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Inversion of deformation fields time-series from optical images, and application to the long term kinematics of slow-moving landslides in Peru

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ABSTRACT

Slow-moving landslides are numerous in mountainous areas and pose a large threat to populations. Many observations show that their kinematics is driven by climatic forcings and earthquakes. In this study, we document the complex interaction between those two forcings on the slow-moving landslide kinematics, based on the retrieval of landslide displacements over 28-years using optical satellite images. To overcome the decorrelation effect over this large time-span, and possible misalignment between images, we develop a method that uses the redundancy of displacement fields from image pairs to derive a robust time-series of displacement. The method is tested on the 28-year long SPOT1/5-Pléiades archive, over an area in Peru affected by both earthquakes and rainfall. Errors are estimated on stable areas and by comparison with one 13-year long and eleven 3-year long GPS time-series on the Maca landslide. The methodology diminishes by up to 30% the uncertainty and reduces significantly the gaps due to decorrelation. The data set allows detecting 3 major landslides, moving at a rate of 35 to 50 m over 28 years, and smaller landslides with lower displacement rates. Time-series obtained over the three main landslides provide interesting results of their long-term kinematics, primarily driven by precipitation. We propose simple statistical hydro-kinematic models, relating yearly motion to seasonal rainfall, to explain the observed time-series. We found that annual precipitation is controlling the landslide displacements after a certain rainfall threshold is reached. Besides this control, we show the possible impact of a local Mw 5.4 earthquake in 1991 on the kinematics of the Maca landslide. Our results suggest that the earthquake accelerated the landslide and has an effect during several years on the precipitation threshold required for triggering a motion. These results suggest that the rainfall threshold can vary in time following strong earthquakes shaking.

1. Introduction

Slow-moving landslides are mass-movements with velocities ranging from a few centimeters to a few meters per year (Hungr et al., 2014). They can affect human settlements, such as villages and roads, and their economic impact is difficult to estimate because of their long-term time evolution (from a month to several decades, Strozzi et al., 2010). Furthermore, those slow-moving landslides may exhibit sudden acceleration phases and flows that are generally difficult to predict and can result in loss of life (Petley et al., 2002; Jongmans et al., 2009).

The kinematics of those active landslides is found to be primarily driven by precipitation and water infiltration (Iverson, 2000; Zerathe et al., 2016). Other sources of external forcing include river erosion (Eilertsen et al., 2008), earthquakes (Lacroix et al., 2014), glacier retreats (Strozzi et al., 2010), atmospheric tides (Schulz et al., 2009) and human activity (Mansour et al., 2011). All these factors act on different time-scales varying from seconds (earthquakes) to several hundreds or thousands of years (glacier retreat). In countries where both earthquakes and climatic triggering mechanisms are relevant, complex interactions are possible between the two mechanisms, in which one mechanism could enhance the conditions for landslide triggering by fracturing/weakening the medium and/or increasing the pore pressure (Jibson et al., 1994). This process is also corroborated by observations over rapid landslides, where increased rates of landsliding have been observed in the years after large earthquakes (Dadson et al., 2004; Lin et al., 2008; Marc et al., 2015), and proposed to be caused by reversible damage of rock mass. In addition to this damage process, earthquakes have been found to also modify the friction at the base of landslides, accelerating slow-moving landslides over several weeks (Moro et al., 2011; Lacroix et al., 2014) even for medium size earthquakes (Mw 6.0) in dry conditions. The number of observations over slow-moving landslides during earthquakes is however, very limited and the understanding of the complex interaction between rainfall and earthquake forcing still requires more observations. In this context, it is very important to monitor their activity over time.

Remote-sensing techniques based on both radar (e.g. Handwerger

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et al., 2013) and optical satellites (e.g. Delacourt et al., 2004) have proven to be efficient for this monitoring purpose. As opposed to Interferometric Synthetic Aperture Radar (InSAR) data, where applications are limited to relatively slow landslides (≤ 1 m/yr) and with favourable slope orientations, optical satellites are particularly well-adapted to monitor objects of small size like landslides, moving at centimeter to decameter rates per year (Kääb, 2002; Casson et al., 2003; Delacourt et al., 2004; Stumpf et al., 2014; Lacroix et al., 2015; Bennett et al., 2016). The landslide motion can be retrieved by a three step process (Leprince et al., 2007) including: (1) orthorectification of the images, (2) coregistration, and(3) correlation between pairs of diachronic images. This process has been applied on pairs of optical images from various platforms, including 0.6 m resolution (pixel-size) Quickbird images (Delacourt et al., 2004), 0.7 m resolution Pléiades images (Stumpf et al., 2014; Lacroix et al., 2015), 2.5 m resolution SPOT5 images (Leprince et al., 2008), 15 m resolution ASTER images (Kääb, 2002), and 15 m Landsat images (Dehecq et al., 2015). All these studies have shown the possibility to retrieve the ground motion with an accuracy of a fifth of a pixel size (Lacroix et al., 2015).

The monitoring of different objects, as landslides, active faults or glaciers, from optical images is affected by clouds, problems of orthorectification, coregistration errors, shadows, changes of the surface state with time, and vegetation changes with time. All these effects induce noise and outliers in the images. Different post-processing filters have therefore been applied to remove these effects (Berthier et al., 2005; Scherler et al., 2008; Heid and Kääb, 2012; Stumpf et al., 2014, 2017), adapted to each of these problems. Other options to detect and monitor ground deformations have been developed, based on the processing of the full Landsat archive (Dehecq et al., 2015; Fahnestock et al., 2015). Those different studies used the pairwise processing of Landsat to produce time-series of deformation fields. This strategy led to better coverage and lower uncertainties of the deformation fields.

The launch of new constellations of optical satellites, with a very good revisit time (Sentinel-2, 5 days; Landsat-7/8, 8 days at the Equator) increases considerably the number of data available over an area. This revisit time enables the creation of time-series of deformation, of large interest for detecting transient signals over different objects, that can be precursors of catastrophic events. At the same time, these large data sets can be used to reduce the uncertainty of the deformation field. Indeed the pairwise process can be improved by taking into account a large number of possible image pairs, providing redundant measurements. This idea is commonly used by the InSAR community, where interferograms are often performed between optimal pairs of images, with limited perpendicular and temporal baselines. This led to different tools (Berardino et al., 2002; Cavalié et al., 2007; López-Quiroz et al., 2009), where phase delay maps between pairs of images are inverted into time-series using the redundancy of the measurements. The redundancy is useful to detect unwrapping errors (López-Quiroz et al., 2009) and limits the impact of the decorrelation noise. This approach has also been used successfully for the processing of time-series of displacement from SAR image correlation (Casu et al., 2011).

As opposed to InSAR, this time-series analysis is new for optical imagery. All the previous studies use raw time-series of deformation coming directly from the correlation of images with respect to a given master image (Travelletti et al., 2012; Fahnestock et al., 2015; Lacroix et al., 2015). When multiple images are acquired at the same time (for instance with agile very high resolution (VHR) satellites), averaging the results over the different multiple image pairs reduces the noise (Stumpf et al., 2017). On glaciers, Scherler et al. (2008) filtered the images by taking into account only the correlated images of 1-year apart. Dehecq et al. (2015) smoothed the glacier velocity field and reduced the noise by integrating several deformation fields of Landsat pairs separated by 1-year.

The idea of this study is to use available optical images to derive a system of redundant measurements of displacement fields, to build robust time-series of deformation fields, and to quantify how the network inversion reduces the errors and uncertainties compared to the pairwise process. For that purpose, we adapt the tools developed for InSAR time-series analysis (Doin et al., 2011) to optical data. We then apply these techniques for the long-term monitoring of slow-moving landslides, using the 30 year long SPOT1–5/Pléiades archive, over an area in Peru affected by both earthquakes and rainfalls, with the aim to better understand the relative contributions of these different forcings to the slow-moving landslide kinematics.

2. Study area

The Colca Valley is located in a volcanic area, in southern Peru (Fig. 1). Due to its geological, tectonic and climatic context, the area is propitious to landslides (Lacroix et al., 2015). Indeed, (1) this valley is constituted of successive layers of volcanic, lacustrine and alluvial deposits, incised by a deep river at a rapid rate of 1 mm/yr over the last 0.6 Ma (Thouret et al., 2007), cutting slopes prone for landsliding. (2) The region is subject to seasonal rainfall, with almost all the precipitation falling between December and April (Zerathe et al., 2016) (Fig. 1). (3) The region is seismically very active (Fig. 1) due to volcanic activity ($Mw \leq 3$), regional tectonics ($Mw \leq 7$; Antayhua et al., 2002), and the subduction of the Nazca plate under the South American plate, 120 km to the West of the Colca Valley ($Mw \leq 8.5$; Chlieh et al., 2011).

In this area, nine active landslides were detected using VHR satellites over the 2013 period (Lacroix et al., 2015). These slow landslides affect the same lithologies (lacustrine deposits) and are concentrated over 200 km^2 (Lacroix et al., 2015) (Fig. 1). Among this population, the Maca landslide has extensively been studied (Zerathe et al., 2016). Its volume is estimated to be about 60 to 100 million m^3. It is made of two main blocks, delimited by a near-vertical scarp measuring 15–20 m in height and spreading over 3.5 km long. The block located near the river is the fastest, moving with a mean velocity of 1.5 m/yr over the period of March to July 2013 (Lacroix et al., 2015). The upper block moves slower, with a velocity of 0.8 m/yr on the same period. The Maca landslide kinematics has been studied with GNSS campaigns since 2001 and continuous GNSS since 2012. In particular, two points, one on the landslide, the other on a stable area, were measured 16 times since 2001 (Zerathe et al., 2016). The uncertainty of these measurements is less than 5 cm. These measurements show that the landslide motion is controlled by the seasonal rain (Zerathe et al., 2016) and regional earthquakes (Lacroix et al., 2014). In addition, 11 GPS markers, also located on the Maca landslide, were measured 13 times between November 2011 and June 2014. These in-situ data will be used for validation of the proposed method.

The concentration of landslides in this valley makes the area of large interest for studying the relative contribution of each trigger to landslides dynamics. Indeed all these landslides are submitted to the same pluviometry and same earthquakes (Zerathe et al., 2016). Looking at a group of slow-moving landslides, subject to the same forcings, is an approach that has proven to be efficient for studying the impact of seasonal rainfall (Handwerger et al., 2013), and earthquakes (Lacroix et al., 2015) on slow-moving landslide kinematics. Little is known, however, about the combined effect of these different forcings. The Colca Valley, therefore, offers a great opportunity to study these combined effects over a population of slow-moving landslides.

3. Data processing

The framework for obtaining deformation time-series from optical images is shown in Fig. 2. The processing chain starts with usual steps that are (i) digital elevation model (DEM) generation, (ii) precise orthorectification, (iii) image correlation (Leprince et al., 2007). The novel contribution to the processing strategy here, is to eventually invert all correlation maps into time-series, exploiting the different possibilities that this inversion can offer to improve the signal to noise ratio.