Documenting Decadal Scale Landslide Movement Using Sequential Lidar and Structure from Motion Digital Elevation Models in the Cincinnati and Northern Kentucky Metropolitan Area

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Motivation for Study

Large, slow-moving landslides in the Cincinnati and Northern Kentucky Metropolitan Area may be intermittently active for years and require regular monitoring if they threaten urban infrastructure and property. Elevation changes between sequential Lidar and SfM surveys can document large vertical changes, but what is the minimum change that can be detected?

Here we measured topographic changes reflecting the movement of two slow-moving landslides over the period of 13 years. One of the landslides is a deep-seated rotational slump. The other is a thin translational debris-slide. In addition to documenting vertical DEM changes in the landslides, we evaluated the repeatability of combinations of Lidar- and UAV-derived surveys by measuring errors in areas outside of the landslide where no change should have occurred and estimate the threshold beyond which real elevation change can be detected.

Methods

To observe movement over 13 years, we used differences between pairs in a series of 1) digital elevation models (DEMs) from county-wide airborne lidar surveys in 2007 and 2012 and 2) structure-from-motion (SfM) DEMs derived from imagery acquired by an unmanned aerial vehicle (UAV) in 2019 and 2020.

The SfM imagery was processed in Agisoft Metashape and georeferenced using ground control points (GCPs) from the 2012 imagery and lidar-derived DEM. Difference maps were made in ArcGIS.

Change detection threshold values were calculated using two methods, both of which use the statistics of elevation differences in areas where no real change should have occurred. The first uses back-calculated estimates of the standard deviation of vertical errors for each individual survey, and the second uses an assumed threshold of ±2 standard deviations. (Haneberg 2017, Haneberg 2018).

Method 1: Individual Survey Errors. The standard deviation of errors of each survey is assumed to be normally distributed and is back-calculated using the standard distribution of errors in the difference map:

$$\sigma^2_{\Delta z,t2\text{-}t1} = \sigma^2_{z,t1} + \sigma^2_{z,t2}$$

where $\sigma_{\Delta z}$ is the standard deviation of error values in the no-change areas of the difference map, and $\sigma_{z,t1}$ and $\sigma_{z,t2}$ σ are the standard deviations of the individual survey errors.

Assuming $\sigma_z = \sigma_{(z,t1)} = \sigma_{(z,t2)}$ the threshold elevation difference that must be exceeded in order for the confidence level (α) to remain below a specified value is calculated:

$$\Delta z_{thr} = 2\sqrt{2}\,\sigma_z \mathrm{erfc}^{-1}(\alpha)$$

where Δz_{thr} is the threshold elevation difference and $\mathrm{erfc}^{-1}(\alpha)$ is the inverse complimentary error function. For α=0.05, this reduces to

$$\Delta z_{thr} = 3.92\sigma_z$$

Method 2: Difference Map Errors. The statistics of the elevation differences in an area where no change should have occurred are calculated. For a confidence level (α) of 0.05 and a normal distribution, the threshold elevation change is ±2 standard deviations.

Debris Slide

This thin translational debris-slide has formed in colluvium and fill. The slope was regraded in 2006, and fill placed along the upper slope below the road by 2010. The progressive changes between 2007 and 2020 are summarized in the captions for Figures 1-5.

Figure 1. Oblique view and photos of the debris-slide in 2019.

Taylor Landslide Elevation Difference from 2007 (Lidar) to 2012 (Lidar)

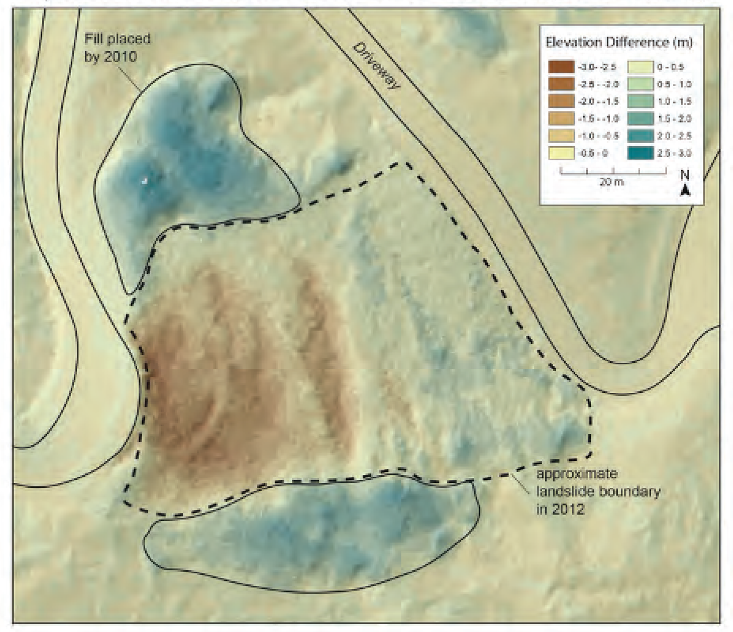

Figure 2. Elevation difference between 2007 and 2012. DEMs derived from county-wide airborne Lidar. Elevation gains of up to 3m are in blue, and losses are in red. Elevation gains at top of slope outside of the landslide area represent the fill placed between 2008 and 2010.

Taylor Landslide Elevation Difference from 2012 (Lidar) to 2019 (SfM)

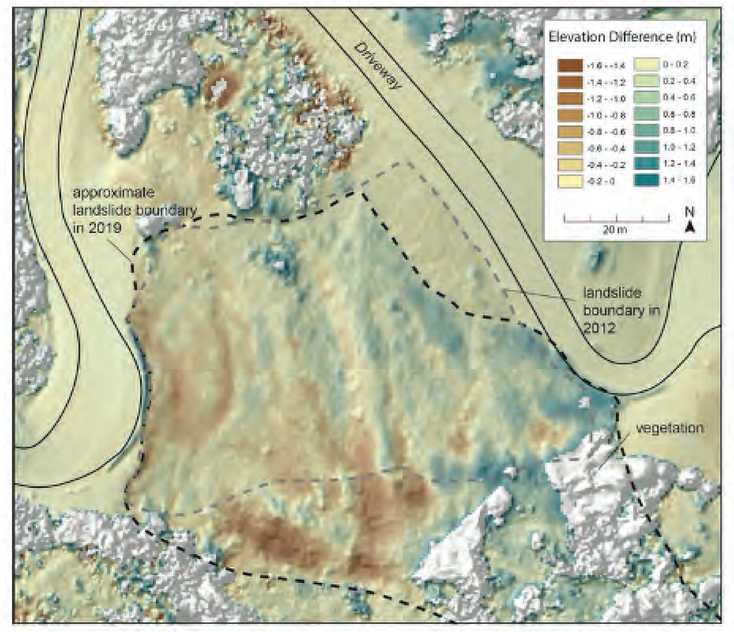

Figure 3. Elevation difference between 2012 (LiDAR) and 2019 (SfM). Elevation gains of up to 1.6m are in blue, and losses of up to 1.6m are shown in red (note the color scale has been compressed from the 2007-2012 map). The landslide has enlarged in the south.

Taylor Landslide Elevation Difference Over 2 Weeks in 2019 (SfM)

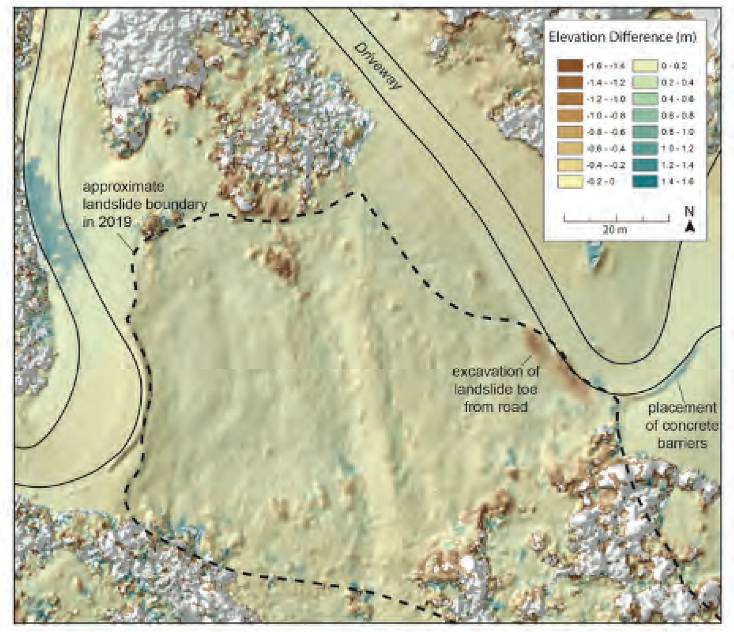

Figure 4. Elevation difference between March 11 and 26, 2019. Both DEMs were derived from SfM. There are some elevation changes due to the excavation of the toe and the placement of concrete barriers.

Taylor Landslide Elevation Difference from 2019 to 2020 (SfM)

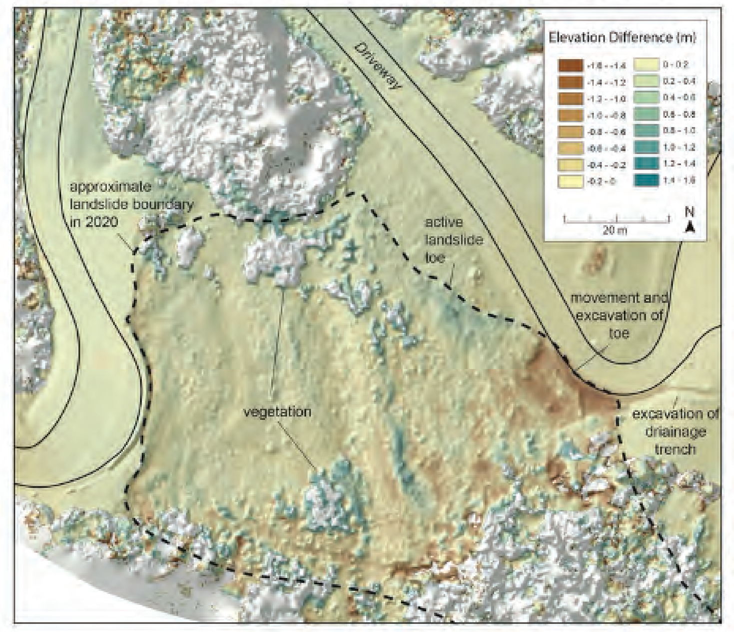

Figure 5. Elevation difference between 2019 and 2020. Both DEMs were derived from SfM. Elevation losses and gains are most apparent in the lower portion of the slide where the toe had mobilized and was being excavated.

Slump

This rotational slump formed in colluvium and fill. Fill was placed on the slope by 2000 when the road was rerouted and landslide activity began by 2004. The progressive changes between 2007 and 2020 are summarized in the caption for figures 7-9.

Figure 6. Oblique image and photos of the slump in 2019.

Highland Landslide Elevation Difference from 2007 (Lidar) to 2012 (Lidar)

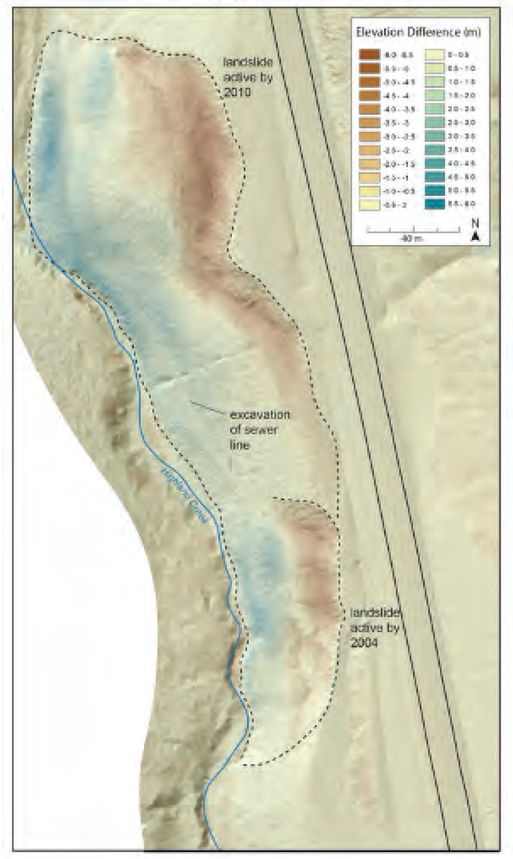

Figure 7. Elevation difference between 2007 and 2012. Both DEMs were derived from county-wide airborne LiDAR. Elevation gains of up to 6m are shown in blue, and elevation losses are shown in red. The southern landslide scarp was active by 2004, and the northern scarp became active by 2010.

Highland Landslide Elevation Difference from 2012 (Lidar) to 2019 (SfM)

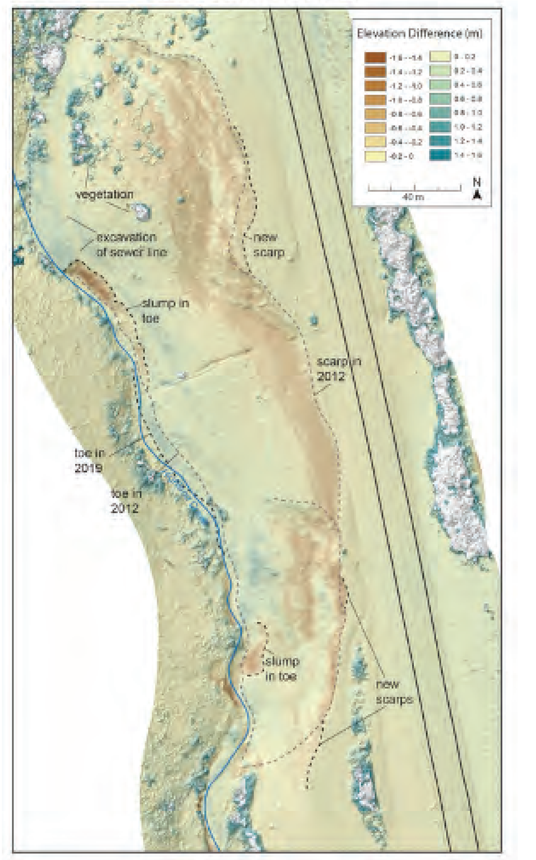

Figure 8. Elevation difference between 2012 (LiDAR) and 2019 (SfM). Elevation gains and losses of up to 2m are shown in blue, and red, respectively (note color scale has been compressed from the 2007-2012 map). The scarp has migrated upslope in a few locations. The toe has extended, and two new slumps have formed in the toe.

Highland Landslide Elevation Difference from 2019 to 2020 (SfM)

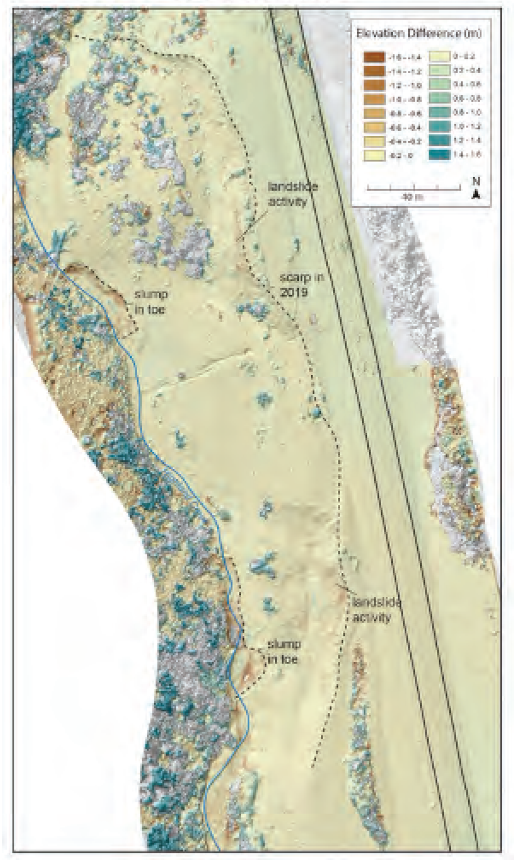

Figure 9. Elevation change between 2019 and 2020 using SfM. Elevation gains and losses of up to 1.6 m are shown in blue, and red, respectively (note the color scale has been compressed from the earlier maps). There is activity along the scarps in two locations and active slumps in the toe.

What is the limit of vertical change that can be detected?

The elevation change maps in Figs 2-5 and Fig 7-9 are displayed with color scales that visually neutralize elevation changes between ±0.2m or ±0.5m, depending on the map. Can smaller changes be detected? To estimate the threshold of detectible change we first evaluate the noise in the difference maps in three areas outside of the landslide where no elevation change is expected (Figures 10 and 11), two in the roadway and one in a grassy area. Then we estimate the threshold of detectible change using two methods based on the statistics of the noise in these no-change areas (Fig. 12)

Figure 10. Orthophoto of Taylor debris slide with sample areas from the landslide and where no elevation change is expected.

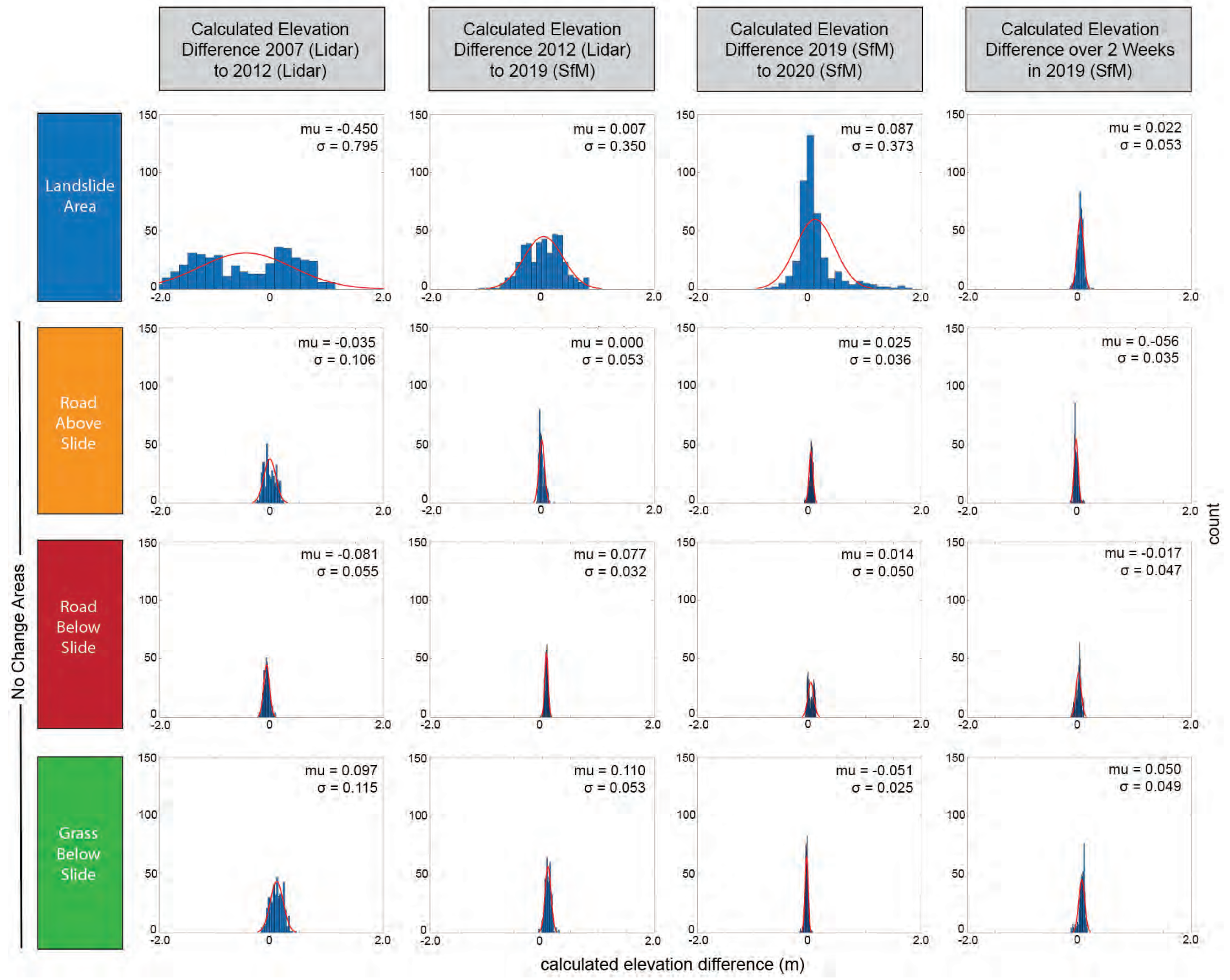

Figure 11. Histograms for each set of difference maps for each area sampled including the landslide itself and the no-change areas outside of the landslide. n = 420 for all sample sets.

We can observe the following from the histograms of the no-change areas:

- The difference between the 2007 and 2012 Lidar surveys is noisier than any other difference map. These Lidar surveys were county-wide surveys not designed for change detection. Differences in the flight paths, equipment and processing among other things could explain the differences between the surveys.
- The "no-change" area that appears to change the most is the grassy area. This could be due to changes in the grass surface due to growing and mowing.
- The difference between the Lidar and SfM map is the most biased: The mean of the difference in the no-change areas is higher than between any other survey at 0.05 ± 0.05 m, though if we toss out the grassy area, these errors are reduced to 0.03 ± 0.04 m.
- The repeatability between SfM surveys is pretty good: The mean and standard deviation in the no-change areas is 0.01 ± 0.04 m.

Threshold Maps Using Statistics of No-Change Areas

Next we compare maps that use two techniques to estimate the change detection threshold for movement between 2019-2020 using SfM DEMs. Map 12a was produced using a change detection threshold of ±0.14 derived from back-calculating the errors in the no-change areas of each individual SfM survey (Method 1). Map 12b was produced using a change detection threshold of ±0.10 using ±2 standard deviations of the errors in the no-change areas of the difference map (Method 2). Map 12c visually neutralizes elevation differences of ±0.20 m with a graduated color scale.

Changes such as the lowering of the scarp area and the internal deformation of the landslide that might be missed in Map 12c are readily visible in Maps 12a and 12b.

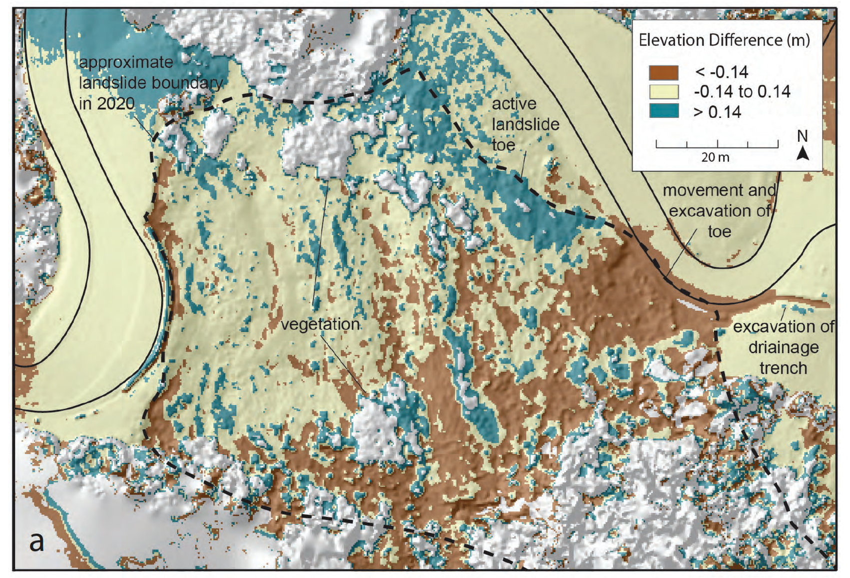

Figure 12a. Method 1: Map uses estimated back-calculated errors from each DEM to calculate a critical elevation difference detection threshold of 0.14 m.

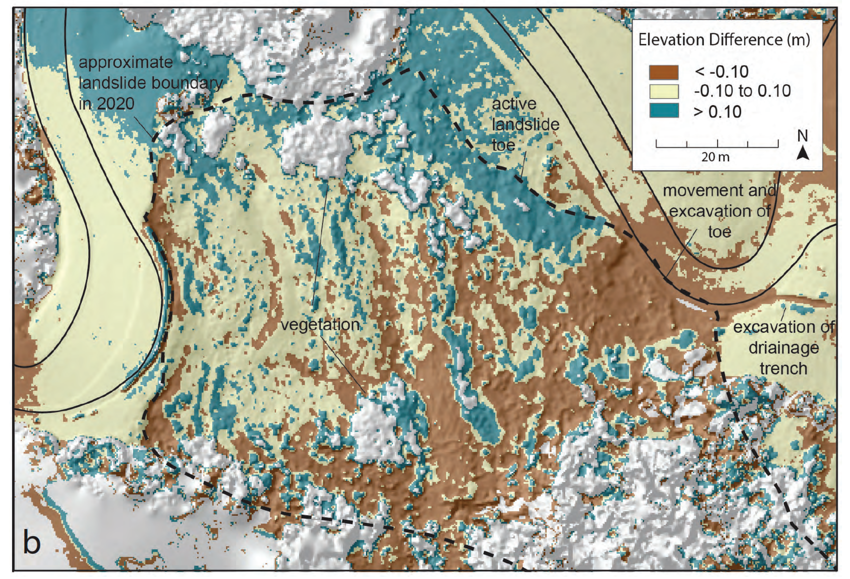

Figure 12b. Method 2: Map uses +/-2 standard deviations of the errors in no-change areas in the difference map to calculate a critical elevation difference detection threshold of 0.10 m.

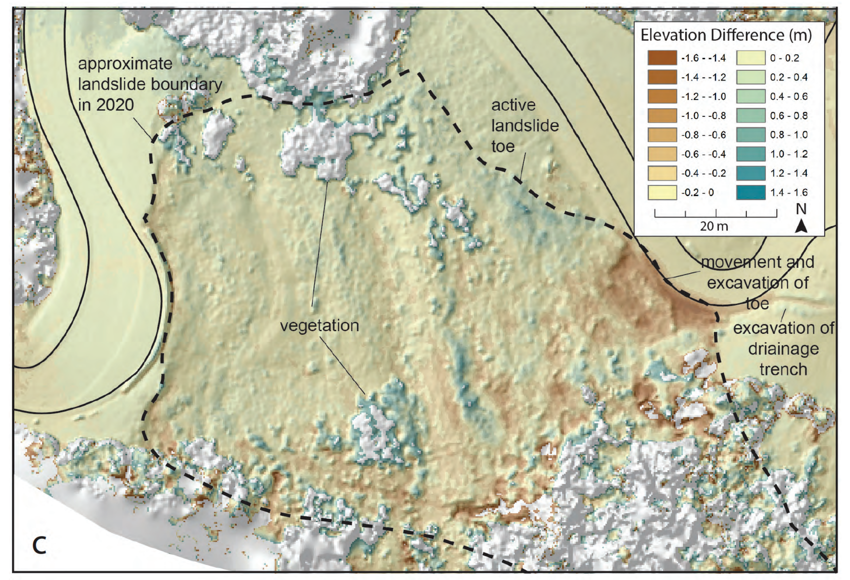

Figure 12c. Map uses a gradational color scale which neutralizes elevation differences between 0.20 and 0.2 m.

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