Geomorphology 285 (2017) 121–136

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Landslide kinematics and their potential controls from hourly to decadal timescales: Insights from integrating ground-based InSAR measurements with structural maps and long-term monitoring data

William H. Schulz [a,*], Jeffrey A. Coe [a], Pier P. Ricci [b], Gregory M. Smoczyk [a], Brett L. Shurtleff [a,1], Joanna Panosky [a,1]

[a] U.S. Geological Survey, Box 25046, MS-966, Denver, CO 80225, USA
[b] Ingegneria Dei Sistemi, Via Enrica Calabresi, 24 - Loc. Montacchiello, 56121 Pisa, Italy

ARTICLE INFO

Article history:
Received 5 April 2016
Received in revised form 1 February 2017
Accepted 18 February 2017
Available online 21 February 2017

Keywords:
Landslide
Earthflow
InSAR
Kinematics
Slumgullion
Stress transfer

ABSTRACT

Knowledge of kinematics is rudimentary for understanding landslide controls and is increasingly valuable with greater spatiotemporal coverage. However, characterizing landslide-wide kinematics is rare, especially at broadly ranging timescales. We used highly detailed kinematic data obtained using photogrammetry and field mapping during the 1980s and 1990s and our 4.3-day ground-based InSAR survey during 2010 to study kinematics of the large, persistently moving Slumgullion landslide. The landslide was segregated into 11 kinematic elements using the 1980s–1990s data and the InSAR survey revealed most of these elements within a few hours. Averages of InSAR-derived displacement point measures within each element agreed well with higher quality in situ observations; averaging was deemed necessary because adverse look angles for the radar coupled with tree cover on the landslide introduced error in the InSAR results. We found that the landslide moved during 2010 at about half its 1985–1990 speed, but slowing was most pronounced at the landslide head. Gradually decreased precipitation and increased temperature between the periods likely resulted in lower groundwater levels and consequent slowing of the landslide. We used GPS survey results and limit-equilibrium modeling to analyze changing stability of the landslide head from observed thinning and found that its stability increased between the two periods, which would result in its slowing, and the consequent slowing of the entire landslide. Additionally, InSAR results suggested movement of kinematic element boundaries in the head region and our field mapping verified that they moved and changed character, likely because of the long-term increasing head stability. On an hourly basis, InSAR results were near error bounds but suggested landslide acceleration in response to seemingly negligible rainfall. Pore-pressure diffusion modeling suggested that rainfall infiltration affected frictional strength only to shallow depths along the landslide's marginal faults, highlighting their importance in controlling landslide stability. Hourly results also suggested that motion propagated along the 3.9-km length of the active landslide, even following sub-millimeter displacements, while strengthening of landslide shear boundaries during faster movement was likely critical in regulating the landslide's motion. Hence, detailed kinematic characterizations obtained from traditional and emerging approaches helped to reveal that mechanisms controlling landslide movement and evolution over decades also are critical to sub-millimeter movement on a nearly continuous basis.

1. Introduction

Landslides sculpt hillslopes, denude mountain ranges, weather and transport soil and rock, and present significant hazards to human safety and the built environment. Studies indicate that landslides are the dominant process controlling hillslope geomorphology and hydrology in many regions (e.g., Schmidt and Montgomery, 1995; Burbank et al., 1996; Roering et al., 2009). Annually, landslides cause >3.5 billion USD in property damage (U.S. Geological Survey, 2005) and loss of thousands of lives (Petley, 2012) worldwide. Hence, great efforts are made to understand how landslides move and mechanisms controlling their movement in order to forecast the evolution of Earth's surface and hazards landslides present. Perhaps the most rudimentary knowledge required for understanding landsliding mechanisms and effects is that of kinematics. Knowledge of kinematics helps to reveal temporally and spatially variable stresses acting within landslides, their boundary

* Corresponding author.
E-mail address: wschulz@usgs.gov (W.H. Schulz).
[1] Formerly with the affiliation they are linked to.

http://dx.doi.org/10.1016/j.geomorph.2017.02.011

geometries, mechanical properties of materials composing landslides, external forcing conditions, and characteristics of future landslide movement.

Landslides often comprise different kinematic elements, and conditions affecting their movement, such as material properties and pore-water pressures, vary in time and space. Hence, landslide kinematic characterization benefits greatly from increased spatiotemporal resolution. Traditionally, spatially dense kinematic data are acquired by mapping landslide features in the field and from aerial photographs to provide temporally discrete characterizations (e.g., Baum et al., 1993, 1998; Smith, 1993; Fleming et al., 1999; Baldi et al., 2008; Coe et al., 2016). Multiple such characterizations are used to reveal landslide motion generally at annual-decadal timescales (e.g., Parise, 2003; Mackey et al., 2009; Mackey and Roering, 2011; Giordan et al., 2013; Guerriero et al., 2014). Recently, the traditional tools have been supplemented by analyses of remotely sensed data. Repeated acquisitions of highly detailed topographic data from lidar may be used to estimate movement of landslides, including at timescales as short as days (e.g., Oppikofer et al., 2009; Prokop and Panholzer, 2009; Aryal et al., 2012; Jaboyedoff et al., 2012). Interferometric synthetic aperture radar (InSAR) methods using data acquired from aerial and satellite platforms may reveal movement of the ground surface at daily to monthly timescales, including movement related to landslides (e.g., Rott et al., 1999; Bürgmann et al., 2000; Schmidt and Bürgmann, 2003; Hilley et al., 2004; Roering et al., 2009; Calabro et al., 2010; Cascini et al., 2010; Handwerger et al., 2013, 2015; Milillo et al., 2014; Schlögel et al., 2015). Ground-based InSAR (GBInSAR) and interferometric real aperture radar are capable of repeatedly surveying landslide areas within minutes with up to millimeter-level accuracy and have been used successfully for measuring landslide kinematics (e.g., Pieraccini et al., 2003; Tarchi et al., 2003; Antonello et al., 2004; Gischig et al., 2009; Barla et al., 2010; Casagli et al., 2010; Lowry et al., 2013). GBInSAR also shows promise for revealing short-term (e.g., hourly or less) differential landslide motion (e.g., Tarchi et al., 2003; Lowry et al., 2013). Spatially dense kinematic data provided by the traditional and more recently developed approaches have proven useful for evaluating landslide evolution and mechanisms controlling their movement; however, much remains to be learned about the evolution of landslide movement and controls thereon, particularly in the short-term for which temporal relations between landslide kinematic elements remain unclear.

We used exceptionally detailed kinematic and structural documentation from the period 1985–1993 (Smith, 1993; Fleming et al., 1999) and GBInSAR displacement data acquired for four days during 2010 to evaluate movement of the large, persistent, well-studied Slumgullion landslide located in Colorado, USA (Fig. 1). We evaluated mechanisms responsible for observed kinematics using data obtained from monitoring of meteorological and groundwater conditions. Our study provides unique views of landslide kinematics and their potential controls at a weekly timescale, and of kinematic evolution over several decades. The study also provides an opportunity to evaluate the ability of GBInSAR for characterizing landslide kinematics compared to traditional approaches. Additionally, our GBInSAR results may reveal for the first time the spatially extensive interplay of landslide kinematic elements at a timescale commensurate with landslide motion.

2. The Slumgullion landslide

The Slumgullion landslide has long been studied. Although first mentioned in a scientific paper during the late 1800s and thought to be deposits from alluvial, glacial, and/or snow avalanche processes (Endlich, 1876), the first accurate description of it as a landslide was from the 1883 confession of the notorious "Colorado cannibal" Alferd Packer who reported (e.g., Gant, 1952) that he left the scene of his crime located adjacent to the landslide by following a big slide of yellowish clay. Later studies revealed it to be a 3.9-km-long, slowly moving, persistent, translational landslide nested within a larger, dormant landslide deposit (e.g., Varnes and Savage, 1996). Slumgullion is best classified as a debris slide (Cruden and Varnes, 1996) because nearly all of its motion appears to occur by sliding along faults bounding the landslide (e.g., Fleming et al., 1999) and it contains >20% sand and coarser material (Schulz et al., 2007, 2009a). Total displacements of hundreds of meters (e.g., Fleming et al., 1999; Coe et al., 2009) result in morphology suggestive of flow and it has been referred to as an earthflow previously (e.g., Keefer and Johnson, 1983; Gomberg et al., 1995; Varnes and Savage, 1996). The active part of the landslide and the underlying landslide deposit comprise deeply weathered Tertiary basalt, rhyolite, and

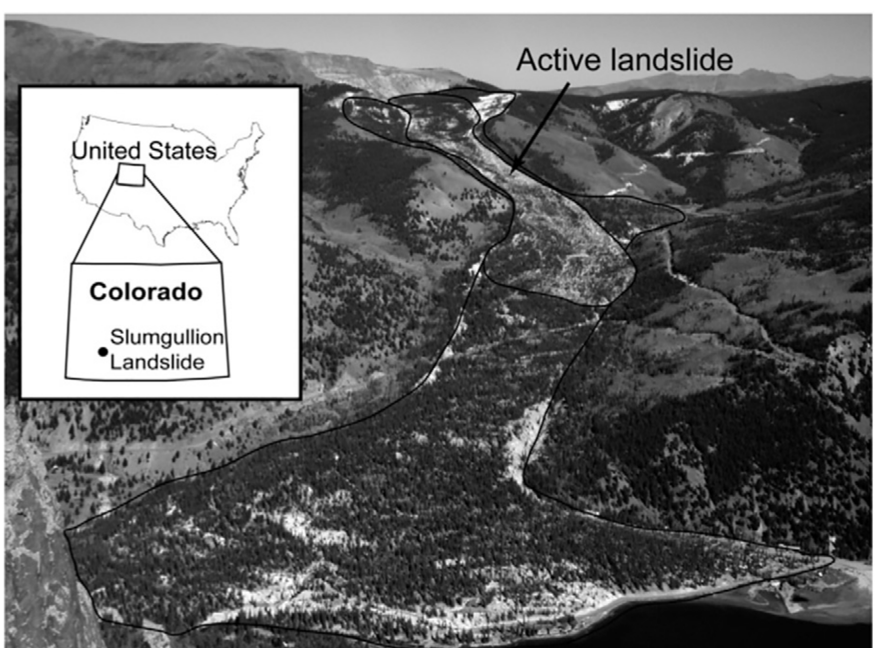

Fig. 1. Location map and photograph showing the Slumgullion landslide. The actively moving part is indicated; lines extending beyond the active part approximately delineate the inactive landslide deposit. The active landslide is 3.9 km long.