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Monitoring the slope movement of the Shuping landslide in the Three Gorges Reservoir of China, using X-band time series SAR interferometry

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Abstract

As the largest water conservation project in China, the Three Gorges Reservoir has attracted a lot of attention. However, the rise in water level due to the dam operation has caused many ecological problems. Since the impoundment of the Three Gorges Reservoir in the year 2003, many landslides have taken place. The Shuping landslide is a reactivated landslide and has been continuously moving since the impoundment. It has resulted in serious dangers to local residence and the role of the Yangtze River as an inland waterway. Spaceborne Synthetic Aperture Radar (SAR) sensors obtain images periodically and regionally, from which the characteristics of the slope movement could be obtained timely and cost effectively. In this study, an adapted time series InSAR technique considering SRTM bias is proposed and used to process TerraSAR-X strip map images with 3 meters resolution which collected in the first quarter of 2012. Compared with previous studies with low resolution SAR data, our results obtain much more stable points and reveal the movement pattern of the active slope of Shuping landslide in detail, and they show that there are two main landslide bodies obviously; one is located in the eastern part of the landslide, while the other is located in the western part of the landslide, the movement velocity is up to 40 mm month^{-1}, and the results are well-consistent with the *in situ* results. Furthermore the active movement boundaries was identified through analysing the time series InSAR results, the shape of the landslide is chair-like, and the boundaries lie mostly along ditches. The results show that more details about the landslide could be revealed using the proposed time series InSAR method and high resolution TerraSAR-X SAR data, and this provide a more comprehensive way for landslide movement monitoring, which will be useful for landslide management.

Keywords: Landslide; Three Gorges Reservoir; Time series InSAR

1. Introduction

Landslide is a typical geological phenomenon commonly occurring in the catchments with large water-level fluctuations, resulting in serious danger to local residents and inland waterways (Bai et al., 2013, 2012). Monitoring the slope movement is important for the understanding

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of the landslide dynamics and early warning of landslide (UNISDR, 2009). Traditional survey techniques such as Global Positioning System (GPS) and levelling have been undertaken to obtain precise *in situ* data on slope movement of landslides (Calcaterra et al., 2010; Gili et al., 2000), but they are considered to be time consuming and can provide measurement for a limited number of points (Khan et al., 2010; Nakagawa et al., 2000). Differential synthetic aperture radar interferometry (DInSAR) is a well-known remote sensing technique (Gabriel et al., 1989) that has been recognized as a powerful tool for monitoring ground surface movement regionally and effectively. Early studies using interferometric combination of pairs of SAR images acquired by the European Remote Sensing satellite 1 (ERS-1) during the Commissioning Phase demonstrated that it is useful for landslide monitoring. The displacement field derived from the interferograms is characterized by a non-uniform displacement gradient from the top to the bottom of the Saint-Etienne-de-Tinee landslide located in SE France (Carnec et al., 1996). Later, significantly more landslide studies with DInSAR technique have been undertaken following the initial studies, which have demonstrated that the DInSAR technique could monitor the slope movement effectively when the DInSAR pair has high coherence (Berardino et al., 2002; Jebur et al., 2013; Nikolaeva et al., 2014; Peyret et al., 2008; Rizzo and Iodice, 2006; Rott et al., 1999).

While the DInSAR technique can monitor the landslide movement, there exist some limitations due to inaccurate topography, dense vegetation, and complex weather conditions especially in mountainous region. This leads to rapid decorrelation of the SAR images. The idea of time series InSAR analysis was first proposed by Usai and Hanssen (1997) to obtain accurate displacement phase information of the low coherence situation that limited the usage of the conventional DInSAR technique. They obtained the land subsidence phase information through analysis of highly coherent features or stable points (SP) on SAR images during a long time span and various time series InSAR analysing techniques were developed later on Berardino et al. (2002), Ferretti et al. (2001), Hooper et al. (2004) and Lanari et al. (2004). And they have been used for landslides in many landslide-prone areas around the world.

The Yangtze River is the world's third longest river. The Three Gorges Dam located on the Yangtze River with a height of 185 m and a length of 2.3 km has the world's biggest hydropower plant in terms of total installed capacity of 3.93×10^{10} m^3 (Suo et al., 2012). The Three Gorges Reservoir contain almost 40 km^3 of water with a surface area of 1045 km^2, the banks of the reservoir is stretched across 21 counties with a distance of 1300 km (Wang et al., 2006). More than 600 km^2 was inundated due to the rising water level rising, resulting in more than 1000 unstable slopes along the bank of the river (Chen and Tang, 2009; Liu et al., 2004). The Shuping slope is one of the largest landslides in the Three Gorges area, which has been reactivated since 2003 and has continued moving till date. Conventional DInSAR has limitations for slope movement monitoring of the Shuping landslide due to dense vegetation and humid climate, only those interferometric pairs with short spatial and temporal baseline could obtain displacement-phase information (Fan et al., 2013; Singleton et al., 2014). To understand the characteristic of the landslide movement, Corner Reflector InSAR (CRInSAR) and offset track methods are used to study the movement of the corner reflectors (CRs) installed on the slope (Fan et al., 2010; Shi et al., 2015; Singleton et al., 2014), for the corner reflectors could obtain much high SNR (Signal-to-Noise Ratio) than the target around on the SAR images especially in rural area, Singleton et al. (2014) provided a throughout study of the Shuping landslide using TerraSAR-X Spotlight, TerraSAR-X StripMap and ENVISAT StripMap imagery and sub-pixel offset time-series technique applied to corner reflectors, they gave the time series movement of the CRs. However there has only about 20 corner reflectors on the Shuping landslide, and this make it impossible to get a comprehensive knowledge of the slope movement. For the time series InSAR studies, Liao et al. (2011) studied the landslide movement using TerraSAR-X stripmap images and obtained several hundreds of stable points. The density is about 40 stable points per km^2 and most of the points have a velocity less than 2 mm year^{-1}. However, only a few points were selected on the active slope as most of the points are located on the stable area of the river bank. Fan et al. (2013) studied the same area using TerraSAR-X spotlight images, the results show that the maximum velocity attained in the Shuping landslide exceeds 20 cm year^{-1}. However, the spotlight image covers a very small area, and furthermore, very few landslides have spotlight data coverage in the Three Gorges area.

In the present study, an adapted time series InSAR method based on Lanari et al. (2004) has been proposed to reduce the topographic estimation error due to SRTM bias and decorrelation effect for ground targets on the active slope. This method has been applied to TerraSAR-X 3-m resolution stripmap images acquired covering Shuping landslide in the first quarter of 2012. The linear movement velocity of the slope was obtained along with the active boundaries. The movement velocity is validated using *in situ* GPS data and the results show that both methods match well. The benefits and limitations of the proposed method have been discussed at the end.

2. Study site and SAR dataset

2.1. Study area

The studied site, Shuping landslide, is located on the southern bank along the Yangtze River (Fig. 1a and b). The landslide belongs to Zigui County in the HuBei Province (Fig. 1a). The Shuping landslide is a large ancient landslide, which is about 47 km away from the Three

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