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Assessing landslide deformation using trees in terrestrial lidar data

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ABSTRACT
Terrestrial lidar scanning (TLS) has become a widely accepted expert tool for monitoring geohazards on bare or sparsely vegetated slopes through change detection. Trees are often ignored during the TLS change detection process; however they can be an important indicator of active slope movement in vegetated areas. A study was undertaken to understand the application of TLS change detection in understanding landslide mechanics on vegetated landslides in the Peace River Valley including considerations for data collection and modifications to current data processing methods. TLS datasets collected in May and October 2018 were used to perform change detection and roto-translation methods were employed to understand landslide mechanics on a partially vegetated slope. Future applications to fully vegetated slopes are discussed.

RÉSUMÉ
Le balayage terrestre par lidar est devenu un outil largement accepté afin de surveiller les géo-aléas sur les sols nu ou partiellement boisé par mesure de détection de changements. La considération des arbres est souvent évitée dans ce processus. Par contre, les arbres peuvent offrir un indice important sur le niveau d'activité d'une pente partiellement boisée. Une étude a été entrepris pour évaluer l'application du balayage terrestre par lidar comme outil afin d'offrir un aperçu des mécanismes des glissements de terrains sur pentes partiellement boisées situées dans la vallée de la Riviere Peace. Cette étude considère la collection et le traitement de données. La collection et le traitement de données (e.g. roto-translation) ont été complété au mois de mai et octobre 2018. La détection de changements a été complété afin de comprendre les mécanismes des glissements de terrains sur une pente partiellement boisée. L'application future de ces méthodes est aussi discutée.

1 INTRODUCTION

Since the mid-2000's, terrestrial lidar scanning (TLS) has become an expert tool for geotechnical applications, including monitoring deformation of sparsely vegetated rock and soil slopes. A limitation of TLS has traditionally been the ability to monitor landslides on heavily vegetated slopes, as ground returns are limited by the presence of trees. Consequently, heavily treed areas are removed or ignored from TLS change detection analysis (Kromer et al., 2017). Trees often provide important evidence of slope movement on landslides, such as recurved trees that may be indicators of ongoing slope creep. The displacement and movement patterns of the tree stems may provide insight into landslide movement rates and mechanisms. On landslides with failure surfaces that are sub-parallel to the ground surface, tracking of tree stems may allow for better detection of these types of movement.

This paper explores the use of TLS scanning for tracking tree stems on partially treed slopes in the Peace River valley in order to track landslide movement. This approach specifically uses the trees captured in the data and the change detection methods developed for exposed rock and soil slopes. Considerations for data collection, modifications to current data processing methods, and future applications are discussed.

2 BACKGROUND

2.1 Motivation

The Site C Clean Energy Project involves the construction of a hydroelectric dam on the Peace River, south of Fort St. John in British Columbia. Construction began in 2015 and is ongoing. The Peace River valley contains an abundance of landslides which have a variety of morphologies and movement types. (Severin, 2004). Monitoring of these landslides is critical for safety during dam construction, headpond operations, reservoir filling, and long-term operation. The most common expected movement types in the study area are shallow, slope parallel colluvial debris slides, rotational earth slides, and translational bedrock and earth landslides, all of which have characteristic expected movement patterns of tree trunks and stems.

A regional-scale airborne lidar scanning (ALS) change detection study, comparing data from 2006 and 2015, was undertaken to identify slopes within the reservoir footprint that have been active in that time period (Mitchell et al., 2017). Using the results from this study, several slopes were selected for more detailed monitoring. Of these slopes, many are at least partially vegetated. While ALS is capable of penetrating vegetation cover to create a bare-earth slope model, high frequency data collection for single, isolated sites can be expensive. A more practical option for surface monitoring of these slopes is the use of TLS, which can be acquired at a higher frequency and high point density of more than 100 points/m^2 (compared to airborne lidar which can be costly and typically 1-3 points/m^2) from an area with good line of sight for the slope of interest, generally the opposite bank of the Peace River.

2.2 Current State of Practice

The typical data processing workflow for performing TLS change detection on bare and sparsely vegetated slopes includes the following steps:

- Align the more recent TLS data to a baseline dataset collected earlier in time using Iterative Closest Point (ICP) alignment techniques (Besl & McKay, 1992). During the alignment process, areas of dense vegetation are typically ignored to improve the accuracy of the alignment.
- Calculate a limit of detection (LoD) based on alignment accuracy between the two datasets.
- Compute the shortest distance change between the two TLS datasets and display the results as colour contoured 3D datasets.

Often the change detection results on heavily vegetated areas of the slope are ignored due to sparse data. In some cases, it is practical to monitor slope movement in treed areas by installing rigid targets (Franz et al., 2016). However, this requires additional cost, sites may be inaccessible to install targets, and targets are often quickly damaged due to environmental conditions or wildlife. Current methods of analysis are largely limited to measuring changes on bare exposed slopes, or using the limited ground returns available in vegetated areas. A limitation of these methods is that landslides with a failure surface that is sub-parallel to the ground surface may exhibit little topographic change between TLS or ALS scans (Figure 1). While the ground surface may appear unchanged, displacement and/or deformation of tree trunks and stems may provide insight into the landslide processes occurring on a slope.

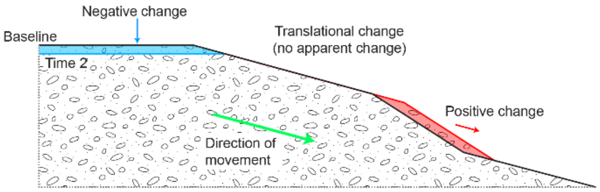

Figure 1. Schematic example of a translational landslide

2.3 Considerations for Treed Slopes

Advances in TLS sensors allow the collection of increasingly dense datasets at larger target distances. This allows imaging of complete tree stems in TLS data collected during leaf-off periods and therefore change measurements can be computed on these tree stems.

Apparent measured change in tree stem position between lidar scans can been affected by factors unrelated or indirectly related to landslide movement including tilting caused by wind or snow load and growth in tree stem diameter over time. The effects of tree stem tilt can be minimized by avoiding scanning during periods of high wind or snow load, and by only utilizing the bottom few metres of tree stem. Tilting of trees caused by landslide movement will often be in an upslope or downslope direction subparallel to the vector of landslide movement, but in some cases may also be quite haphazard.

Growth in tree stem diameter may be sufficient to influence their apparent position between scans obtained several years apart. Assuming no eccentricity in growth, apparent movement towards the scanner should be about half the increase in diameter between scans. Growth rates vary amongst species and according to a large number of local and regional factors including variability in soil moisture and nutrients, length of growing season, and availability and competition for sunlight. Stadt et al. (2007) provide examples of stem diameter growth rates for trees commonly found in mature boreal mixed forests in a range of ecozones in Alberta. In this study, the annual mean radial growth was found to range from 0.02 to 0.04 cm/year on average, with maximum rates just below 0.40 cm/year. It should be possible to differentiate detected slope movements from tree stem growth provided landslide movement rates exceed the radial growth rate over the comparison period. Tree tilting caused by landslide displacement tends to result in eccentric growth in tree stem diameter (e.g. Malik et al. 2016) with wider tree rings developing on the upslope part of the stem. Consequently, the effects of growth of tree stem diameter on apparent stem position detected by the lidar scanner may vary depending on whether the tree stems facing the lidar scanner are tilted upslope or downslope.

2.4 Deformation Patterns

It is anticipated that the apparent tree deformation patterns will be characteristic of the landslide mechanism present at a given slope. Schematic diagrams illustrating hypothetical tree deformation patterns for different landslide types are presented in Figure 2. For a rotational slide, it is anticipated that trees will exhibit backward tilting in the zone of depression below the headscarp, forward tilting at the toe, and may tilt in either direction within the centre of the slide depending on the internal deformation processes occurring (Figure 2a). For a landslide exhibiting shallow creep or translational movement subparallel to the slope, trees will likely remain upright but may exhibit curving at the base of the stem due to slow deformation processes (Figure 2b). For a sub-horizontal translational slide (Figure 2c) it is anticipated that trees may exhibit backward tilting in the graben or zone of depression below the headscarp, forward tilting at the toe of each landslide section, and will remain mainly upright within the centre of the sliding mass. For a debris avalanche it is likely that any trees remaining on the slope at the margins of the slide may have fallen or will be leaning significantly, and that trees at the base of the slope will have been pushed forward by the debris (Figure 2d).

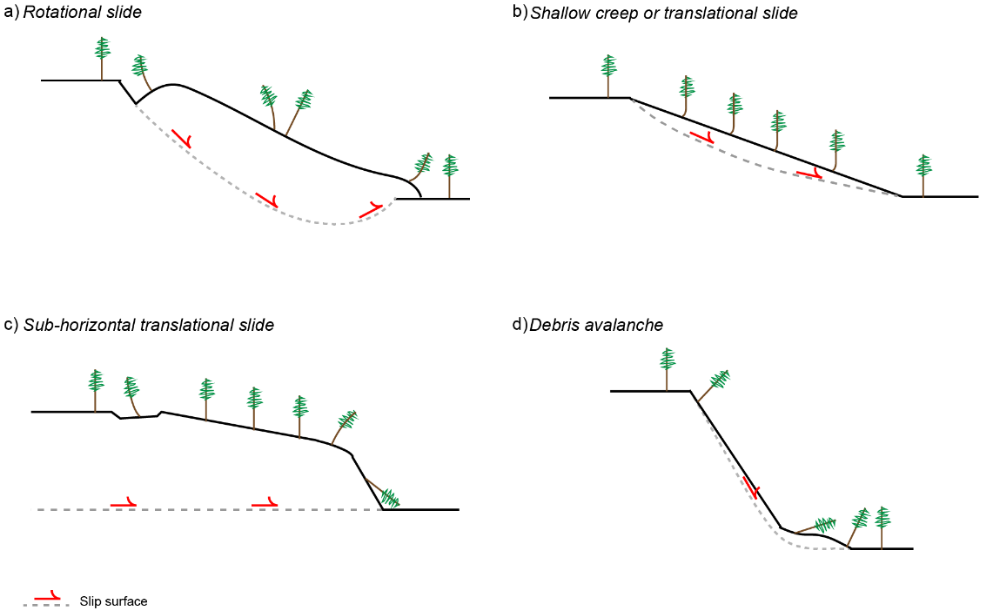

Figure 2. Schematic example of expected tree deformation patterns from a) rotational slides, b) shallow creep or translational slides, c) a sub-horizontal translational slide and d) a debris avalanche.

3 CASE STUDY

A study was undertaken for an active slope on the North bank of the Peace River to understand how TLS data may be used to track slope deformation in vegetated areas. Images of the slope in Figure 3 show curved and leaning trees, indicating that the slope has been recently active.

3.1 Site Background

The study slope has been classified as a compound earth slide in shale bedrock colluvium with an approximate source volume of 1 million m^3. This slope was determined to be recently active based on ALS change detection results (Figure 4a and 4b), which indicate reactivation of the colluvial material at the toe of the landslide. The entire landslide complex resembles the case of a multi-level sub-horizontal slide, and mechanism of the recent movement is interpreted to be mainly translational movement along a bedding plane in the underlying shale bedrock (similar to Figure 2c), suggested by a lack of change within the middle portion of the active area (Figure 4d). Visual observations made in the field suggest that trees in the active area are more or less upright until they start to lean and fall over the edge of the bank. Given that the Peace River is continuously eroding the toe of the landslide, and the translational movement can not be characterized well using ALS change detection, it is difficult to estimate the displacement rate of the slide

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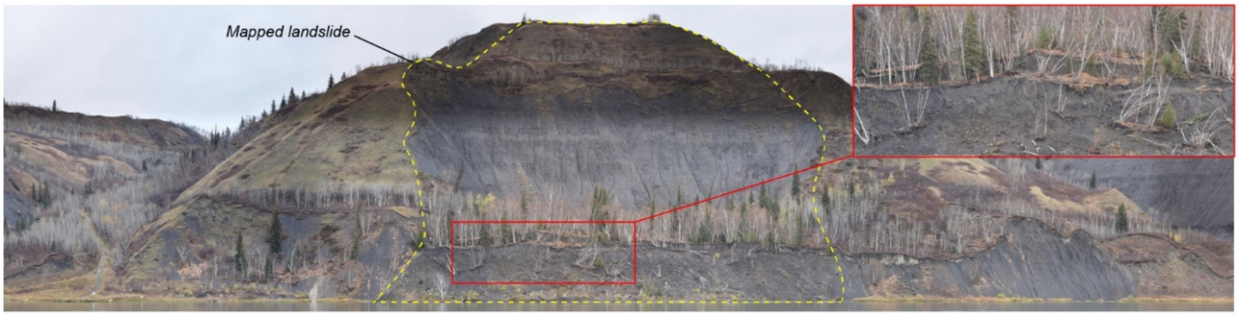

Figure 3. Overview of the study slope showing tilted and deformed trees at the landslide toe.

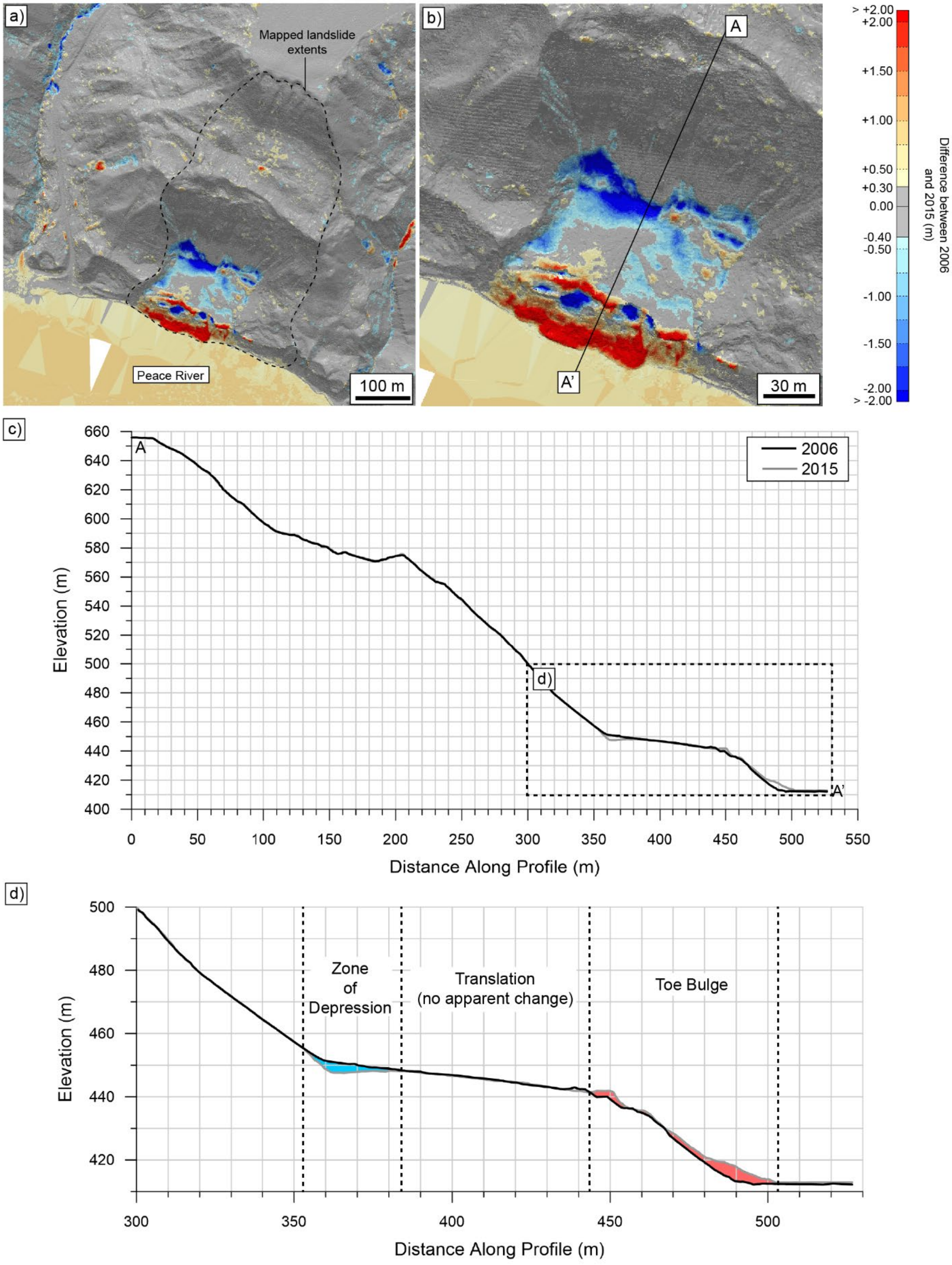

Figure 4. a) and b) ALS change detection results between 2006 and 2015 for the study slope and c) and d) slope profiles through airborne lidar data showing landslide displacement

3.2 Data Collection and Processing

TLS data were collected in May and October 2018 using a Teledyne-Optech Polaris LR scanner. The timing of the scans was selected to avoid snow cover and full leaf cover. Data were collected from a single scan station on the opposite bank of the Peace River with an average point spacing of 10 cm. The data were cleaned and then processed using PolyWorks (InnovMetric, 2019). The October 2018 data were aligned to the May 2018 data using Iterative Closest Point (ICP) alignment techniques and differences between the two models were computed using a shortest distance measurement. To align the October 2018 to the May 2018 model, only exposed, stable slopes were used to maximize the accuracy of the alignment.

In addition to the shortest distance change detection measurement, rigid object roto-translation methods developed for tracking rock block deformation (Rowe et al, 2018) were used to quantify the displacement rates and vector directions of individual trees across the landslide by selecting pairs of tree stems from the aligned datasets.

3.3 Results

The shortest distance change detection results are presented in Figure 5 with a LoD of +/- 0.10 m. The results show an overall positive displacement of the landslide toe (movement towards the TLS scanner, coloured yellow to red). Negative changes are also present on the toe of the landslide due to erosion and slumping of blocks off the front of the toe. Tree stems and leaves upslope of the landslide toe show evidence of displacement towards the scanner. Leaves outside of the active landslide area do not show any changes greater than the limit of detection suggesting that the changes measured within the leaves are not related to noise but in fact indicate translational movement.

The results of the roto-translation analysis are presented in Figure 6 and Table 1. The results suggest that the direction of landslide movement is typically south-southwest and displacement between the two scans was between 0.6 and 2.1 m depending on the area of the landslide. Trees closer to the toe of the landslide generally exhibited more displacement with a steeper plunge angle, which is consistent with the observation that the trees generally remain upright on the flat area of the slope and begin to fall over once the slope begins to steepen.

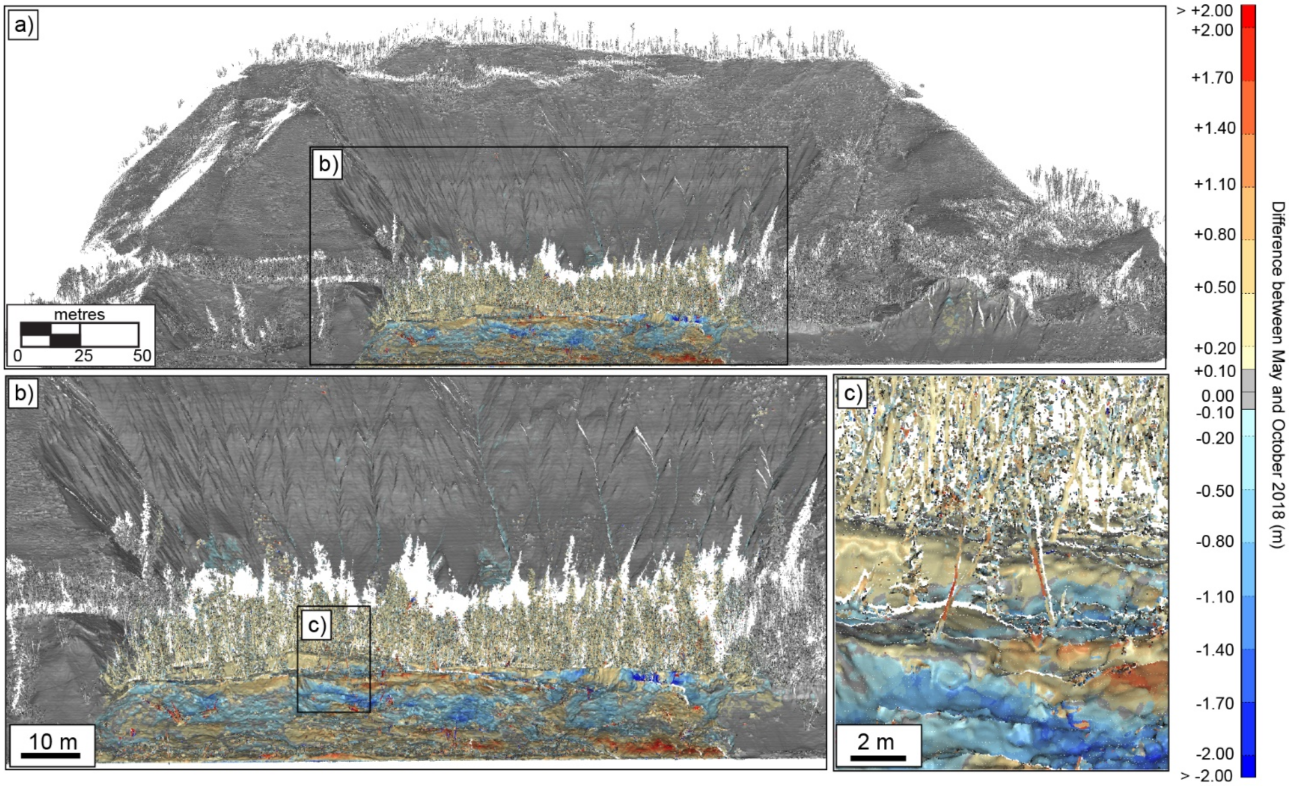

Figure 5. TLS change detection results for the study slope showing a) the entire slope, b) the active portion of the landslide and c) displacement of individual tree stems.

Table 1. Roto-translation results for individual tree stems

ID	Translation (m)	Azimuth (º)	Plunge (º)
1	0.6	210	-28
2	1.8	201	-21
3	2.1	199	-24
4	0.6	199	0
5	0.9	203	-17
6	0.7	189	-11
7	0.6	192	-4
8	0.7	200	-15

4 DISCUSSION

The results of the analysis demonstrate that by including treed areas in the TLS analysis, slope movement can be identified within treed areas and changes in tree stem position can be used to identify landslide displacement rates. While the shortest distance change maps (Figure 5) provide measurements of displacement magnitudes on the tree stems the magnitudes may not be accurate on lower parts of the tree stem. In the case of translational movement, the shortest distance measurements will only be equal to the true displacement of the tree at stem heights greater than the magnitude of the displacement. At lower stem heights, the shortest distance measurement will be measured between the tree stem and the ground surface, since the new ground surface will be closer to the lower parts of tree stem than the original position of the tree. (Figure 7). The shortest distance measurements cannot be easily validated using specific point displacement measurements as the limited number of data points and lack of distinct features on tree stems makes this difficult. For these reasons, use of the roto-translation methods may provide the most reliable estimate of displacement magnitudes and directions.

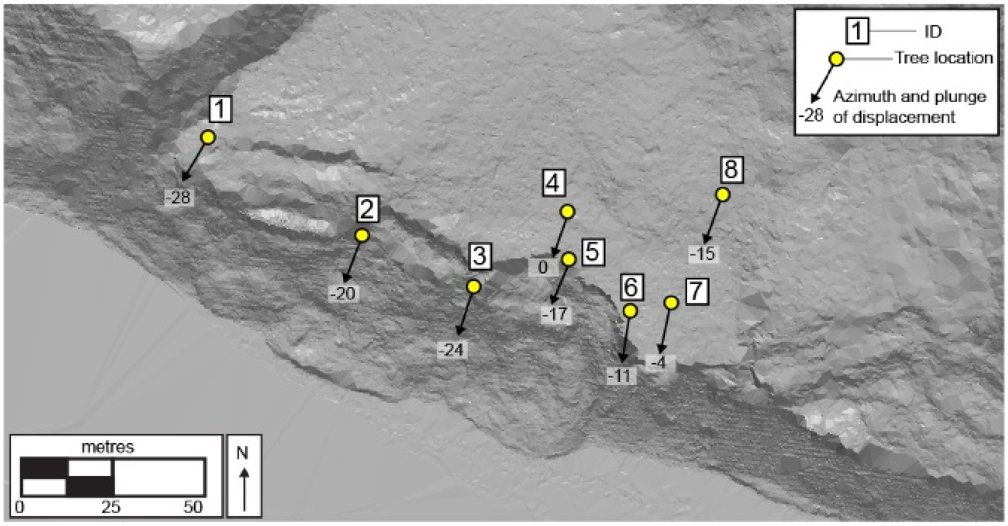

Figure 6. Roto-translation tracking locations and displacement vectors.

The study slope presented in this paper provided an ideal case where landslide movement was occurring in a treed area, and areas of stable, exposed slopes were present to be used in the ICP alignment. To better understand how these methods may be applied to fully vegetated slopes, the data were re-aligned using only points belonging to trees on stable parts of the slope. The resulting limit of detection was only 0.01 m greater than the initial alignment, suggesting that the analysis could be successful on a fully treed slope with a similar level of confidence. The increase in the limit of detection may be attributed to fewer data points used for the alignment, tree growth between scans, or noisier data in the foliage.

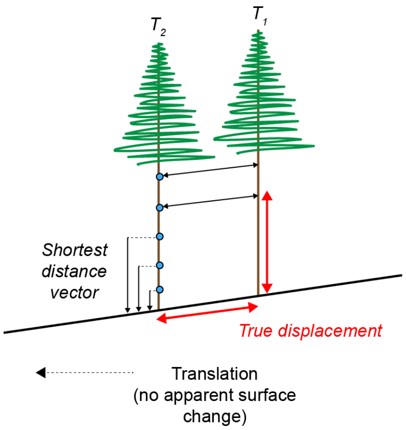

Figure 7. Schematic diagram illustrating limitations of shortest distance change measurements.

5 CONCLUSIONS

Tilting, curving, and displacement of trees can indicate ongoing slope movement within vegetated landslides. Ground inspections of these slides may provide a qualitative assessment of movement, but quantifying displacement rates can be difficult. ALS has the ability to penetrate through vegetation, however it can be difficult to detect displacement on translational landslides using ALS change detection when the shear surface is sub-parallel to the slope surface. The work presented in this study demonstrates that vegetation in TLS data can be utilized to better characterize landslide displacement rates where data in treed areas may have previously been omitted or ignored during change detection analyses. Next steps include applying these techniques to additional slopes with different landslide types and slopes that are more heavily or entirely vegetated.

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