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Strong near-surface seismic anisotropy of Taiwan revealed by coda interferometry

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ABSTRACT

We report the near-surface (<400 m) primary wave velocity (V_p), shear wave velocity (V_s), V_p/V_s ratio, Poisson's ratio and V_s anisotropy of Taiwan by applying seismic coda interferometry to 34 borehole-surface station pairs. We find clear characteristic $\cos 2\theta$ dependence of V_s in all the determinations, and about half of the amplitudes of anisotropy are larger than 10%, with the largest amplitudes up to 34%. The patterns of anisotropy fall into two categories, OPA (Orogeny-Parallel Anisotropy) and SAA (Stress-Aligned Anisotropy). Both types of anisotropy fit well the local geological fabrics and/or the ambient stress, and show strong correlation with the Poisson's ratios at the borehole sites. With these new findings and reported tomographic results, we infer that the SAA are likely confined to the uppermost portion of the crust, in particular to the fluid-saturated late-Quaternary deposits. The strong near-surface anisotropy also implies that delay times contributed by the shallow crust might have been underestimated in studies of shear-wave splitting measurements using the direct arrivals of earthquake waves.

1. Introduction

Seismic anisotropy of the Earth interior has been extensively studied in the past decades, ranging from the inner-core, core-mantle boundary, uppermost mantle to the crust, and the results have provided important constraints to the Earth structure, in complement to that provided by the variations of isotropic velocity (e.g., Montagner and Tanimoto, 1990; Tanimoto, 1991; Silver, 1996; Gung et al., 2003; Panning and Romanowicz, 2004; Deuss et al., 2010; Huang et al., 2015). Interestingly, but not surprisingly, the near-surface (∼few hundred meters in depth) seismic anisotropy is much less explored because the commonly applied methods, such as the surface wave tomography, receiver functions and shear-wave splitting (SWS) measurement using earthquake data, do not have the adequate fine resolution for the near-surface seismic structure. Recently, it is reported that the near-surface seismic anisotropy can be well resolved by applying ambient noise tomography to a small area with dense seismic array (Lin et al., 2013), however, the array density required for the extraction of high frequency surface waves is a demanding task for larger scale applications.

In this study, we aim to better understand the near-surface seismic anisotropy of Taiwan. The island of Taiwan is located along the active arc-continent collision boundary between the Philippine Sea Plate (PSP) and the Eurasian Plate (EP), and is known for its tectonic complexities both in the subsurface plate interactions and mountain building processes between EP and PSP and the surface geological features (Fig. 1) (e.g., Angelier, 1990; Teng, 1996; Ho, 1997; Wu et al., 2014). There are several previous studies of anisotropy in Taiwan, either by SWS measurements using teleseismic events (Rau et al., 2000; Huang et al., 2006; Kuo-Chen et al., 2009) or by examining the azimuthal variations of P wave arrival times using active sources (Kuo-Chen et al., 2013), which have shown that the fast directions of the seismic anisotropy are generally parallel to the trend of the mountain belts, i.e., the orogeny-parallel direction. Besides, the anisotropy with fast directions perpendicular to the mountain belt, i.e., parallel to the maximum compressional stress, in the foreland of the mountain belt has been reported by SWS studies using local shallow (<40 km) earthquakes (Chang et al., 2009). Recently, the 3-D crustal models of V_s anisotropy, constructed from noise-derived surface waves, demonstrate that the orogeny-parallel anisotropy (OPA) is confined to the upper crust; nevertheless, the general distribution of the depth-integrated anisotropy over the crust remains the OPA pattern (Huang et al., 2015).

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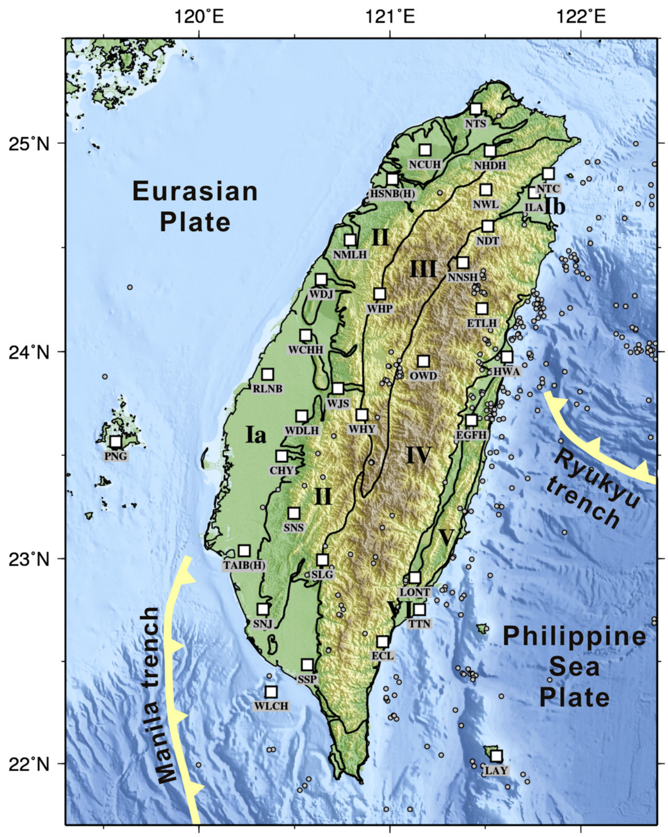

Fig. 1. The distribution of 34 borehole sites (open squares) and 398 local earthquakes (open circles) used in this study. The dark lines are boundaries of major tectonic units in Taiwan, and the indices shown in each geological unit are as follows: (I) Coastal Plains, including the Western Plain (Ia) and Ilan Plain (Ib), (II) Western Foothills, (III) Hsuehshan Range, (IV) Central Range, (V) Costal Range, and (VI) Longitudinal Valley.

While the above studies agree with the fact that the crustal anisotropy are closely linked to the main geological structures and the ambient stress field, none of them provide direct assessment to the near-surface anisotropy.

Taking advantage of the borehole seismic array recently (2011–) deployed by the Central Weather Bureau (CWB) of Taiwan and the Broadband Array in Taiwan for Seismology (BATS), we are able to apply the seismic interferometry technique to the vertical station pairs composed of the borehole and the overhead surface stations. In addition to V_s, the V_s azimuthal anisotropy can be obtained by examining the polarization of the vertically propagating shear waves using the extracted empirical Green's functions (EGFs) (e.g., Miyazawa et al., 2008; Lewis and Gerstoft, 2012; Nakata and Snieder, 2012).

In the following, we first briefly introduce the data and method. We then present the results of the measurements, including V_p, V_s, V_p/V_s ratio and V_s azimuthal anisotropy, and discuss their associations with local geology, ambient stress field, Poisson's ratio and the SWS studies. Finally, we summarize the major findings and implications of this study. Because the methods employed here have been well-established, we present details of the method and data processing in the supplementary material, where the validation and uncertainty estimates of the measurements are also provided.

2. Data and method

Data recorded by 34 island-wide borehole seismic stations deployed by CWB and BATS are used in this study (Fig. 1). Two strong motion sensors are equipped at each borehole site, with one on the surface and the other in the subsurface near the bottom of the borehole ranging from 100 to 400 m depth. Detailed station information is given in the supplementary material (Table S1).

2.1. Orientation correction of the borehole data

Accurate orientation in sensors of the station pairs is critical to the extraction of shear wave EGFs using seismic interferometry. Since the orientation of borehole sensors is usually not as reliable as the surface one, we examined the orientation of the borehole data using the surface orientation as a reference. This can be easily done because the largest amplitude of the cross-correlation function (CCF) of the borehole-surface station pairs appears when both orientations are consistent. The results show that the orientations are significantly biased in about half of the stations, which required corrections prior to the following data processing. Details of the data processing for CCFs and the correction procedure are given in the supplementary material.

2.2. Extraction of EGFs and measurement of azimuthal anisotropy

With the vertical borehole-surface station pairs, the EGFs for the structure in between can be extracted by cross-correlating either their continuous records or earthquake coda waves, or, by applying the de-convolution method to the earthquake signals recorded by both stations (e.g., Nakata and Snieder, 2012; Mehta et al., 2007). Since the borehole depths are rather shallow ($\leq$400 m), high frequency EGFs are preferred in order to accurately determine the V_s azimuthal dependence. Thus, the earthquake-based approaches, i.e., the de-convolution and coda cross-correlation methods, are considered in this study, as the high-frequency body waves in signals excited by the local earthquakes is much stronger than those in the ambient seismic noises.

We find that EGFs derived from the above two earthquake-based methods are fairly consistent in both the estimated isotropic velocities and the pattern of V_s azimuthal anisotropy. Since both methods are potentially sensitive to the incident angles of the earthquake waves, we have conducted a series of experiments to further assess the reliability of the resulting EGFs (supplementary material). The results indicate that EGFs extracted by the de-convolution method is more sensitive to the incident angles of earthquake waves, which is understandable, as the direct waves are used in this method. We also find that, the discrepancy between the estimated velocities by coda cross-correlation and those by the de-convolution method using events with near-vertical incident angles are very small ($\sim$2%). Accordingly, we employ the coda cross-correlation method to derive the EGFs of S waves and P waves in this study.

The coda waves of 398 local earthquakes with ML > 4.0 (Fig. 1) during the time period from 2011 to 2014 are used to derive the high frequency (2–8 Hz) EGFs. To evaluate the V_s at any polarization directions, we first compute CCFs for the four combinations of horizontal components between the borehole and the surface stations, i.e., C_{NN}, C_{NE}, C_{EE}, and C_{EN}. The CCF for any given directions, θ, is then given by

$$C_{\theta\theta} = C_{NN}\cos\theta\cos\theta + C_{EN}\sin\theta\cos\theta + C_{NE}\sin\theta\cos\theta + C_{EE}\sin\theta\sin\theta, \quad (1)$$

where θ is the azimuth, i.e., angle measured clockwise from the north. The anisotropy property is estimated by using the following relationship (e.g., Alford, 1986), $V_s(\theta) = V_{iso} + V_{ani}\cos 2(\theta - \varphi)$, where V_{iso} is the isotropic V_s, V_{ani} the anisotropy coefficient, and φ is the fast polarization direction (FPD). We search for the optimal parameters, V_{iso}, V_{ani} and φ based upon the least-squared fitting criteria. Once the best-fitting parameters are located, the strength of anisotropy is defined by $(V_{fast} - V_{slow})/V_{fast}$, where V_{fast} and V_{slow} are V_s evaluated at the fast and slow polarization directions respectively.