

Temporal changes of seismic velocity associated with the 2006 Mw 6.1 Taitung earthquake in an arc-continent collision suture zone

Tai-Chieh Yu¹ and Shu-Huei Hung¹

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[1] To detect temporal changes of elastic properties associated with the 2006 Mw 6.1 Taitung earthquake in south-east Taiwan, whereby the collision between the Luzon arc riding on the Philippine Sea plate and the Asian margin is taking place, we construct the Green's functions from auto- and cross-correlation function (ACF and CCF) of continuous ambient noise between stations. Time lapse changes in the retrieved coda arrivals are estimated for monitoring spatio-temporal variations of seismic velocities around the ruptured fault zones. To the south of the main shock epicenter where the earthquake may have ruptured along two perpendicularly-intersecting fault planes resulting in intense coseismic slip and widely-dispersed aftershocks, the ACFs (2–8 Hz) at nearby stations reveal a large, sudden velocity drop of over 1% after the event occurrence. The CCFs (0.1–0.9 Hz) also show moderate reduction about 0.1% for the interstation paths traveling through the southeast quadrant of the focal sphere which has experienced the maximum peak ground acceleration and dilatational strain change. The intense seismic shaking combined with the rupture-induced damage near the junction of the two faults is the most plausible cause for such localized, but significant coseismic velocity reduction. The response of groundwater levels to precipitation is in-phase correlated with velocity variations over 3 years of investigation. Unlike the postseismic surface displacements gradually relaxed, the velocity remained slow until October 2006 due to the typhoon-induced heavy rains between May and September. **Citation:** Yu, T.-C., and S.-H. Hung (2012), Temporal changes of seismic velocity associated with the 2006 Mw 6.1 Taitung earthquake in an arc-continent collision suture zone, *Geophys. Res. Lett.*, 39, L12307, doi:10.1029/2012GL051970.

1. Introduction

[2] In recent years it has been well documented that the empirical Green's function (EGF) for the impulse response of the Earth can be retrieved from cross correlation functions (CCFs) of earthquake-generated coda waves [Campillo and Paul, 2003] or of continuously recorded ambient noise between two stations [Shapiro and Campillo, 2004]. The property holds when a diffuse wave field is achieved by scattering from random heterogeneity and/or when the

distribution of noise sources is isotropic. As such, seismic velocity changes induced by earthquake and volcanic activities or seasonal and hydrological fluctuations can be detected by the time-lapse phase shifts of the extracted EGFs [Sens-Schönfelder and Wegler, 2006; Stehly et al., 2007; Wegler and Sens-Schönfelder, 2007; Brenguier et al., 2008a, 2008b].

[3] Because no active seismic source is needed for ambient noise cross correlation, the extracted EGFs became widely used in monitoring seismic velocity changes that strongly depend on rock mechanical properties and stress variations in seismogenic zones. A sharp velocity drop was commonly observed immediately after earthquakes in various tectonic regimes and occasionally succeeded by gradual recovery [Brenguier et al., 2008b; Wegler et al., 2009; Chen et al., 2010]. Such time-lapse variations have been attributed to coseismic dilatational strain and postseismic stress relaxation [Brenguier et al., 2008b; Xu and Song, 2009], fault zone damage and healing [Li et al., 2003; Peng and Ben-Zion, 2006], and nonlinear site response under strong ground shaking [Rubinstein and Beroza, 2005].

[4] In reality, the wave field is not fully diffuse and noise distribution is strongly azimuthally-dependent. These would result in amplitude asymmetries between the acausal and causal parts of the CCFs and phase errors in the extracted ballistic waves [Stehly et al., 2006; Yang and Ritzwoller, 2008]. Though the resulting velocity bias may be negligible in noise-based surface wave tomography [Tsai, 2009], the apparent phase shift due to a time-varying, nonisotropic noise field can be falsely attributed to the change in subsurface elastic properties. Given the commonly uneven distribution of noise sources, such biased effect can be mitigated by using the coda waves which have much smaller phase errors owing to long range correlation of more diffuse, multiply-scattered wave fields [Froment et al., 2010]. With increasing lapse time, the later coda arrivals which scatter more times and travel longer paths would accrue more observable phase shifts for reliably detecting small temporal velocity changes.

[5] With greatly increasing interest in understanding both time- and space-varying mechanical properties and stress conditions in seismogenic zones, we used coda waves extracted from ambient noise cross correlations, a recently-developed approach to monitor seismic velocity changes associated with the 2006 Mw 6.1 Taitung earthquake in an arc-continent collision boundary zone. Compared with coseismic surface displacement from GPS and strong-motion data, peak ground acceleration (PGA), static volumetric strain, and slip distribution on the ruptured fault planes, we deduce the plausible mechanisms that cause the temporal and

¹Department of Geosciences, National Taiwan University, Taipei, Taiwan.

Corresponding author: S.-H. Hung, Department of Geosciences, National Taiwan University, No. 1, Sec. 4, Roosevelt Rd., Taipei 10617, Taiwan. (shung@ntu.edu.tw)

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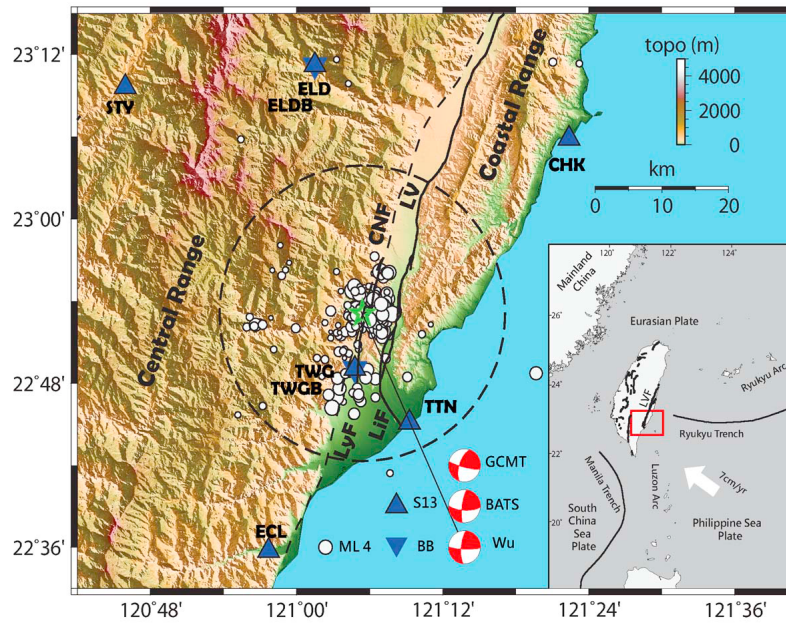


Figure 1. Map showing the topographic features and major faults in the study region. Abbreviated names for the faults are: CNF, Central Range Fault; LVF, Longitudinal Valley Fault; LyF, Luyeh Fault; LiF, Lichi Fault. Inset map shows the plate configuration around Taiwan, where the LVF is marked as the collision suture zone between the Luzon arc and Eurasian continent. The star and circles denote the epicenter of the Mw 6.1 Taitung earthquake with a focal depth of 10 km and aftershocks within the next 8 days [Wu *et al.*, 2006], with the size proportional to the Richter magnitude. The centroid moment tensor from the global CMT (GCMT) and Taiwan BATS solutions and the first-motion focal sphere all indicate a NNE-striking, left-lateral strike-slip faulting mechanism. The blue triangles and inverted triangles represent the short-period (S13) and broadband (BB) stations from CWBSN and BATS, respectively. The dashed line encircles the rupture zone with a radius of 20 km.

spatial distribution of relative velocity perturbations before and after the earthquake. We also address the potential impact of the seasonal precipitation on groundwater levels and subsequent changes of subsurface velocities over three years of monitoring.

2. Study Area, Data and Method

[6] Eastern Taiwan is located on one of the most earthquake-prone seismic zones in the world, as a result of oblique collision between the northern Luzon arc on the Philippine Sea plate and the eastern margin of the Asian continent [Teng, 1990]. The plate suture zone lies inside the 150-km long, NNE-trending Longitudinal Valley (LV) bounded by the Central Range Fault (CNF) on the west and the Longitudinal Valley Fault (LVF) on the east. The LVF branches into several fault strands at its southern terminus, where the Luyeh Fault (LyF) and Lichi fault (LiF) are bounded on both sides of the Peinanshan massif [Lee *et al.*, 1998; Yu and Kuo, 2001] (Figure 1).

[7] On April 1, 2006, a Mw 6.1 shallow earthquake with a predominant strike-slip focal mechanism struck between the eastern edge of the Central Range (CR) and southwestern part of the LV near Taitung County [Wu *et al.*, 2006] (Figure 1). From the aftershock distribution and finite-fault source inversion, the rupture area of the main shock is about 20 km in length and 20 km in depth [Wu *et al.*, 2006; Mozziconacci *et al.*, 2012]. We thus select stations located within a radius of 30 km from the epicenter which have continuously recorded seismic data for at least two months

before and after the main shock. A total of 6 short-period and 2 collocated broadband stations operated by the CWB (Central Weather Bureau) and BATS (Broadband Array in Taiwan for Seismology), meet the selection criteria for extracting time-varying EGFs from auto- and cross-correlation of ambient seismic noise (Figure 1).

[8] We first divide continuous vertical-component raw seismograms recorded over almost three years from August 2005 to June 2008 into one-day segments and remove the mean, trend, and instrument response of each seismic trace segment. To suppress predominant earthquake-generated signals prior to computing a cross-correlation function (CCF) between two stations, we perform prewhitening of the amplitude spectra of obtained ground velocity seismograms, followed by band-pass filtering between 0.1 and 0.9 Hz to extract the signals of ambient noise in the secondary microseism band peaked around 4 s in Taiwan [Chen *et al.*, 2011] and then one-bit normalization to keep only phase information [Stehly *et al.*, 2006]. Prior to computing an auto-correlation function at individual stations, we filtered raw velocity seismograms with a high-frequency, 2–8 Hz passband and flattened narrow spectral peaks in the filtered seismic records due to industrial or site resonance. Time-domain normalization is then made by clipping the amplitudes larger than the standard deviation of the background noise in the quiet days [Wegler and Sens-Schönfelder, 2007] (see details of data processing in the auxiliary material).¹

¹Auxiliary materials are available in the HTML. doi:10.1029/2012GL051970.

[9] For a medium experiencing a homogeneous velocity decrease, the time delay $\delta\tau$ of a short-term, current Green's function (CGF) relative to the long-term, time-averaged reference Green's function (RGF) would increase linearly with the lapse time τ of the CGF. The slope of the regression line between $\delta\tau$ and τ through the origin is equal to the negative of the average fractional velocity perturbation $\delta v/v$, i.e., $\delta\tau = -\tau \times (\delta v/v)$. The RGF is constructed by stacking all the CCFs or ACFs over 3 years. In order to obtain stable and reliable estimates of small temporal perturbations in seismic velocities, stacks of one-day ACFs or CCFs are generally needed to improve the emergence of coherent coda arrivals. While simultaneously retaining the optimal time resolution, we examine the stability versus the length of stacked time window and choose 5- and 35-day sliding windows shifted by one day to obtain the short-term ACFs and CCFs, respectively (Figure S1 in Text S1). Figure S2 in Text S1 illustrates temporal variations in the waveforms of the short-term EGFs constructed from the 5-day stacked ACFs at station TWG and 35-day stacked CCFs between station TTN and TWG. With shorter stacking lengths used, the resulting coseismic velocity changes remain significant in spite that the estimated arrival time shifts become more scattered with larger uncertainties (Figure S3 in Text S1). Both the moving window cross spectral method (MWCSM) [Poupinet *et al.*, 1984] and stretch technique [Wegler *et al.*, 2009] are employed for estimation of relative time shifts between CGFs and RGF which yield very similar results (Figures S4 and S5 in Text S1).

3. Results

[10] The 5-day stacked ACFs in the lapse times between 2 and 12 s which mainly comprise scattered coda energy are used to measure their arrival time shifts relative to the corresponding RGF. In spite that no data is available during the period of March 28 to April 13, 2006 when the Taitung earthquake struck, we still observe clear phase delays at 2–12 s lapse times two weeks after the earthquake.

[11] Figure 2a shows temporal velocity variations determined from the measured time shifts between the 5-day stacked ACFs (CGFs) and 3-year average ACF (RGF) at short-period TWG, TTN, and broadband TWGB stations using the stretch technique. It is equivalent to find the optimal time-stretching trial for the RGF which yields the maximum waveform correlation coefficient (CC) between the CGFs and stretched RGF also shown in Figure 2a. The collocated TWG and TWGB yield similar temporal variations which reveal a prominent sudden decrease in seismic velocity perturbation of about -1.6% shortly after the earthquake. It is also noticed that the abruptly reduced velocity remains low until October 2006; afterwards it starts to gradually increase to the pre-earthquake state. For station TTN about 20 km southeast of the epicenter, the coseismic velocity reduction of -0.27% is much less significant but still discernible above the standard deviation. For the rest of farther stations, the extracted coda arrivals yield no statistically significant velocity perturbation larger than the standard deviation and detection threshold of 0.05% .

[12] For the CCFs, we select the causal and acausal signals in the time window from 6 s after the maximum amplitude arrivals to 100 s to estimate time-lapse changes of relative velocity perturbations by the MCSWM. For the station pairs

traveling through the southeast (SE) and northwest (NW) quadrants of the focal sphere separated by the fault plane and auxiliary plane of the Taitung earthquake, the obtained velocity perturbations all indicate sudden coseismic drops, though, except for TTN-TWG, the reduction levels for the other three pairs with longer interstation distances fall just slightly above the detection uncertainty (Figure 2b). For the rest of the pairs that connect one station much farther from the epicenter, the estimated velocity perturbations are generally insignificant with large uncertainties or below the detection threshold of $\pm 0.05\%$. The overall distribution of the detected coseismic velocity changes suggests that the subsurface disturbance mostly occurred in a small area around the south and southeast portions of the main shock rupture zone.

4. Discussion and Conclusion

[13] To examine which part of the scattered energy makes a predominant contribution to temporal velocity changes at TWG, we measure the lapse-time dependent phase shifts by correlating 5-day stacked ACFs with the RGF in every consecutive 2 s time window shifted by 1 s. The coda at 2–5 s yields the largest arrival time delay after the earthquake (Figure 3a). In mid-May of 2006, the first typhoon (Chanchu) which has impacted Taiwan brought heavy rains in southeast Taiwan and the coda at 5–12 s began to experience a slight delay. During the annual typhoon season generally accompanied by high precipitation between mid-July and September, the 5–12 s coda primarily contributes to the mean arrival time delay. The coseismically reduced velocity remained persistently low during this extended rainy period, not recovered gradually as the postseismic relaxation of the surface displacements along the NNE-striking LV fault measured by the GPS site TTUN near TWG (Figure 3b).

[14] It is noticed that the monthly average groundwater level (GWL) exhibits an annual periodic variation with the precipitation rate, but the response of the GWL conspicuously lags behind for several weeks (Figure 3b). During high rainfall episodes in the summer, the excessive rainwater infiltrates through unsaturated layers and then raises the GWL. Consequently, the change in the water table depth may affect the subsurface velocities, as manifested by the peak arrival-time delay of the coda which initially appears in the lapse-time window of 2–5 s and shifts to 5–12 s after mid-July [Sens-Schönfelder and Wegler, 2006] and the strong in-phase correlation between velocity changes and GWL fluctuations (Figure 3b).

[15] To investigate what mechanisms essentially cause coseismic velocity drops, we demarcate the spatial extent of the impacted areas bounded by the scattering regime of the delayed coda waves. Under crude approximations of ACFs as singly backscattered shear waves with the propagation speed v emitted and received at common source and receiver, the coda arriving at lapse time t would encapsulate medium property information within a spherical shell of radius $vt/2$ centered at the station [Aki and Chouet, 1975]. Taken the shear wave speed about 1.5–2.0 km/s at shallow depth beneath the southern LV [Huang *et al.*, 2012], the region susceptible to velocity reduction is bounded by concentric spherical shells between radius of 1.5 and 5 km centered at station TWG. Even though the later coda in the CCFs up to 100 s results in a much broader single-scattering

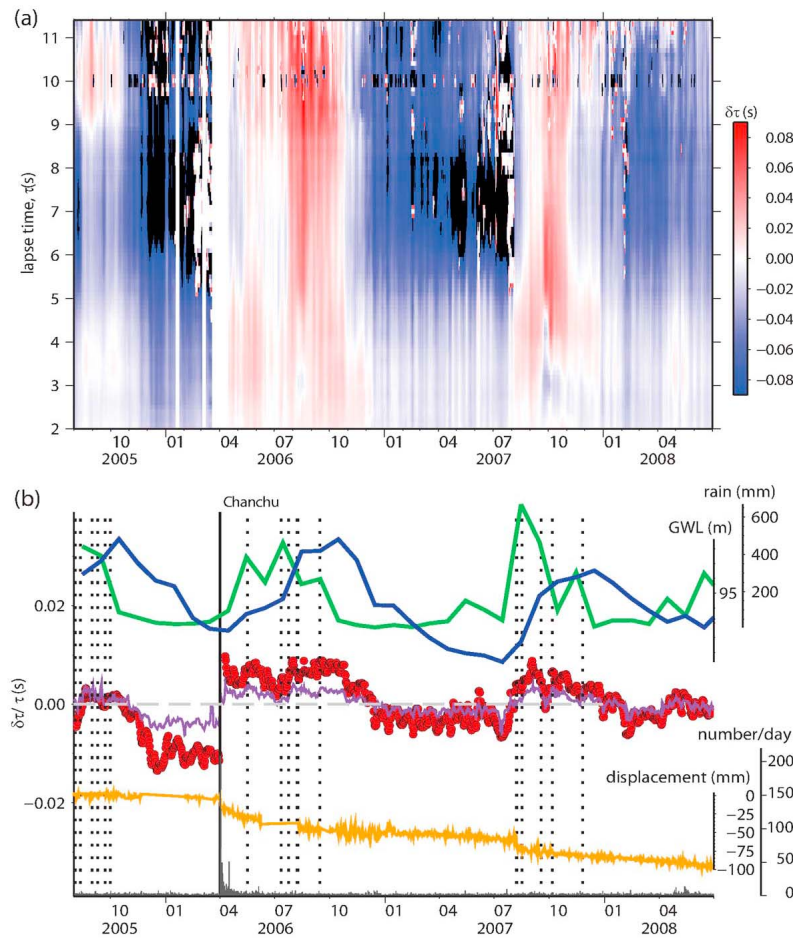


Figure 3. (a) Relative arrival-time shifts ($\delta\tau/\tau$) of the coda measured in 2-s lapse-time window of the ACFs shifted by every 1 s at TWG. Red and blue colors represent the travel time delays and advances of 5-day stacked ACFs relative to the RGF. (b) Comparison of temporal changes in the mean arrival-time shifts of the 2–12 s ACFs at TWG (red dot) and the time shifts averaged over all the station pairs (purple curve) with monthly average GWL (blue curve), precipitation rate (green curve), surface displacement parallel to the N18°E striking fault (orange curve), and seismicity rate (histogram) over 3 years. Dashed lines mark the dates of the typhoons that affected Taiwan in 3 years. The seismicity rate is computed by ZMAP software using the events within a radius of 20 km from the main shock location.

[16] Based on an elastic half-space dislocation model [Okada, 1992] and the slips on the two segments of NNE-trending planar fault planes for the Taitung earthquake [Wu *et al.*, 2006], we compute coseismic static volumetric strain in the crust with uniform Young's and shear modulus using Coulomb 3.0 [Lin and Stein, 2004; Toda *et al.*, 2005] (Figure 4a). Dilatational strain change at 5 km depth occurs in the SE and NW quadrants of the main shock focal sphere. Some coda arrivals from the CCFs sampling the structure within the scattering spheroidal shells embedded in these two quadrants reveal clear phase delays, consistent with the anticipated velocity decrease in the dilatation regions. While the ACFs at TWG/TWGB lying close to the fault trace in the transition between compression and extension yield much larger velocity drops after the earthquake, those at TTN and the CCFs between TTN and TWG located inside the dilatation area show much less reduction. An alternative mechanism other than volumetric strain change is thus required to explain the largely reduced velocity.

[17] Nonlinear ground response in soil and sediment layers has been proposed to explain why shear wave speed

commonly decreases but rarely increases during the strong shaking of large earthquakes [Rubinstein and Beroza, 2005]. Dense strong-motion network of CWB recorded peak ground acceleration (PGA) greater than 0.4 g in the Taitung plain, where around midway between TWG and TTN was exposed to the most intense shaking over 0.6 g (Figure 4b and Figure S6 in Text S1). The coda arrivals in the ACFs at TWG and CCFs between TTN and TWG all appear to scatter through this region and reveal the most significant velocity reduction. This suggests that nonlinear site response would have lowered the shear strength at shallow depths. While TWG is situated inland on a site of hard meta-sandstone and TTN near the coast on the deposits of unconsolidated rocks, the maximum PGA values recorded nearest to the two stations are comparable, 0.45 g and 0.57 g, respectively (Table S1 in Text S1), but the velocity drop derived from the ACFs at TWG is as much as 5 times greater than that from the CCFs between TTN and TWG. As the two largest PGA values lie at the periphery and outside of the scattering region for the ACFs at TWG as delineated by a spherical shell of radius 5 km centered at TWG (Figure 4),

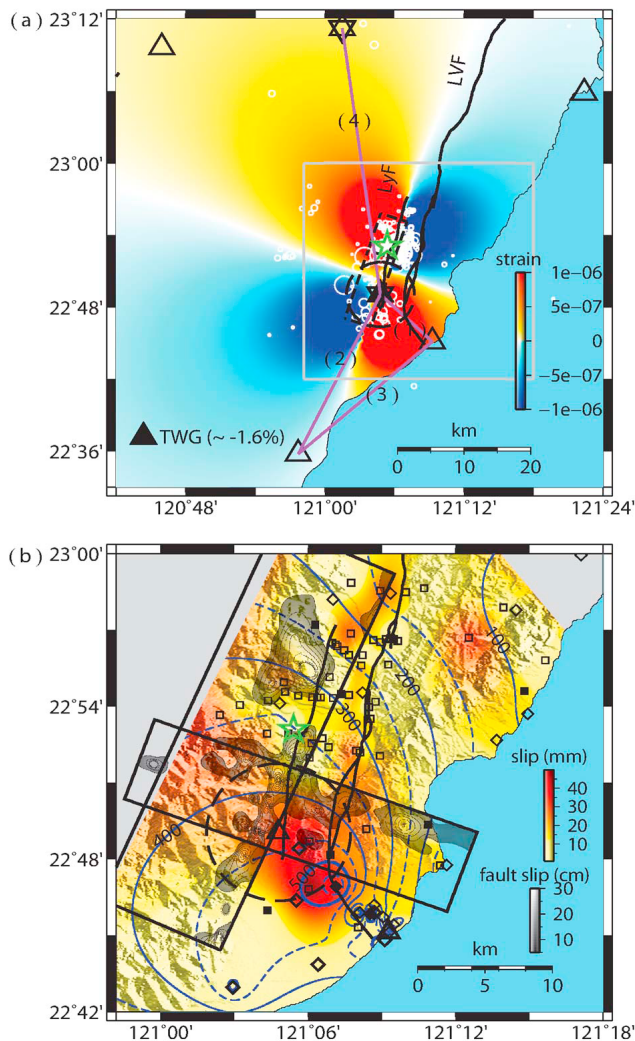


Figure 4. (a) Static volumetric strain changes at 5-km depth induced by the slip along two NNE-striking fault segments [Wu *et al.*, 2006]. The black dashed lines delineate the fault slip plane of the Taitung earthquake projected on the surface. The epicenter of the main shock and aftershocks in the next 8 days are shown respectively by the star and white circles with the size inversely proportional to the focal depth. The purple lines are the interstation paths that experience coseismic velocity drops. The dashed circle with a radius of 5 km bounds the scattering region of the coda at lapse time 5 s from the ACFs at TWG (black triangle). (b) Lateral variations of coseismic surface slip and peak ground acceleration (PGA) in the region outlined by the grey lines in (a). Colored images show surface displacements measured from the 52 campaign-mode (open squares) and 7 continuous GPS sites (solid squares) [Chen *et al.*, 2009] and interpolated with minimum curvatures. The PGA recorded by dense strong motion network (diamonds) is contoured and annotated at an interval of 50 and 100 gal, respectively, with the peaked values occurring at the stations denoted by solid diamonds. The rectangular boxes delineate the surface projection of the two perpendicularly-intersecting fault planes with gray shaded areas displaying the slips greater than 5 cm from the finite-fault inversion [Mozziconacci *et al.*, 2012].

it implies that some additional cause may contribute to the large velocity reduction localized near TWG.

[18] Even though no surface rupture is found around the fault zone, coseismic surface displacement measured by GPS and leveling shows that to the immediate east of TWG, about 10 km southeast of the epicenter has the maximum vertical offset of ~ 100 mm as well as significant horizontal shortening and left-lateral motion across the NNE-SSW striking rupture fault [Chen *et al.*, 2009] (Figure 4b). Lee *et al.* [1998] combined geodetic trilateration data and field survey of geological and morphological features to conclude that there is an E-W trending, subsurface reverse fault cutting across the Peinanshan massif. A finite-fault slip model from joint inversion of teleseismic, strong-motion, and geodetic data further demonstrates that the Taitung earthquake initially ruptured along a west-dipping, NNE-striking listric fault; shortly after that, an early afterslip was activated along an ENE-striking, south-dipping fault plane [Mozziconacci *et al.*, 2012]. The patches of slip concentration at the junction of the two causative faults in 0–10 km depths lie inside the scattering region for the 2–5 s ACFs at TWG, where a group of aftershocks is dispersely distributed at depths less than 10 km (Figure 4b). In addition that the amplification of ground shaking may lower the shear velocity in the shallow layer, the rupture induced damage near TWG at the intersecting fault zones can conceivably further reduce the velocity to a greater extent.

[19] To conclude, we use late coda arrivals from the correlation of anisotropic noise field to precisely monitor temporal velocity perturbations induced by the Taitung earthquake that occurred in the arc-continent collision suture zone of SE Taiwan with predominantly strike-slip motion. The fault zone damage along with the following typhoon rainy season mainly caused the coseismically reduced velocity to remain slow for several months. Annual periodic variations in seismic velocities are closely linked to the GWL fluctuations modulated by seasonal rainfall and typhoon activity in Taiwan.

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