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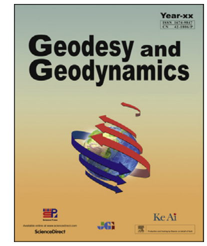

Recent developments in seismological geodesy

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ABSTRACT

With the advanced development of the modern geodetic techniques, the geodetic observations have been proved to be more powerful to uncover the geophysical phenomena, especially the seismic one, than that in the past time. The recent developments and achievements in the seismological geodesy are summarised here. Several popular geodetic techniques, such as high-rate GNSS, InSAR and Satellite Gravimetry, are introduced first to present their recent contributions in studying the seismic deformations. The developments of the joint inversion of the seismic source parameters from multiple observations are then highlighted. Some outlooks in seismological geodesy are presented in the end.

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1. Introduction

Earthquake, as one of a tremendous natural disaster, has been studied for more than 200 years but is still not fully understood. The triggering time and location of the future earthquake are unpredictable in the current. The sudden release of the huge seismic energy does not provide people any chances to be sheltered from the hazard. Thousands of people were killed or injured and trillions of U.S. dollars were lost only by several disastrous earthquakes in the latest decade. The 2008 Ms8.0 Wenchuan earthquake in China killed more than 60,000 people and injured about 30,000 people. More than 40 million people were suffered. The economic loss exceeded 10 trillion RMB. Moreover, the disastrous tsunamis were triggered in a chain by the 2004 Mw9.2 Sumatra earthquake in Indonesia [1] and the 2011 Mw9.0 Tohoku-Oki earthquake in Japan [2]. The nuclear power station was damaged by the last one and thousands of peoples were suffered from the nuclear leakage. The huge destructions from the seismic hazard prompt us for the further understanding of the earthquake to avoid or decrease any damages from the earthquake. Besides, the tsunami would always be excited by the mega thrust earthquake in the plate boundary. The study of the tsunami early warning

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from the real-time product by monitoring earthquakes is also highly significant in the recent.

Since 1950's, with the advanced development of specific techniques, the traditional geodesy was modernised in the presence of Global Navigation Satellite Systems (GNSS), Very-Long-Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), Interferometric Synthetic Aperture Radar (InSAR), Satellite Altimetry and Satellite Gravimetry [3]. The global and continuous operation of these geodetic techniques can provide us high-quality observations from different perspectives which cover a highly wide band in the spatial and temporal domains. The modern geodesy provides us with a more critical insight into the earth science than the traditional geodesy and seismology. The surface deformation, the changes of geoid and gravity, etc., can be determined with the high precision by the modern geodetic techniques. These measurements together with the traditional seismological and/or the geological measurements can be further analysed to study the features of earthquakes, the interior structure of the earth, etc., which forms a specific concept of seismological geodesy. The combination of the modern geodesy and seismology provides us with an opportunity to study the interior earth and the global deformation dynamically with the various scales [4].

In this review paper, the application of high-rate GNSS, InSAR and satellite gravimetry in seismology are summarised in the first three sections. The development of the joint inversion of the earthquake mechanism and rupture process from the multi-observations is presented in the fifth section. Some personal thoughts in seismological geodesy have prospected in the last section.

2. High-rate GNSS in seismology

GNSS observations have shown great potential in geophysical studies as a geodetic technique for several decades [5]. Since the pioneering works of Bock et al. [6], Nikolaidis et al. [7] and Larson et al. [8], GNSS kinematic solutions started to play an essential role in seismology, because they proved the capability of GNSS to resolve seismic waves generated by moderate-to-strong earthquakes at distances of a few kilometres up to thousands of kilometres, regardless of relative kinematic positioning mode [7], precise point positioning mode [9], and variometric approach [10], although it shows large uncertainty in the vertical direction [11]. These solutions show extraordinary ability in capturing long-wavelength ground motion comparing with the traditional seismic record. Although the seismic instruments are more sensitive than high-rate GNSS, they are easily contaminated by the clipping and tilting of the sensor, which will distort the waveforms when integrating. P/S phases [8,9,12], direct surface waves [13,14], ScS phase [15], regional surface-wave dispersion [16], Earth's free oscillation [17] and multiple surface waves [18] were successfully detected from the high-rate GNSS recordings.

However, high-rate GNNS recordings at a sampling frequency of 1 Hz, even 5 Hz, are usually aliased when suffering large seismic events at near field [19]. Despite many empirical baseline correction strategies on seismic recordings proposed [20], the integration of observations from high-rate GNSS and seismometer gives full play to their respective roles. A multi-rate Kalman filter was developed to fuse raw accelerations and displacements of collocated accelerometer and GNSS [21]. Emore et al. [22] recovered seismic displacements in the 2003 *Mw*8.3 Tokachi-Oki earthquake through an inversion method that simultaneously estimates ground displacement from accelerometer data and GPS displacements. Bock et al. [23] estimated broadband coseismic displacement in the 2010 *Mw*7.2 Baja California earthquake using the multi-rate Kalman filter in a simulated real-time mode, which was applied to rapid earthquake magnitude determination and tsunami early warning [24,25]. Niu et al. [26] proposed an adaptive multi-rate Kalman filter based on the variance component estimation to deal with the time-varying rotation of the seismic sensor. Instead of loosely integrating the GPS-derived displacements and accelerometer data, some tightly integrating filters dealing with GPS phase and range observations were developed [27–29].

Ji et al. [30] showed the potential of both dynamic and static displacements from high-rate GNSS to infer the finite fault slip history of the 2003 *Mw*6.5 San Simeon earthquake in U.S, which proved the complementary role of high-rate GNSS to study the rupture process of the earthquake. Despite the consistency between the solutions from high-rate GNSS and seismometer, Miyazaki et al. [31] proved that the geodetic measurements are more sensitive to the cumulative slip distribution than the seismic one when inferring the fault slip history of the 2003 *Mw*8.3 Hokkaido earthquake in Japan. Since that, the source properties of several great or moderate earthquakes were investigated through the observations of high-rate GNSS [32,33]. Avallone et al. [12] presented the observations of a very-high-rate GNSS of 10 Hz in the 2009 *Mw*6.3 L'Aquila earthquake. It was concluded that the minimum sampling rate of GNSS should be 2.5 Hz if the kinematic observations of the seismic waves were not aliased. The changes of the radiated seismic waves from the specific geological structure were also detected by high-rate GNSS [34,35]. Most of the continuous GNSS networks are not overlapped with the seismic networks in space. Hence, the successful application of high-rate GNSS in capturing the dynamic seismic waves and inferring the seismic source may claim the indispensable function of the geodetic measurement in seismology.

3. InSAR in seismology

3.1. *Monitoring coseismic deformation*

InSAR, which can obtain the large-scale, minor-magnitude position change, is a unique technique to monitor crustal deformation, especially for the seismic deformation across active fault belts. With the pioneering work of Massonnet et al. [36], the geodetic measurement of InSAR from the ERS-1 satellite was first introduced to detect the permanent coseismic deformation induced by the 1992 *Mw*7.3 Landers earthquake in U.S. The geodetic inference of this shallow earthquake from InSAR was highly consistent with the field