parameter p from the actual locations of the shot to the station by ray tracing in this 1D model. Figure 2.6 shows the elevations of the TAIGER

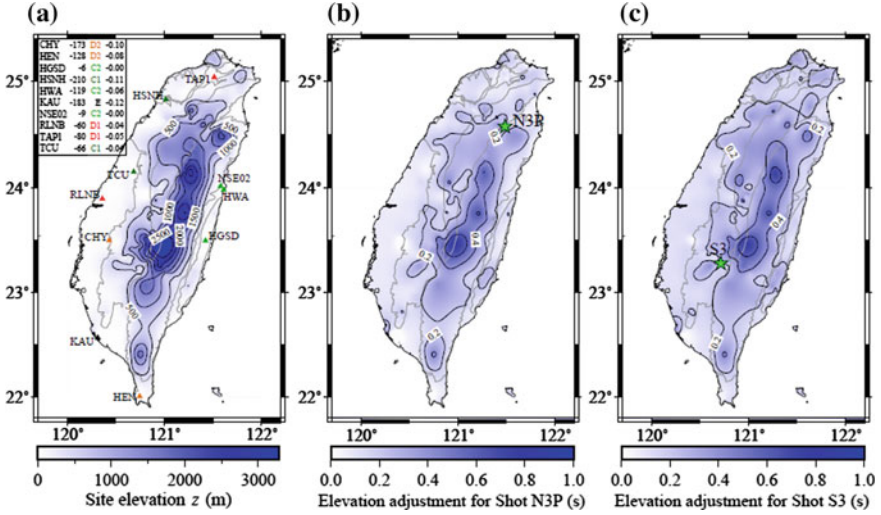


Fig. 2.6 **a** Elevations of stations and explosions. The ten down-hole stations with negative elevations are shown by the *triangles* with the corresponding color for their site classes used in Fig. 2.4. Their elevations in meters, site classes, and the station part of elevation effect (z_R/α_0 in Eqs. 2.8 and 2.9) in sec are listed in the inset box. **b** and **c** Distributions of the travel time adjustment δt_{SR} due to source and receiver elevations (Eq. 2.5) to P-wave travel times from Shots N3P and S3, respectively. Reprinted from Lin et al. (2011) with permission Bulletin of the Seismological Society of America

explosions and stations and the estimated time adjustments δt_{SR} for Shots N3P and S3. The highest station is located at an elevation of 3845 m in the Jade Mountain, which yields the largest travel time adjustment of ~ 0.71 s. The travel time adjustments for all shot are shown in Fig. 2.7.

2.2.2 Elevation-Adjusted First-Arrival Times

After the time delays owing to the elevation effects at the stations and explosion sites are removed, we obtain the adjusted first-arrival times, $T_{S_0R_0}$, which retain only the P-wave travel times accrued within the sub-sea level structures. These in situ measured travel times are then employed to interpolate the variations of the observed first-arrival times emanating from the shots using a minimum-curvature interpolation scheme built in the GMT plotting software (Wessel and Smith 1998). The resulting P-wave travel time distributions from 10 explosions are displayed in Fig. 2.8, where white corresponds to the zero travel time at the shot locations and red color represents the travel time of 50 s and longer. In the vicinity of the shot sites, the P waves only travel a small distance through the region near the surface and therefore the travel time patterns are characterized by the variations of shallow velocity structures near the explosions. As the traveling distance increases, the P waves penetrate deeper and the travel time patterns reflect structural variations at greater depths. Convex and concave geometries of the travel time contours indicate P waves traveling at higher and lower speeds, respectively, along their propagation paths than those along neighboring paths. For example, the contours are slightly convex south of the northern shots, N2, N3 and N3P (Fig. 2.8b–d), and north of the southern shots, S3 and S4 (Fig. 2.8h, j). This indicates that the P waves travel faster at shallower depths beneath the Central Range than the surrounding regions. On the other hand, the concave patterns northwest and southwest of Shot S3 (Fig. 2.8h) are, respectively, related to the presence of the low velocity zones at shallow depth in Chiayi and Kaohsiung regions. We note that the travel time contours may exhibit fictitious patterns introduced by the interpolation scheme, particularly in places where the spatial sampling is sparse. For example, travel time variations from two co-located shots, N3 and N3P, shown in Fig. 2.8c, d, respectively, should be very much alike. However, they are actually quite different in central and southern Taiwan. In particular, in southern Taiwan the travel time contours from N3P are very irregular, whereas those from N3 are almost flat. Because of the much smaller yield for Shot N3, there are fewer first-arrival time picks available for the travel time interpolation than N3P, and as a result the two travel time patterns are similar only in regions near Shots N3 and N3P, where the sampling of the first-arrival times (denoted by solid blue triangles in Fig. 2.8c, d) is dense. Because of this reason, it is important to remember that contours in regions with few observations must be taken with a grain of salt.

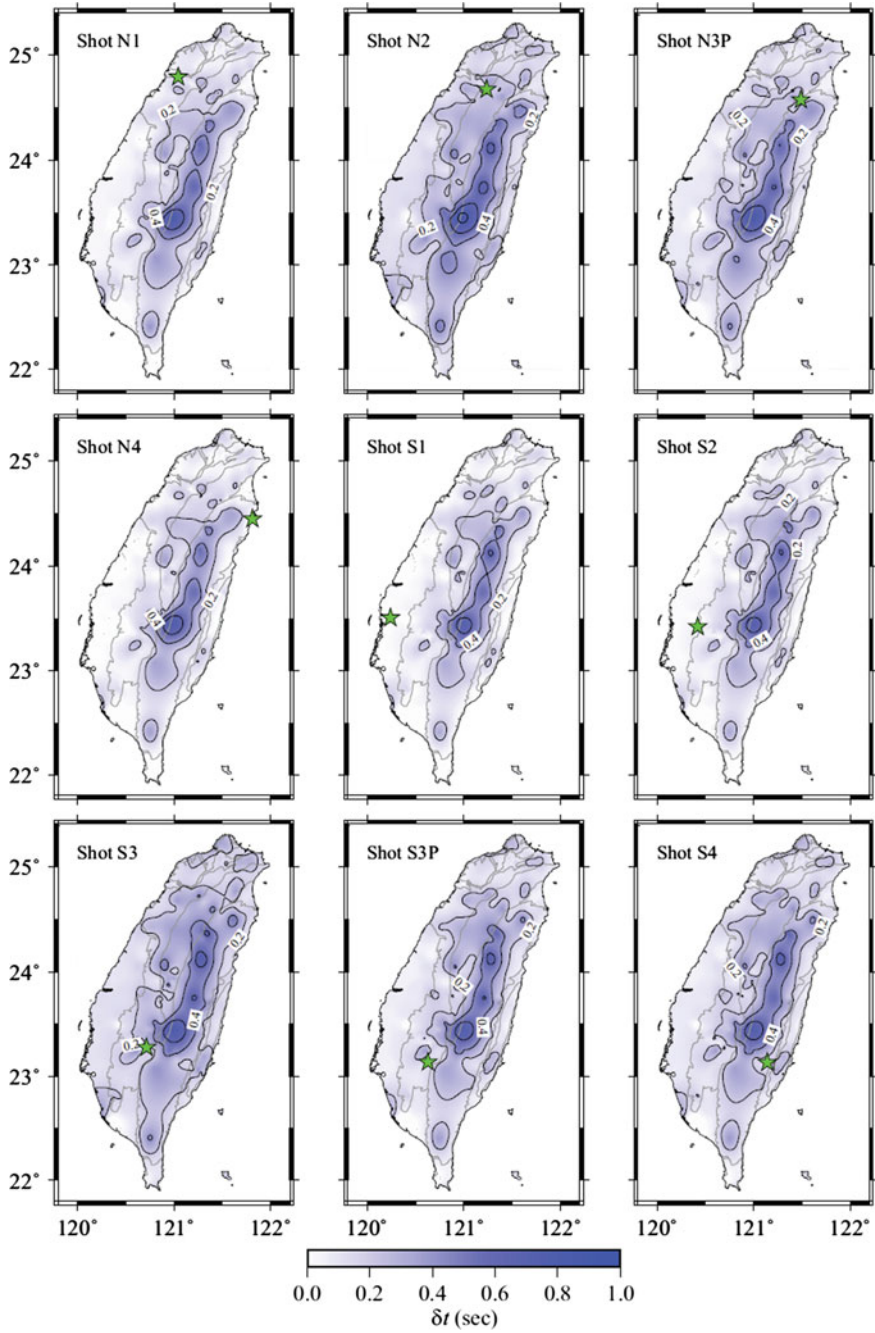


Fig. 2.7 Plots similar to those in Fig. 2.6b, c but for all shots. Shot N3P and N3 are collocated, so only nine plots are shown. Reprinted from Lin et al. (2011) with permission Bulletin of the Seismological Society of America

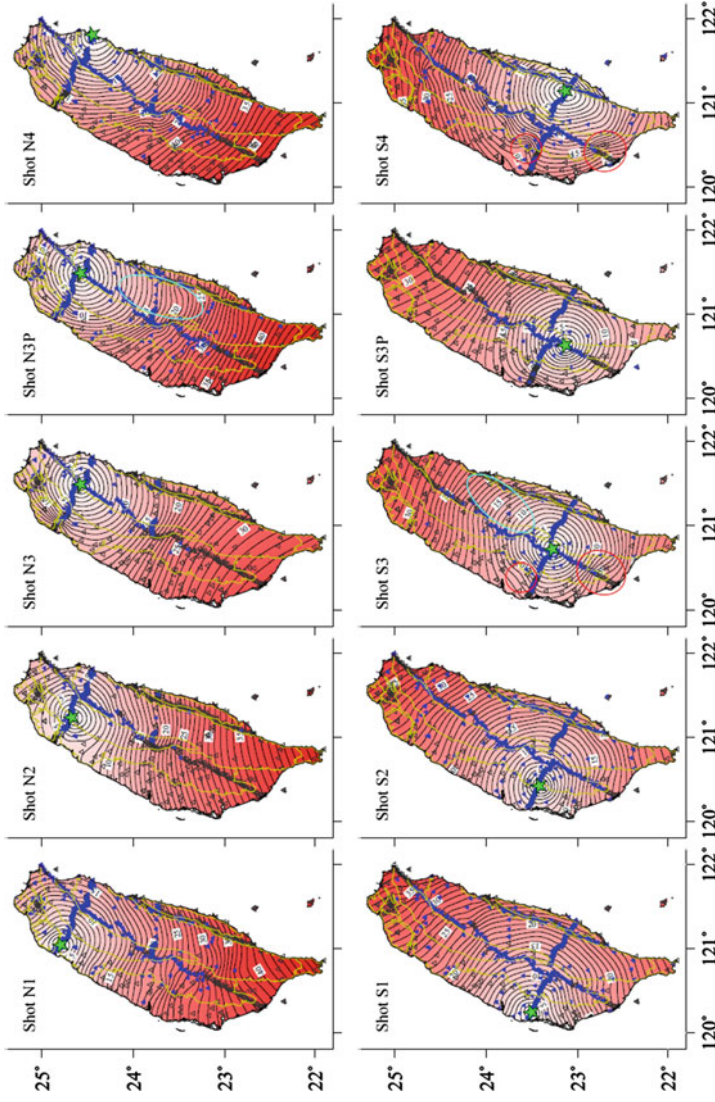


Fig. 2.8 Observed P-wave travel times from the 10 TAIGER explosions. Stars indicate shot locations. Stations are denoted by triangles, with solid blue ones indicating those at which accurate first-arrival times can be obtained. Cyan ellipses enclose regions of convex contours near Shots N3P and S3 indicating a higher P-wave speed at shallow depth beneath the Central Range, while red ellipses mark the concave contours indicating a low velocity zones at shallow depth in Chiayi and Kaohsiung regions. Reprinted from Lin et al. (2011) with permission Bulletin of the Seismological Society of America

2.3 Model Predictions of First-Arrival Times

Since the 1990s, the CWBSN stations have provided a good coverage on the Taiwan island to monitor seismic activities occurring in the region. The CWB catalog which routinely reports earthquake source information and P and S arrival times has helped produce a number of tomography models of the crust and uppermost mantle structures beneath Taiwan to improve our understanding of regional tectonics. In this study, we want to evaluate the validity of the resolved heterogeneous structures by comparing the first-arrival times predicted by the tomography models with the ground-truth data obtained from the TAIGER explosion records.

2.3.1 Regional Models for Taiwan

Many P and S velocity models for the crust and uppermost mantle beneath Taiwan have been published in the past two decades. In this study we consider four models that span the entire region, including a regional 1D model (Shin and Chen 1998, hereafter referred to as 1D) and three 3D models (Rau and Wu 1995; Kim et al. 2005; Wu et al. 2007, hereafter referred to as R95, K05, and W07, respectively). Figure 2.9 displays the map views of P-wave speed perturbations of the three 3D models with respect to the 1D model at the depths of 5, 13, 25, and 35 km. Model R95 (Rau and Wu 1995) was obtained using arrival times from 1197 regional earthquakes. The model was discretized into a 3D grid with 8 points vertically down to 80-km depth and a non-uniform horizontal grid spacing of 20–35 km. In contrast, model K05 (Kim et al. 2005), based on $\sim 27,000$ arrival times of P and S waves from 1218 earthquakes, was parameterized uniformly with a 8-km horizontal grid spacing and a 2-km vertical spacing down to 148-km depth. Model W07 was derived from an even more extensive dataset: $\sim 300,000$ P arrival times and $\sim 174,000$ S-P differential times from 17,206 regional earthquakes. The 3D model grid is also non-uniform, with horizontal grid spacing of 7.5–20 km and 17 grid points vertically down to a depth of 200 km. The long-wavelength features are generally in good agreement among the 3D models such that they all reveal a region of low V_p in the western coastal plain and a high V_p at shallow depth (see the maps for 5-km depth in Fig. 2.9), but significantly lower V_p than in the surrounding region at great depths beneath the Central Range (see the maps for 25- and 35-km depths in Fig. 2.9). Model R95 has the smoothest structure while W07 yields the strongest lateral variations with many short-wavelength anomalies superimposed on the long-wavelength structures. All the models use the contour of a subjectively-chosen velocity at the base of the crust to delineate the Moho depth, inferring that the maximum Moho depth reaches to 50–60 km beneath the Central Range.

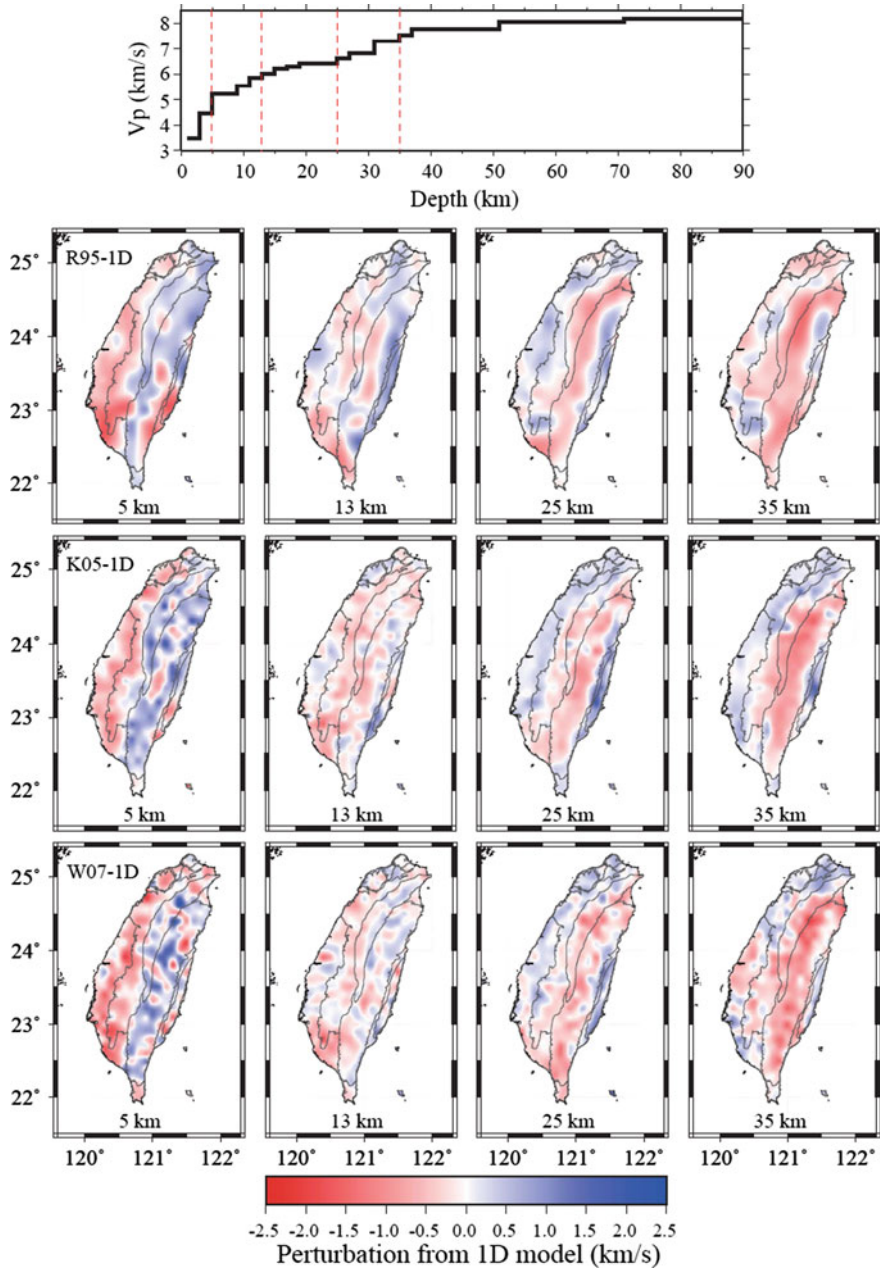


Fig. 2.9 P-wave velocity models considered in our study. *Top* panel shows the 1D model, and the *bottom* three rows show, from *top* to *bottom*, the perturbations of the 3D models R95, K05 and W07 relative to the 1D model at four different depths. In each row, the depths from *left* to *right* are 5, 13, 25 and 35 km, with P-wave speeds of 5.25, 6.02, 6.62 and 7.53 km/s, respectively, in the 1D model. Reprinted from Lin et al. (2011) with permission Bulletin of the Seismological Society of America

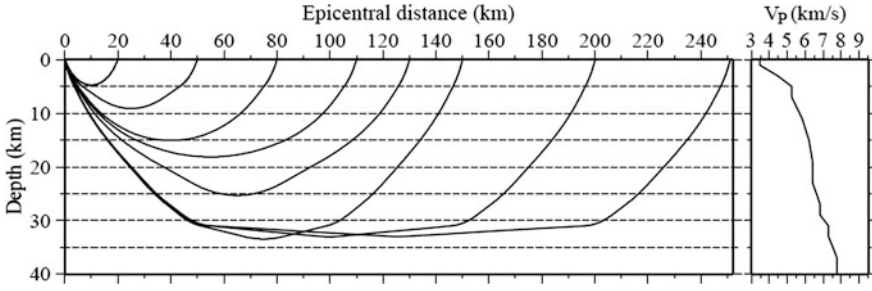


Fig. 2.10 *Left* Typical ray paths for the first arrivals at several epicentral distances. Note that there is a factor of 2 vertical exaggeration. *Right* The 1D model used in the ray tracing. It is a smoothed version of the 1D model shown in Fig. 2.9. Reprinted from Lin et al. (2011) with permission Bulletin of the Seismological Society of America

In order to establish an intuition between the first-arrival times and the depth distribution of wave speed, a few first-arrival ray paths are displayed in Fig. 2.10. These ray paths are calculated by the ray tracing algorithm of Zelt and Smith (1992) in a smoothed version of the 1D model in Fig. 2.9. Ray paths in 3D models are apparently dependent not only on epicentral distance, but also on the specific locations of source and station. However, except for stations close to the explosions, almost all first-arriving P waves propagate through the structure beneath the Central Range, where the Moho is relatively deep. Therefore, the typical ray paths in Fig. 2.10 suggest that almost all of our first-arrival time picks are obtained from Pg waves with a maximum penetration depth of about 35 km.

2.3.2 Numerical Simulations

We employ a staggered-grid finite-difference algorithm (Olsen 1994) with an accuracy of fourth order in space and second order in time to simulate 3D seismic wave propagation through the four models we consider here and calculate the synthetic seismograms from 10 explosions recorded at sea level. Although the recently developed spectral-element method (SEM) provides an accurate approach to model the topography effect on seismic wave propagation (e.g. Komatitsch and Tromp 1999, 2002; Chaljub et al. 2003; Lee et al. 2008), it is a major task to implement a different structural model in the SEM simulation. Therefore, it is not appropriate for this study because of our need to analyze multiple structural models.

The structural volume in our numerical simulations covers an area of 3.5° in latitude by 2.14° in longitude and extends from sea level down to a depth of 80 km. The entire model is discretized into a total of $2240 \times 1304 \times 458$ nodes with a uniform grid spacing of 175 m, resulting in the synthetic P waveforms with

accuracy up to about 4 Hz. To ensure numerical stability, the time step needed to advance the wavefield is 0.008 s.

For the four Taiwan regional models, the model parameters at each finite-difference grid point is obtained by a linear interpolation using the values at the 8 surrounding points in the model grid. For the 10 explosion shots, two of which (N3 and N3P) are co-located, a total of 36 simulations were carried out. A first motion detection program is used to automatically pick the onset times of first arrivals predicted by the four models.

In Fig. 2.11, we present the model-predicted first-arrival times by displaying the differential travel times between 3D and 1D models for Shots N3P (Fig. 2.11a–c) and S3 (Fig. 2.11d–f), since they are the most representative explosion shots in northern and southern Taiwan, respectively. As mentioned previously, interpolation of sparsely sampled travel times may generate artificial patterns caused by interpolation. Since the numerical simulation can provide seismograms and first-arrival time picks at all grid points in the model, we use samples of first-arrival times obtained at a large number of closely-spaced grid points (black dots in Fig. 2.11a, d) that more uniformly cover the study region to obtain lateral variations of the differential travel times between the 3D and 1D models shown in Fig. 2.11.

As seen in Fig. 2.9, the deviations of P-wave velocities of the 3D models from the 1D model are positive at shallow depth and negative at greater depth beneath the Central Range. Effects of these velocity perturbations on the variations of differential travel times between 3D and 1D model are evident in Fig. 2.11. Near Shot N3P in northern Taiwan (Fig. 2.11a–c), the differential times are negative (blue), consistent with higher P-wave velocities at shallow depth beneath the Central Range, whereas further south they become positive (red), caused by lower P-wave velocities at greater depth. Such depth-dependent velocity structure beneath the Central Range has similar effects on the predicted first-arrival times for Shot S3 in southern Taiwan (Fig. 2.11d–f), leading to an opposite distribution of the differential travel times varying from negative in the south to positive in the north. The differential travel times for 3D models K05 and W07 have positive values in the western foothills (WF) and coastal plain (CP), where the V_p anomaly relative to the 1D model is negative at shallow depth. All 3D models yield positive differential travel times localized in the Kaohsiung region in the southwest from Shot S3, where the P-wave speeds at depth less than 10 km are significantly lower than the surrounding regions (see Fig. 2.9). In addition, the differential travel times in Models K05 and W07 for Shot S3 are positive in Hengchun Peninsula at the southern tip of Taiwan, in contrast to those in R95. This difference is directly related to the different near-surface velocity perturbations beneath Hengchun Peninsula (see the maps for 5-km depth in Fig. 2.9), which are negative or slower in K05 and W07 relative to the 1D model, but positive or faster in R95.

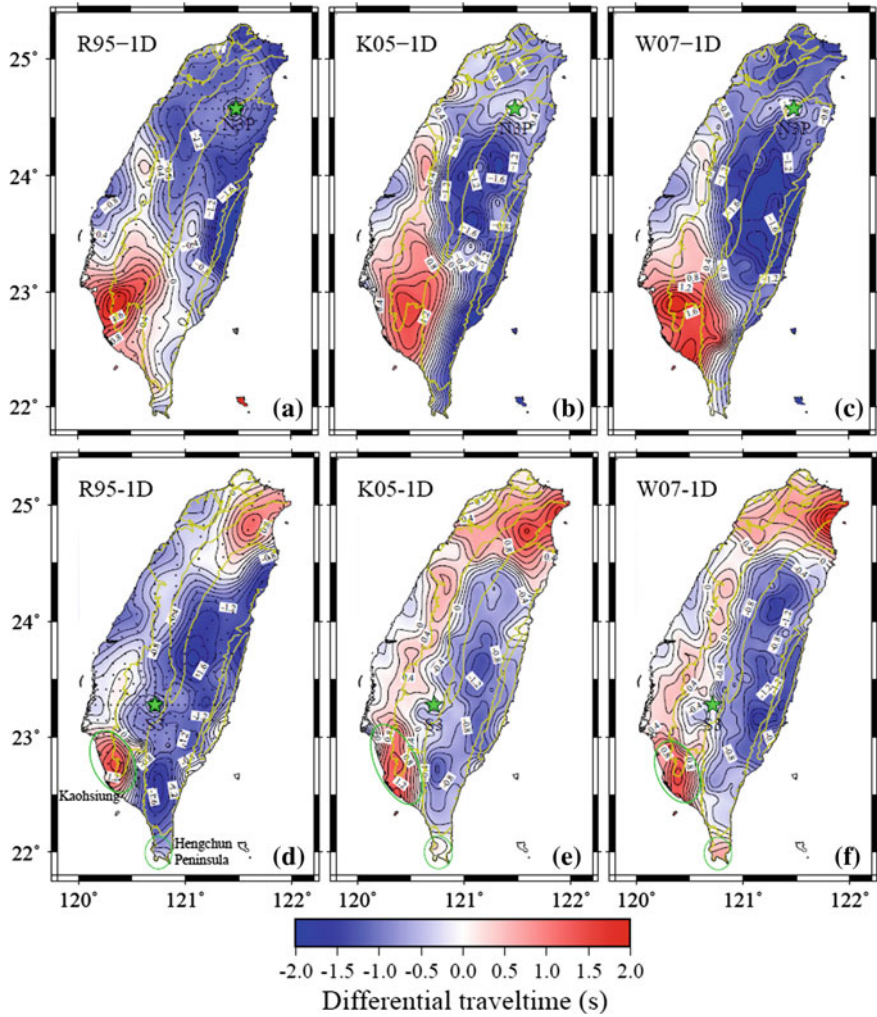


Fig. 2.11 Differential P-wave travel times for Shots N3P (*top row*) and S3 (*bottom row*) obtained by subtracting the first-arrival times predicted by the 1D model from those by individual 3D models, with Model R95 in (a) and (d), K05 in (b) and (e), and W07 in (c) and (f). Stars indicate the locations of the shots. The color scheme assigns a cool (warm) color for a negative (positive) differential travel time observed at a given location on sea level, implying that the arriving P-wave takes a shorter (longer) time in the 3D model than in the 1D; that is, it travels from the shot to the given location with a higher (lower) wave speed in the 3D models than in the 1D model. Reprinted from Lin et al. (2011) with permission Bulletin of the Seismological Society of America

2.4 Comparisons Between Observed and Model-Predicted First-Arrival Times

In order to evaluate the capability of the 1D and 3D models in predicting the ‘ground-truth’ first-arrival times obtained from the explosion records, we conduct a systematic comparison between the observed and model-predicted P-wave travel times. The distributions of the travel time residuals for Shots N3P and S3 obtained by subtracting the model-predicted first-arrival times from the observed ones are shown in Fig. 2.12. As noted before, the interpolation of travel time variations may introduce artificial patterns in places where the samples of first-arrival times are sparse. Therefore, if we perform a point-by-point subtraction of the model-predicted first-arrival times from the observed ones at all of the interpolated locations, the residual distribution can be falsely represented by fictitious residuals. We therefore divide the island of Taiwan into $0.13^\circ \times 0.13^\circ$ squares, with each square having an overlap with each of the adjacent square, and the width of each overlap is one-fifth of the side of the square. For each square, we calculate the average of the residuals from all the samples obtained in that square. The square size is chosen to simultaneously prevent artifacts arising from interpolation and retain robust, small-scale features in the residual distributions.

The residuals of travel times in the 1D and 3D models from Shots N3P and S3 are shown in Fig. 2.12. It is obvious that all the 3D models yield smaller travel time residuals than the 1D model, indicating a significant improvement in the fit of the observed travel times by the tomography models. The residuals in the three 3D models from Shot N3P (Fig. 2.12b–d) are all negative (blue) in northern and central Taiwan closer to the shot site and positive (red) further south. These patterns suggest that the current 3D tomography models are not fast enough at shallower depth and not slow enough at greater depth under the Central Range. Even though the 3D models have predicted a higher V_p at shallow depth and a lower V_p at great depth than the 1D model under the Central Range, they still underestimate the amount of velocity perturbations. Similarly, the residuals from Shot S3 shown in Fig. 2.12f–h are positive (red) in Chiayi and Kaohsiung regions, indicating that the 3D models are not slow enough at shallow depth there. The positive (red) residuals in the northwest corner of the island are found in Models R95 and W07 (see Fig. 2.12b, d), which suggests that these two models are too fast at shallow depth in northern Taiwan. The overall residual patterns for the different models from the other 8 shots are similar and they are presented in the same way in Fig. 2.13. Notwithstanding that all 3D models are superior to the 1D model in predicting the observed travel times, there are still rooms for improvements.

We compare the statistical distributions of the travel time residuals for the four models to quantitatively assess their effectiveness in replicating the observed ‘ground-truth’ travel times. Figure 2.14a shows the plot of the number of picks vs. residual values for the entire dataset. The number of picks for a residual value is counted from the total number of picks whose residuals are within a ± 0.1 s bin around the given residual value. To further investigate the contribution to the

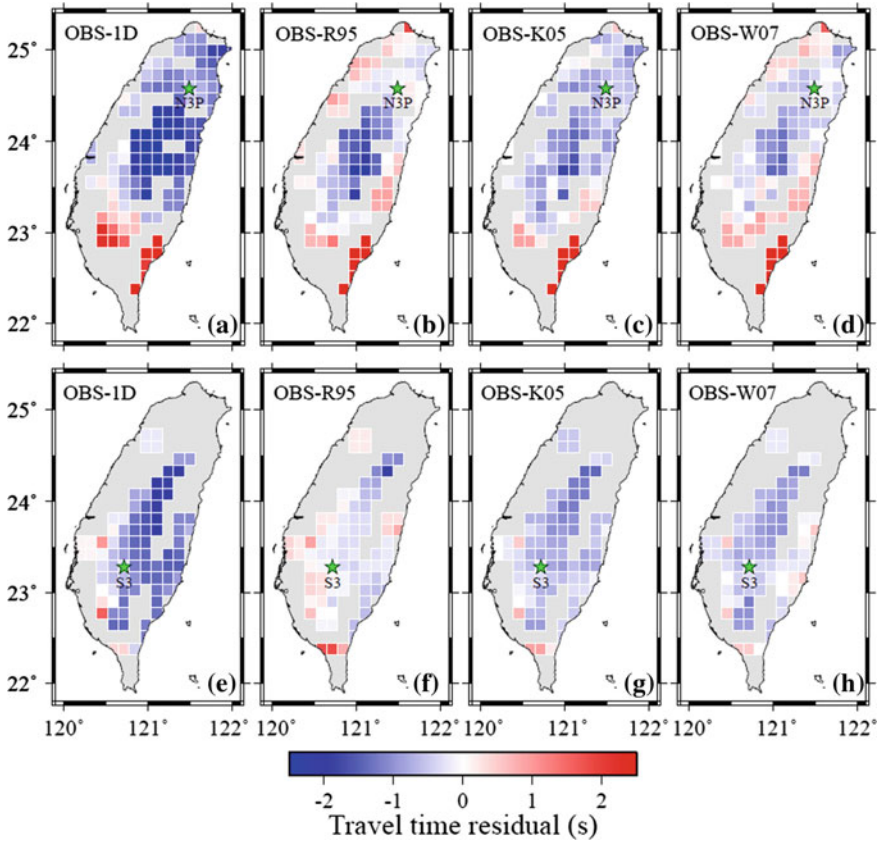


Fig. 2.12 Travel time residuals for Shots N3P (a–d) and S3 (e–h) obtained by subtracting individually the model-predicted first-arrival times from the observed ones. Stars indicate the locations of the shots. The entire island is divided into $0.13^\circ \times 0.13^\circ$ squares, with each square having an overlap with each of the adjacent square, and the width of each overlap is 1/5 of side of the square. The residual in each square is estimated by averaging all the residuals obtained at the stations within the square. The color scheme assigns a cool (warm) color for an average negative (positive) residual within a given square, implying that on average a P wave arriving within the square would take a shorter (longer) time than the model-predicted times; that is, it actually travels with a higher (lower) P-wave speed from the shot to the specific square than that suggested by the four models. Squares with no observed first-arrival times are masked out with gray color. Reprinted from Lin et al. (2011) with permission Bulletin of the Seismological Society of America

residuals from the structure under the tectonic units, WF and CP, we separate the dataset into two groups: one for the first-arrival picks associated with P waves only traversing WF and CP, and the other for the remaining picks. The statistical distributions of the residuals for the two groups are plotted in Fig. 2.14b, c. In Table 2.2, we also compare the statistical values of the mean, root-mean-square (RMS), variance (VAR), and skewness of the four models for the three sample sets with different path combinations as in Fig. 2.14a–c.

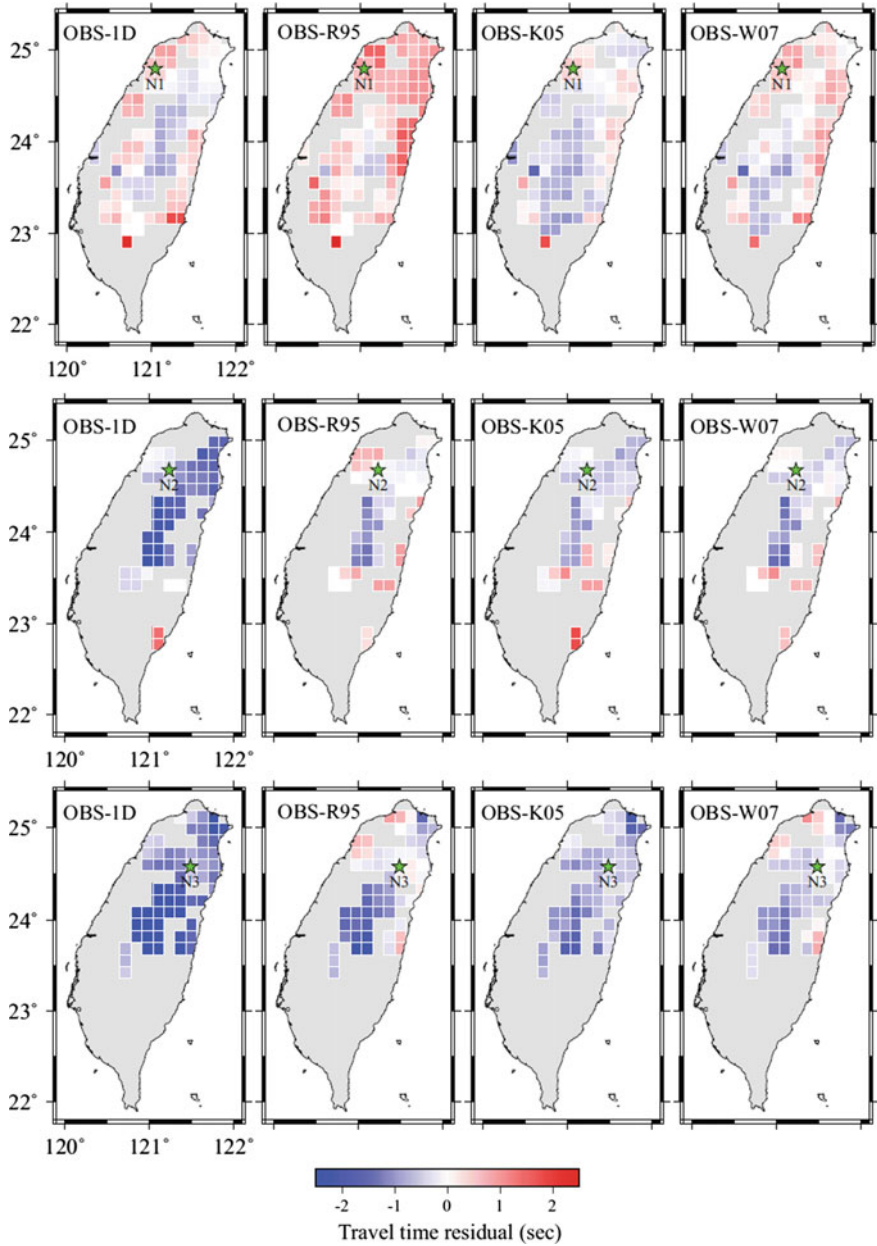


Fig. 2.13 Travel time residuals of the observed first-arrival times relative to the model predictions for Shots N1, N2, N3, N3P, N4, S1, S2, S3, S3P and S4. Stars indicate the shot locations. Plots for Shots N3P and S3 are the same as in Fig. 2.12. Reprinted from Lin et al. (2011) with permission Bulletin of the Seismological Society of America

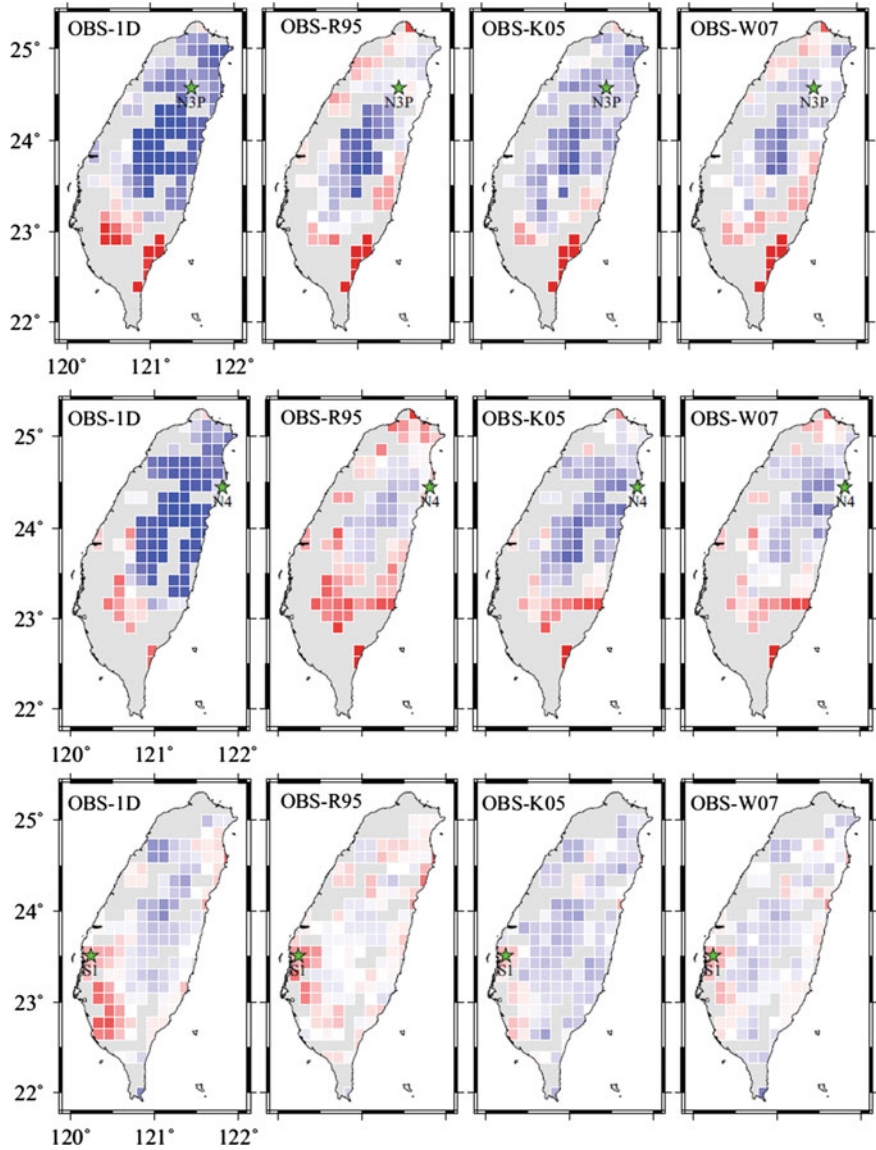


Fig. 2.13 (continued)

The 1D model represents the average velocity structure in the Taiwan region. Even though the resulting travel time residuals have the largest mean (negative), variance, and RMS values among all the four models, their distributions are the most symmetric with the smallest skewness values. The large negative spike near -2 s for the 1D model (black lines in Fig. 2.14a, c) is mostly due to the fast anomaly at

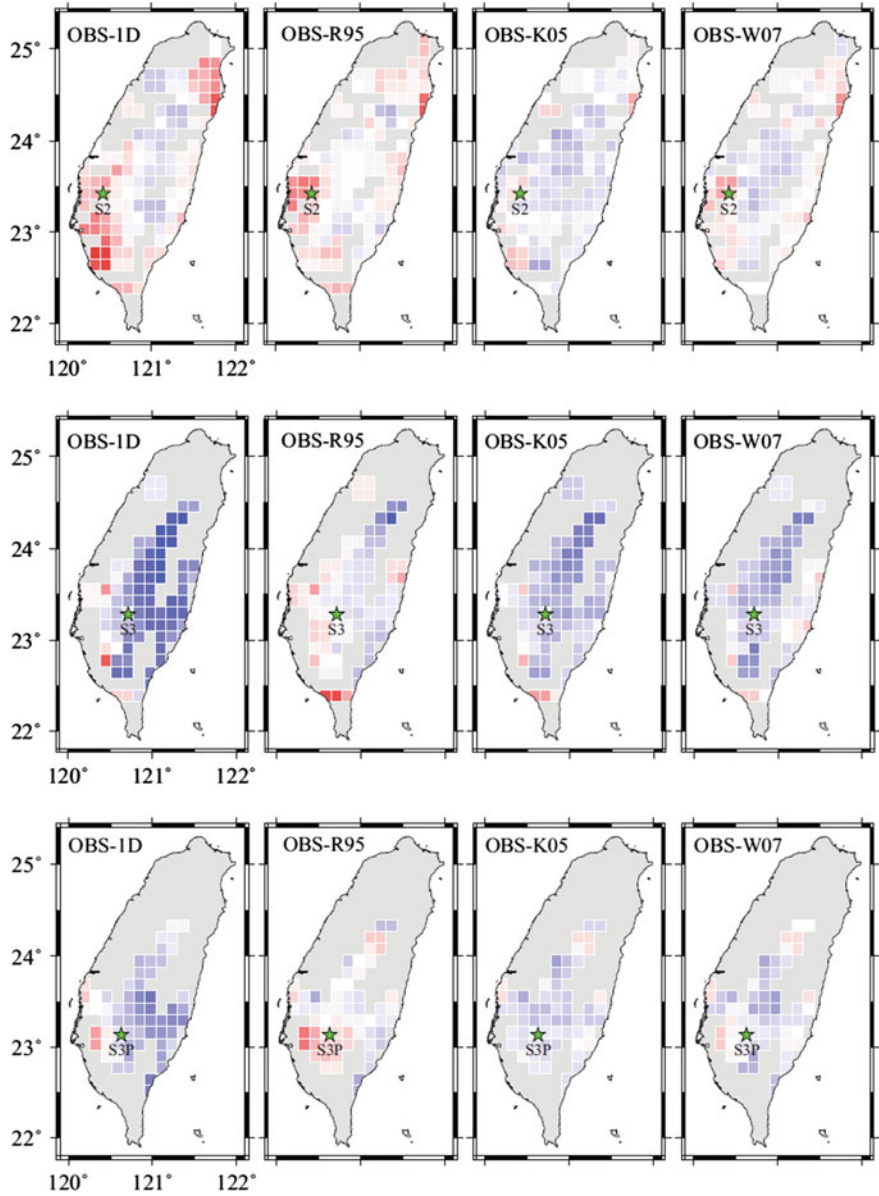


Fig. 2.13 (continued)

relatively shallow depth under the Central Range, which can also be observed in Fig. 2.12a, e. Since the residual distributions for the whole dataset and those excluding the paths through WF and CP are almost indistinguishable, we thus discuss the results from these two sets of the residuals together (see Cases a and c in

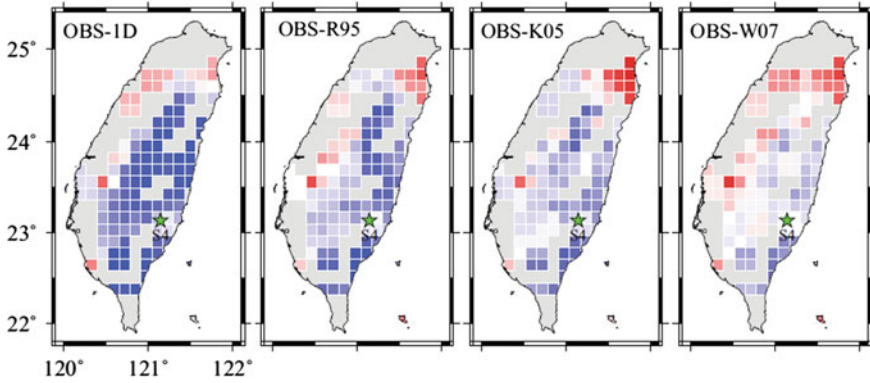


Fig. 2.13 (continued)

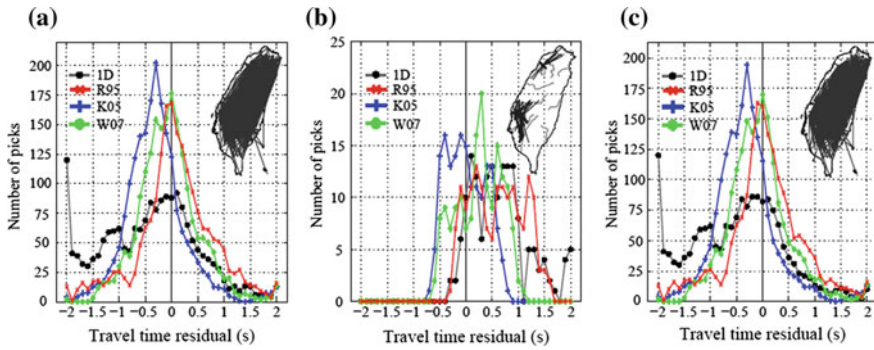


Fig. 2.14 Statistical distributions of travel time residuals for the 1D model (*gray line*) and the 3D models R95 (*red*), K05 (*blue*) and W07 (*green*). The three panels correspond to the residual distributions **a** from all first-arrival time picks; **b** from the picks with propagation paths (*black lines* in the inset map) only traversing the shallow depths under the western foothills and coastal plain; and **c** from all picks except for those in (**b**). In all three panels, the number of picks for a specific residual value is counted from the total number of picks whose residuals are within a ± 0.1 s bin around the given residual value. Inset maps illustrate the corresponding ray path distributions. In **a** and **c**, the large negative spike near -2 s for the 1D model (*black lines*) is mostly due to the fast anomaly at relatively shallow depth under the Central Range, which can also be observed in Fig. 2.12a and e. Reprinted from Lin et al. (2011) with permission Bulletin of the Seismological Society of America

Fig. 2.14 and Table 2.2). It is evident that the residuals of Models R95 and W07 have mean values very close to zero and display symmetric distributions. This suggests that the resolved velocity perturbations are less biased toward either the positive (fast) or negative (slow) anomaly. The means of the residuals for the other two models are shifted to negative values, implying that on average they are too slow, particularly for Model K05 which is the slowest among the four models. The spreads or variances of the residuals for the 3D models are clearly smaller than that

Table 2.2 Statistics of residuals for three types of paths in the four models

Case		Statistics	1D	R95	K05	W07
(a)	Picks for all paths	Mean (s)	−0.53	0.08	−0.27	−0.03
		RMS (s)	1.16	0.79	0.75	0.66
		VAR (s^2)	1.07	0.62	0.49	0.44
		Skewness	−0.01	0.02	2.29	1.24
(b)	Picks for paths traversing WF and CP only	Mean (s)	0.66	0.59	0.01	0.24
		RMS (s)	0.86	0.77	0.37	0.49
		VAR (s^2)	0.30	0.24	0.14	0.18
		Skewness	0.68	0.05	0.20	−0.21
(c)	Picks for all paths except for those in (b)	Mean (s)	−0.60	0.05	−0.29	−0.05
		RMS (s)	1.18	0.79	0.77	0.67
		VAR (s^2)	1.03	0.62	0.51	0.45
		Skewness	0.03	0.09	2.38	1.32

for the 1D model, so are the RMS values. As such, the 3D models provide a much improved fit to the observed travel times when lateral velocity heterogeneities are properly taken into account. The residuals for Model W07 yield the smallest mean, variance and RMS values, about 12% smaller than those for R95 and K05, indicating that it has the best overall performance in predicting observed P-wave travel times.

A positive skewness value indicates that the residual distribution has a longer tail to the right of the mean than to its left, and vice versa. Both the skewness values of the residuals for Models K05 and W07 are significantly greater than zero. Besides using the CWBSN data, these two models employed more data recorded by the dense but highly unevenly-distributed stations from temporary seismic arrays and the strong-motion network, respectively. Although more data constraints in K05 and W07 yield a better fits to the observed travel times than Models R95 and 1D, such non-uniform path coverage may cause a skewed residual distribution.

While considering the residuals from the P waves only traversing WF and CP (Case b in Table 2.2 and Fig. 2.14), the residuals of Model K05 instead lead to the smallest RMS and variance, and has the mean closest to zero, indicating that the shallow velocity structures under WF and CP are best represented by those revealed in Model K05. We note here that the numbers of picks in Case (b) are far fewer than those in Cases (a) and (c). More data may be needed to make the inference from Case (b) statistically significant.

2.5 Summary

More than 6000 first-arrival times have been carefully and manually picked from seismic records of an active-source experiment in the TAIGER project, with an accuracy of ± 0.01 s or less for most of the measurements. This ground-truth dataset

of P-wave travel times provides the most reliable criterion against which all tomography models in the Taiwan region can and should be tested.

The observed first-arrival times reveal our long-held understanding of lateral structural variations in the crust and uppermost mantle beneath Taiwan. At shallow depth, P-wave speed is higher under the Central Range than the surrounding regions, but the pattern is reversed at greater depth. Furthermore, regions of strong low-velocity anomalies exist at shallow depth in Chiayi and Kaohsiung regions. Comparisons of the differences between the observed and model-predicted first-arrival times demonstrate that the 3D tomography models R95, K05 and W07 all yield smaller travel time residuals than the 1D model, indicating significant improvements of the 3D models over the 1D model. Despite the fact that overall the 3D models predicted the correct distributions of high and low wave-speed regions, they do actually underestimate the amplitudes of lateral velocity heterogeneities, leaving plenty of rooms for further improvement in the 3D structural images beneath Taiwan. Statistical analysis of the residuals calculated by subtracting the model-predicted first-arrival times from the observed ones shows that the 3D model W07 (Wu et al. 2007) has a mean closest to zero, a RMS residual value about 12% smaller than the other 3D models R95 and K05, and thus provides the best fit to the ground-truth travel times. Among the three 3D models, Models R95 and W07 yield the most symmetric residual distribution with the mean closest to zero, while the residual distributions for Model K05 has negative mean and positive skewness, implying that the velocity structures resolved in Model K05 is on average biased to be too slow. Considering a small sample of travel time residuals obtained from the P waves only traversing the western foothills and coastal plain, the statistical results suggest that the residuals for Model K05 lead to the smallest RMS and variance values, and provide potentially the best fit to the observed first-arrival times in the western foothills and coastal plain regions. In the next chapter, we utilize the same dataset of the accurate first-arrival times from the active-source experiment of the TAIGER project to investigate the isotropic velocity structure in the crust beneath Taiwan.

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