Surface Wave Group Velocity Tomography Imaging from Ambient Noise for Fujian Province and Its Adjacent Areas

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Two-month continuous waveforms of 108 broadband seismic stations in Fujian Province and its adjacent areas are used to compute noise cross-correlation function (NCF). The signal quality of NCF is improved via the application of time-frequency phase weighted stacking. The Rayleigh and Love waves group velocities between 1s–20s are measured on the symmetrical component of the NCF with the multiple filter method. More than 5,000 Rayleigh wave dispersion curves and about 4,000 Love wave dispersion curves are obtained and used to invert for group velocity maps. This data set provides about 50km resolution that is demonstrated with checkerboard tests. Considering the off great circle effect in inhomogeneous medium, the ray path is traced based on the travel time field computed with a finite difference method. The inverted group velocity maps show good correlation with the geological features in the upper and middle crust. The Fuzhou basin and Zhangzhou basin showed low velocity on the short period group velocity maps. On the long period group velocity maps, the low velocity anomaly in the high heat flow region near Zhangzhou and clear velocity contrast across the Zhenghe-Dapu faults, which suggests that the Zhenghe-Dapu fault might be a deep fault.

Key words: Fujian; Ambient noise; Surface wave group velocity; Tomography imaging

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INTRODUCTION

Fujian Province and its adjacent regions are situated along the intersection of the Pacific, Philippine and Eurasian plates and the stress field is dominated by the NW and NE direction. As the continental margin of the Eurasian plate, this region has evolved from during the multiple stages of tectonic events since the Neoproterozoic Era and several NE and NW-oriented deep faults were formed during the complex evolution (Bureau of Geological and Mineral Resources of Fujian Province, 1985). The Fujian region is divided into three tectonic units: the northwestern uplift, the southwestern depression, and the eastern volcanic fault-sag according to several geological factors (e.g. magmatism, metamorphism). Therefore, Fujian is considered as an ideal area to study the seismogenic process and geodynamics of continental margins. Numerous seismic studies based on deep seismic sounding and receiver function methods have been conducted (Liao Qilin et al., 1990; Xiong Shaobai et al., 1991; Wang Chunyong et al., 1995; Zhu Jinfang et al., 2006; Zheng Hongwei et al., 2013), providing important information for the understanding of tectonic evolution and seismogenic mechanisms in this area. Due to limited budgets, deep seismic sounding can’t provide full coverage. Studies based on passive sources are more practical, but the lack of seismicity in most areas makes it difficult to conduct local seismic tomography, whereas the receiver function study coverage is also very limited due to shortage of broadband seismic stations (Cai Huiteng et al., 2014; Ding Xueren and Wu Changjiang, 1999; Qiu Yi et al., 2013; Duan Gang, 2016). After the remarkable study by Shapiro N.M. et al. (Shapiro N.M. et al., 2004, 2005), the ambient noise tomography has been widely used in various scales seismic imaging (Yao Huajian et al., 2006; Lin Fanchi et al., 2007; Zheng Sihua et al., 2008; Yang Yingjie et al., 2008a; Fang Lihua et al., 2009; Guo Zhi et al., 2009; Li Yu et al., 2010; Zhou Yingjie et al., 2012). The noise cross-correlation function (NCF) computed with two stations’ continuous waveform is a good approximation of the Green’s function that has been approved in theoretical and experimental studies. The strongest signal on the NCF is surface wave and its dispersion curve and waveform is utilized with the surface wave tomography. With a few broadband stations in 2000s, Jin Xing et al. (2007) inverted the average group velocities of 3s–5s Rayleigh wave. Li Jun et al., (2011) exacted more than 300 Rayleigh and Love waves group velocity dispersion curves between 1s–40s by using records of 25 broadband stations from the Fujian network, and utilized this data set to invert average S-wave velocity models in crust. Liang Fuhua et al. (2012) obtained the 3s–5s lateral variation Rayleigh wave group velocity by using 69 broadband stations from Fujian Province and its adjacent regions, and found that the pattern has been related to the surface structure and geothermal anomaly distribution. Yao Shengke (2013) studied the 4s–32s Love wave group velocity maps and inverted the S-wave velocity structure based on the horizontal component recording. However, most of the previous studies are based on the early sparse broadband station network, and the resolution is limited.

Since 2012, the Fujian Earthquake Agency has conducted the “Fujian and Taiwan Strait Sea-Land Joint Invert Deep Crustal Structure” experiment, and deployed more broadband stations in the Fujian region (Fig.1), which makes it possible to improve resolution of the ambient noise tomography. In this study, we use the continuous waveform records of 108 broadband stations in Fujian Province and its adjacent areas to conduct ambient noise tomography and invert the group velocity maps of Rayleigh and Love wave between 1s–20s.
1 DATA AND METHODS

We obtained continuous waveform records of 108 three-component broadband stations in June and July, 2016 in Fujian Province and its adjacent regions (Fig. 1). The method of data processing follows the popular one by Bensen et al. (2007).

The raw data was sampled in 100Hz. They are much higher than our interest frequency band and decimated into 10Hz. To compute the tangential-tangential NCF where Love wave signal emerges, records of two horizontal components are rotated to radial and tangential directions that are defined with coordinates of two stations. Then, the continuous records are chopped into one-day long and the time- and frequency domain normalization is applied. The pass band of the frequency domain normalization is 0.05Hz—3.00Hz covering the microseism frequency band. The prepared one-day long data is used to compute daily NCFs. As demonstrated in Zeng and Thurber ’s study (2016), the time-frequency phase weighted stacking developed by Schimmel and Gallart (2007) can significantly improve the signal quality of NCF in a short time period. It also used to stack daily NCFs to get final NCF. One example is shown in Fig.2, where the virtual source is the WEZ station in the Zhejiang region. As shown in record sections, the apparent velocity of the Rayleigh wave is close to 3.2km/s indicated by dashed line, while the Love wave travels faster.

Since the symmetrical component provides higher signal-to-noise ratio, the group velocity is measured on it with the time-frequency analysis method (FTAN) based on multiple filters. Fig.3 shows the results of time-frequency analysis for KMBN and WEZ station pair. The energy is mainly concentrated in two frequency bands; 0.05Hz—0.20Hz and 0.25Hz—0.50Hz, and corresponding group velocities range from 2.5 to 5km/s. The dispersion curves are picked at the maxima on each frequency (black line in Fig.3).

In order to automatically pick the dispersion curve, we use a reference dispersion curve
Fig. 2  Record sections of vertical-vertical and tangential-tangential NCFs between WEZ and other stations
Red lines denote an apparent velocity of 3.2 km/s

Fig. 3  Diagram of time-frequency analysis of one NCF sample
Color represents energy while the black line denotes picked dispersion curve
derived from an average 1D model, which is based on the Qiu’s model (Qiu Yi et al., 2014; Table 1). Two quality controls are also used: signal-to-noise ratio and distance between stations. Signal-to-noise ratio (SNR) is higher than 5 and distance between stations is larger than 1.5 times wavelength. Finally, we obtain 5,778 dispersion curves for Rayleigh wave and more than 4,000 Love wave dispersion curves between 1s−20s period. Fig. 4 shows the measured average group velocities (dotted line) and the reference dispersion curve (solid line). As the histogram shows, the number of the picked dispersion curve is more than 3,000 for most periods. Although picking the quantity of the Love wave is fewer than that of the Rayleigh wave, the number about 4,000 for every period.
Table 1 1D structure model of Fujian Province

<table>
<thead>
<tr>
<th>Thickness (km)</th>
<th>( V_p ) (km/s)</th>
<th>( V_s ) (km/s)</th>
<th>Density (g/cm(^3))</th>
<th>( Q_s )</th>
<th>( Q_p )</th>
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<td>2.56</td>
<td>2.17</td>
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<td>100</td>
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<td>1000</td>
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<tr>
<td>4</td>
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<td>3.51</td>
<td>2.69</td>
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<tr>
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<tr>
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<td>7.99</td>
<td>4.20</td>
<td>3.33</td>
<td>500</td>
<td>1000</td>
</tr>
</tbody>
</table>

We invert the 2-D group velocity maps of each period with picked dispersion data. In order to simplify the calculation, most surface wave tomography inversions adopted the assumption that surface wave propagates along the great circle path between two stations. However, this assumption introduces artificial errors when strong lateral velocity variation exists. Therefore, we adopt a more accurate 2-D tomography method. Similarly with local earthquake tomography, the ray path is traced in updated model at the beginning of each iteration. The travel time field is computed with a finite difference method solved by the eikonal equation, then the steepest descent algorithm is used to trace ray paths. The inversion part is computed using the traditional LSQR algorithm.

The resolution of our data set is investigated with checkerboard tests. The grid spacing of the input model 25km and the size of the anomaly cell is 50km×50km. Fig.5 shows the results of the Rayleigh wave group velocity map at 5s, and it indicates that the 50km×50km anomalies can be well recovered in the Fujian area, and also partly recovered in the center part of the Taiwan Strait.

2 RESULTS

We obtained the group velocity maps of Rayleigh and Love waves in the period range 1s~20s in Fujian Province and its adjacent areas. The surface wave group velocity reflects the S-wave velocity structure down to depths of about 1/3~1/2 wavelength. Therefore, the surface wave group velocity maps obtained in this study are mainly controlled by S-wave velocity structures in the upper and middle crust. To better demonstrate them, we calculate sensitivity kernels (Fig.6) of four representative periods group velocity based on the 1-D average velocity model (Table 1). The Love and Rayleigh wave group velocities of 2s~5s mainly reflect S-wave velocity at the top 10km, especially it is very sensitive to the shallow structure that is not well resolved by the previous studies. The Rayleigh wave at 10s~15s is still sensitive to the velocity structure of the lower crust. Our data set mainly reflects the S-wave velocity structure within 20km deep.

Fig.7 and Fig.8 show tomography results of the Rayleigh and Love waves, respectively. Both the Rayleigh and Love wave group velocities of 8s show a significant difference in the northern and southern Fujian region, which is separated by the Yong’an-Jinjiang fault. Group velocity in the northern part is much higher than that of the southern part. In the three tectonic units, the northwestern uplift consists of metamorphic rocks, while the southwestern depression consists of shallow metamorphic rocks with folds and faults that resulted in relative low velocity. In the eastern Fujian region, high velocity volcanic rocks are widely exposed. However, the Fuzhou and Zhangzhou basins in this area show obvious low velocity zone, which should result from the thick low velocity sediment in basin. The NW and NE-oriented faults running in these two basins and hot springs that suggests high porosity of the crustal materials, which may also reduce seismic velocity.
Fig.4  Average picked group velocities of Rayleigh (a) and Love (b) waves and histogram of picks Black line denotes the reference dispersion curves while red dots denote average picked one

Fig.5  Checkerboard test result of Rayleigh wave at 5s
(a) Recovered model; (b) True model

Fig.6  Sensitivity kernels of group velocities
(a) Rayleigh wave; (b) Love wave

The group velocities of the long periods (12s–18s) reflect the seismic velocity structure in the middle and lower crust. A dominant feature is the velocity contrast in eastern (high velocity) and western part (low velocity). However, the Zhangzhou basin is imaged as a low velocity zone at 12s–15s group velocity maps, indicating the low velocity body in the Zhangzhou basin extends to the middle crust. One possible interpretation is that the high heat flow in this area causes partial
Fig. 7  Group velocity maps of Rayleigh wave

Fig. 8  Group velocity maps of Love wave

melting of the middle and low crust, resulting in the low velocity anomaly.

Considering the average depth of Moho in the Fujian region is about 30km, its lateral variation has an effect on Rayleigh group velocities at long periods. Receiver function study (Huang Hui et al., 2010) suggests that the Moho becomes shallower from the west to the east in Fujian area and clear jumps are observed across the Changle-Shao’an and Zhenghe-Dapu faults. Our Rayleigh wave group velocity maps correlates well with this pattern. Similar velocity jump is also imaged on the Love wave group velocity map across the Zhenghe-Dapu fault, which indicates
that this fault reaches the lower crust. However, such velocity jumps are not well resolved through the study of Rayleigh wave group velocity. It may be caused by the S-wave anisotropy.

3 CONCLUSIONS AND DISCUSSION

With a new efficient time-frequency phase weight stack algorithm, we obtained high quality NCFs of vertical and tangential components in a short time period and measured thousands Rayleigh and Love wave group velocity dispersion curves between 1s–20s. This data set provides a resolution of up to 50km×50km in the Fujian region. For short periods, the tomography reveals the following features; velocity contrast across the Yong’an-Jinjiang fault and strong low velocity anomaly in the Fuzhou and Zhangzhou basins. For long periods, the main features are different between the eastern and western parts and one low velocity anomaly in the northwest of Zhangzhou that may be due to the partial rock melt of the middle and lower crust caused by the high heat flow in this area.

Thanks to the dense seismic network, the ambient noise tomography provides a higher resolution result. However, this data set is still difficult to resolve in small-scale features, such as faults. In the future, using dense temporary stations will help to improve lateral resolution, and provide more effective evidence for the seismogenic zone in our study area. The denser array also makes it possible to extract short-period surface wave data, which may better constrain the shallow structure for strong ground motion study. As shown in Fig.6, the surface wave group velocity is an average result of the S-wave velocity structure in a certain depth range. Therefore, inverting the S-wave velocity structure can better image the seismic velocity structure. The anisotropy also will be taken into account in the next study.

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