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Automated quantification of distributed landslide movement using circular tree trunks extracted from terrestrial laser scan data

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ABSTRACT

This manuscript presents a novel algorithm to automatically detect landslide movement in a forested area using displacements of tree trunks distributed across the landslide surveyed repeatedly using terrestrial laser scanning (TLS). Common landslide monitoring techniques include: inclinometers, global position system (GPS), and interferometric synthetic aperture radar (InSAR). While these techniques provide valuable data for monitoring landslides, they can be difficult to apply with adequate spatial or temporal resolution needed to understand complex landslides, specifically in forested environments. Comparison of the center coordinates (determined via least-squares fit of the TLS data) of a cross section of the tree trunk between consecutive surveys enable quantification of landslide movement rates, which can be used to analyze patterns of landslide displacement. The capabilities of this new methodology were tested through a case-study analyzing the Johnson Creek Landslide, a complex, quick moving coastal landslide, which has proven difficult to monitor using other techniques. A parametric analysis of fitting thresholds was also conducted to determine the reliability of tree trunk displacements calculated and the number of features that were extracted. The optimal parameters in selecting trees for movement analysis were found to be less than 1.5 cm for the RMS residuals of the circle fit and less than 1.0 cm for the difference in the calculated tree radii between epochs.

1. Introduction

Landslides are persistent natural hazards that result from downward sliding of an earth mass. Landslides can be triggered by a variety of factors such as precipitation, groundwater fluctuations, seismic activity, erosion, and human activities which destabilize the slope through geometric or loading changes (Fernandez Merodo et al., 2004). They have both direct and indirect effects on people and the environment. Large landslides can destroy or damage everything in their path when a failure occurs (i.e., people, roads, houses). Further, the immediate impact of a landslide is often overshadowed by the aftermath. Landslides often damage or block roadways that are necessary to link remote population centers, causing hardship for everyone affected.

1.1. Landslide monitoring

Landslide movement is often determined be a wide variety of monitoring techniques, including inclinometers, Global Positioning System (GPS), Interferometric Synthetic Aperture Radar (InSAR), and Light Detection and Ranging (LIDAR). These techniques each have positive and negative attributions for landslide monitoring dependent on landslide characteristics. This section will discuss these techniques, with the exception of LIDAR, which will be addressed in more detail in the following section.

Wieczorek and Snyder (2009) describe using inclinometers to monitor movement at discrete locations on a landslide by placing a hollow metal tube inside a drilled hole and periodically monitoring the variation of the original inclination of the tube. Although inclinometers provide subsurface detail of landslides, which other techniques do not capture, they have poor spatial resolution. They can also break when a landslide moves too quickly.

Permanently mounted GPS units have been used to monitor surficial landslide movement by analyzing positional changes of the GPS units compared to stable units in a GPS network. Wang (2011) showed landslide movement could be determined by GPS within 2 mm horizontally and 6 mm vertically with four hour observations and an open view of the sky. However, the cost of permanently mounting the survey-grade GPS units necessary for this detection is too high to mount more than a few receivers on a single slide, limiting spatial resolution and the number of landslides that can be monitored. Often this is only suitable for landslides near high population areas.

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Interferometric Synthetic Aperture Radar (InSAR) determines displacement from the phase change between radar images. Rosen et al. (2000) describes how vegetation canopies affect InSAR imaging by reporting a height of somewhere between the ground and the top of the canopy and reduces correlation between images because of volumetric scattering. Hence, it can be very difficult to apply for landslide monitoring in heavily forested environments. InSAR provides increased spatial coverage, but is limited in temporal coverage by repeat passes.

1.2. LIDAR background

LIDAR is an active optical remote sensing technology that measures the distances and angles to objects from a scanner to create complete 3D models of *XYZ* coordinates, termed point clouds. A laser pulse is emitted from the scanner, reflects off a target, and returns to the scanner, providing the two way travel time used to determine the distance from the scanner for each target. Scanners are a line of sight technology: if the complete laser pulse reflects from an object, no points are detected behind the object, creating an occlusion (shadow). When only part of the laser pulse reflects back from a small object, the remaining light continues and multiple *XYZ* coordinates (returns) can be obtained from one laser pulse (Renslow, 2012). Multiple returns enable improved penetration of vegetation canopy compared to many other techniques.

LIDAR has proven to be an effective tool for landslide analysis ranging from detection and characterization of mass movement and monitoring at the regional scale with airborne laser scanning (ALS) to terrestrial laser scanning (TLS) providing site specific details at improved resolutions (cm level) (Jaboyedoff et al., 2012). TLS has been successfully implemented for geological characterization and assessment of landslides (Collins and Sittar, 2008; Collins and Stock, 2012; Dunning et al., 2010).

Laser scanners have also proven to be an effective way to monitor coastal erosion and cliff collapses (Olsen et al., 2009; Rosser et al., 2005; Young et al., 2009). Young et al. (2010) performed a comparison between TLS and ALS for sea cliff erosion analysis and concluded that ALS has superior coverage capturing the cliff-top and crest, which is useful for detecting large or deep seated landslides but may not detect surficial landslides, erosion hotspots, or detailed change that can be picked up by a TLS. Monitoring areas of increased erosion and detailed change is necessary to understand the landslides occurring along the Oregon coast.

Several agencies have started using mobile (vehicle-based) laser scanning (MLS) in aspects such as asset inventory (Olsen et al., 2013a). For example, Lehtomaki et al. (2011) presents the application of using segmentation to extract poles and tree trunks from urban areas using MLS. Segmentation was used due to a lower point density than TLS and noise, which allows for only part of the cylindrical targets to appear. Although some trees were detected that were uniformly spaced along the road, the tree canopies were problematic. Hence, this approach is not suited for a heavy forest environment.

1.3. Study area

The northern Oregon coastline extends south from the mouth of the Columbia River to Florence. Landslides are a persistent problem along the Oregon coast due to weak soils and high concentration of erosional processes, resulting in slope failures and coastal erosion. Erosion on the toe (base) of the sea cliff causes destabilization and can result in the formation of notches or sea caves. North and Byrne (1965) determined that land sliding is active along 130 of the 240 km of coastline. Further, additional landslides can be triggered by seismic sources, such as the Cascadia Subduction Zone, which extends under the coast range where the North American tectonic plate is overriding the Juan de Fuca plate 60–120 km west of the coast (Mitchell et al., 1994). Within Lincoln County, Oregon there are several translational landslides moving through Tertiary (6–63 million years old) sedimentary rocks with coastal bluffs 20–60 m high (Priest et al., 2011). Priest and Allan (2004) describe these landslides from the Miocene age as thick to thin-bedded, very fine to medium grained, micaceous and carbonaceous arkosic sandstone and massive silty sandstone and are common with single block failures exceeding 100 m in width.

One of the most widely researched landslides along the Oregon coast is the Johnson Creek Landslide (JCL), located about 2 km south of Otter Rock and 11 km north of Newport along Highway 101 (Priest et al., 2006; Schulz and Ellis, 2007; Priest et al., 2011; Schulz et al., 2012). JCL is a translational, seaward-dipping landslide displacing through a coastal bluff consisting of Miocene siltstone and sandstone overlain by Quaternary marine terrace deposits (Priest et al., 2011). These investigations have found that the basal slide plane generally runs parallel to the dip of the Miocene rocks; however, the slide plane slopes inward toe block which tilts backwards. The primary extents of the landslide measures approximately 360 m wide, 200 m long (Schulz and Ellis, 2007).

Prior subsurface exploration of JCL has characterized and monitored the landslide movement (Landslide Technology, 2004; Priest et al., 2008; Schulz and Ellis, 2007). However, these efforts have been met with difficulty. Erosion pins were initially intended to monitor erosion, but too many pins were lost over the first winter season, preventing accurate determination of the total amount of erosion. Inclinometer casings were installed to measure landslide movement, but movement was so excessive that it prevented the inclinometer survey; therefore, manual extensometers of wire rope were installed to obtain measurements of movement. Landslide Technology (2004) and Priest et al. (2008) performed slope stability analyses to evaluate the influence of groundwater conditions, geotechnical parameters and toe erosion on the amount of landslide movement. The slope stability analyses determined the landslide is least stable in the southern portion of the landslide and increases in stability moving northward.

Priest et al. (2008), Olsen et al. (2012), and Olsen (in Press) used TLS to model the erosion of the bluff face as well as quantify landslide movement. Olsen et al. (2012) estimate landslide movement by manual extraction and comparison of features (houses, trees and stairwells) along the crest of the coastal bluff face of the landslide, concluding that areas of increased landslide movement also experience more erosion. Hence, for improved understanding and representation of the landslide movement, displacement needs to be monitored throughout the entire landslide area because of the variable movement.

1.4. Purpose

The aim of this research is to develop an automated algorithm that determines landslide movement along an eroding coast in a forested area using dense, time-series data acquired using terrestrial laser scanning. Specifically, key objectives were to:

- Develop a consistent, systematic, monitoring technique using existing (natural), durable features since artificial instrumentation is often destroyed from landslide movement.
- Map displacement across the slide so that one can identify distinct landslide blocks and understand the complexities of non-uniform landslide movement.
- Distinguish between erosion and landslide movement components of change observed between repeat surveys.
- Evaluate the sensitivity of methodology to input parameters.