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Variations in seismic velocity and attenuation associated with seismogenesis: A numerical verification using ambient noise

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ABSTRACT

Seismic velocity variations associated with the seismogenic process have been studied worldwide for almost half a century since the dilatancy hypothesis proposed in early 1970s. However, the reports in seismogenesis-associated variations in attenuation are rare. Reports on simultaneous variation of velocity and attenuation are even rarer. The conventional way to obtain the seismogenic temporal variation in velocity and attenuation is through the observation of travel time and amplitude variations of microseismicity in a seismogenic zone. Anyhow, for some major earthquakes there may not always be microseismicity prior to the mainshock. Thus, obtaining a complete record of seismic velocity and attenuation variation from microseismicity is severely limited if pre-mainshock microseismicity exists. In contrast, seismic ambient noise is an ideal source for crustal stimulation for monitoring temporal variations in velocity and attenuation in a seismogenic zone. In this paper the seismogenesis-associated seismic velocity and attenuation variations shown as some observable parameters in ambient noise measurements are verified using a numerical simulation approach. First, based on the temporal variation in seismic velocity observed along the Longmenshan fault associated with the 2008 Wenchuan earthquake, we divided the seismogenic process into six phases upon velocity drop stages in an elliptic area in the crust. Second, using finite difference time domain method we generated 30-minute low frequency ambient noise over a vertical profile of 200×45 km and recorded it with a 90-station array on the surface. Next, we processed the synthetic ambient noise records to get the auto-correlation function (ACF), cross-correlation function (CCF), Rayleigh wave dispersion curve, and horizontal-to-vertical spectral ratio (H/V). Finally, we examined the temporal variation of these parameters versus the phases of the seismogenic process and found the most pronounced changes occur in the phase with the largest velocity drop and the recovery phase directly before the mainshock.

1. Introduction

Seismic velocity variations associated with the seismogenic process is a topic interesting to seismologists worldwide for almost half a century since the dilatancy hypothesis proposed in early 1970s (Brady, 1974, 1975; Nur, 1972; Scholz et al., 1973; Whitcomb et al., 1973). Besides the dilatancy hypothesis other physical processes in the crust may also cause seismic velocity variations such as shear weakening (Boitnott and Kirkpatrick, 1997). Regardless of which mechanism dominates the seismic velocity variation associated with a particular earthquake the most critical and fundamental issue is the robust observation of seismic velocity variations in a period of months to years before the and shortly after the main rupture, with the time range proportional to the size of the pending earthquake. Closely related to the velocity changes is another possible change in seismic attenuation that involves seismic wave amplitude measurement. In general, precisely catching the amplitude change is more difficult by using nature seismicity in comparison with searching for velocity variations due to additional dynamic parameters are needed besides precise identification of arriving phases as the only kinematic parameter needed for velocity studies.

It is necessary to have microseismicity around a seismogenic zone for using the conventional approach to obtain the measurements of velocity and amplitude variations. For example, Wang et al. (2011) studied the variation of Vp and Vs associated with the 2008 Wenchuan earthquake based on the arrival times from the regional seismic network. Repeat earthquakes known as doublets and multiplets are valuable data resource for studying earthquake rupture process (Li et al., 2011). It is also a relatively straightforward means to track the amplitude changes. However, it is relatively rare to find the doublets in a relatively focused seismically active region in a prolonged period (months to years) required for monitoring the seismogenesis (Schaff and Richards, 2004). An important limitation for many big earthquakes is that there may not always be microseismicity prior to the main shock for obtaining a complete tracking record of seismic velocity and amplitude variations including both before and after the main

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shock. For this reason a complete record of seismogenic-associated seismic velocity and amplitude variations is valuable and relatively rare to find in the literature.

Active seismic monitoring is an attractive supplementary approach due to its high mobility and high flexibility in array geometry design to monitor the seismogenic zone in depth using a most cost-effective array with ideal size and geometry (Niu et al., 2008; Wang et al., 2009a, 2009b). In the field test phase of the active source monitoring system a level of ~1% surface wave velocity drop directly after two M~4 aftershocks of the Wenchuan Earthquake was observed (Wang et al., 2009a, 2009b; Yang et al., 2010). In addition to monitoring velocity changes, the active source experiment is also ideal to observe amplitude changes associated with the seismogenic process. However, active seismic monitoring is expensive for its mechanic source and power supplies for long-term operation and maintenance.

Another potential means to catch possible precursory velocity variations is to continuously monitor the ambient seismic noise over a seismic network (e.g., Yang et al., 2007) in the pending seismogenic zones. The advantages of using ambient noise monitoring approaches include 1) no local microseismicity is required, therefore it is more practical in some regions; and 2) it is much more economical in comparison with active source monitoring. In the last decade, there have been numerous reports on successful extraction of useful kinematic and dynamic, geological and geotechnical information from ambient noise observations at a wide frequency band and spatial/temporal scales (e.g., Bensen et al., 2007; Bussat and Kugler, 2011; Chen et al., 2009; Shapiro et al., 2005; Weaver, 2005; Yang et al., 2007).

Ambient noise tomographic imaging techniques have been successfully applied to study magmatic activities in some volcanic areas. Due to the relatively short characteristic time of magmatism in comparison with that of seismogenesis, the probability of catching the variations in seismic velocity and amplitude prior to a volcanic eruption is much higher. Numerous studies having been reported on this application (e.g., Brenguier et al., 2011; Duputel et al., 2009; Mordret et al., 2010).

Besides a wide spectrum of interest of using ambient noise for earthquake engineering studies (e.g., Chen et al., 2009) a number of research groups also explored the possibility for using the ambient noise tomography to investigate seismogenic-associated velocity variations. Xu and Song (2009) reported the temporal changes of surface wave velocity calculated from station pairs over a large area associated with 3 major Sumatra earthquakes in 2004, 2005, and 2007. They found that one excellent station pair (PSI in Indonesia and CHTO in Thailand) shows significant time shifts (up to 1.44 s) after the 2004 and 2005 events in the Rayleigh waves at the period band of 10–20 s (0.1 to 0.05 Hz). They also observed strong time delay anomalies (up to 0.68 s) near the epicenter after the 2007 event. They interpreted the observed phenomena as stress build-up and subsequent relaxation in upper-mid crust in the immediate vicinity of the rupture and the broad area near the fault zone. However, there have been few reports on investigating the amplitude variation associated with the seismogenic process based on ambient noise observations.

Nevertheless, simultaneous observation of the variations of seismic velocity and amplitude around a major earthquake via ambient noise is not common. Theoretically, however, it is well known that the dispersive and the absorptive characteristics of a material are interplayed with each other through the Kramer–Kronig relationship (e.g., O'Donnell et al., 1981). In this paper we take a numerical approach to look into the possibility of simultaneously investigating the seismic velocity and amplitude variations associated with the seismogenic process of a significant earthquake from ambient noise. In this study, for seismic velocity changes the observables are the surface wave phase velocity dispersion relationship extracted from the ambient noise empirical Green's function. For amplitude changes the observables are the horizontal to vertical spectral ratio (H/V). As a case scenario study, we take the crustal structure and seismogenic source of the 2008 Wenchuan Earthquake as the model and study the possibility of catching the velocity and amplitude variations through ambient noise array observations.

This paper is organized as follows. First we describe the observed seismic velocity variation associated with the 2008 Wenchuan earthquake. Then we state and justify the physical parameters used in the model simulation (Section 2). Next we describe the numerical simulation technique (Section 3) and the main results (Section 4). After we discuss the result implications (Section 5) the paper is concluded by restating the major conclusions (Section 6).

2. Summary of major findings on seismic velocity variation associated with the 2008 Wenchuan Earthquake and the regional crustal structure model

2.1. Summary of the observed velocity variations

Using 10 years of seismic records acquired from the regional network Wang et al. (2011) reported the seismic velocity variations around the main shock of the 2008 Wenchuan earthquake based on 4838 phase arrivals from 450 seismic events. The analysis results shown that both the P-wave velocity (Vp) and S-wave velocity (Vs) started to decrease about 4 years before the mainshock and recovered to the background values half year before the mainshock (Fig. 1). The velocity ratio Vp/Vs has relative smaller changes but has shown the same trend. After the mainshock both Vp and Vs are stayed in higher than average values, but the Vp/Vs ratio was high at the first couple of months after the mainshock and dropped to the average value afterwards (Fig. 1). This observation on seismogenic-associated velocity variations for the 2008 Wenchuan earthquake provides the basis for looking into if it is possible to monitor this velocity variation, along with possible amplitude, through continuous ambient noise measurements using numerically simulated synthetic records. For this purpose we have divided the temporal variation into six phases as shown with shadings in Fig. 1 to characterize the seismogenic process to be discussed in Section 3 in more detail.

2.2. Background velocity structure model

After the 2008 Wenchuan earthquake an intensive period of study on the earth structure around the epicenter area and along the seismogenic Longmenshan Fault has generated numerous new findings (e.g., Li et al., 2009; Liu et al., 2009; Wu et al., 2009; Zhang et al., 2009; Zhu et al., 2008). Based on these studies we extracted a background layered earth structure model as summarized in Table 1 to be used in our numerical model to simulate the ambient noise interactions with the earth in different seismogenic phases.

3. Numerical simulation of the seismic ambient noise (FDTD part) and data processing

In this section we describe the approach of the numerical simulation philosophy, and present and justify the selection of model parameters such as the size, the frequency content, the location of the seismic sources and receiving array. The selection of these values is trying to be as realistic as possible to those published values for Wenchuan earthquake among numerous publications.

3.1. Numerical simulation of different phase of seismogenic process

For this study we used a two-dimensional finite difference time domain (FDTD) method to model the interaction of the ambient noise with the crustal structures (Liu and Arcone, 2003; Peng et al., 2010). The model can be regarded as a vertical cross-section perpendicular to the seismogenic fault through the epicenter of the Wenchuan earthquake. The lateral width of the model is 200 km and the depth is 55 km. The left and right sides and the bottom of the model are