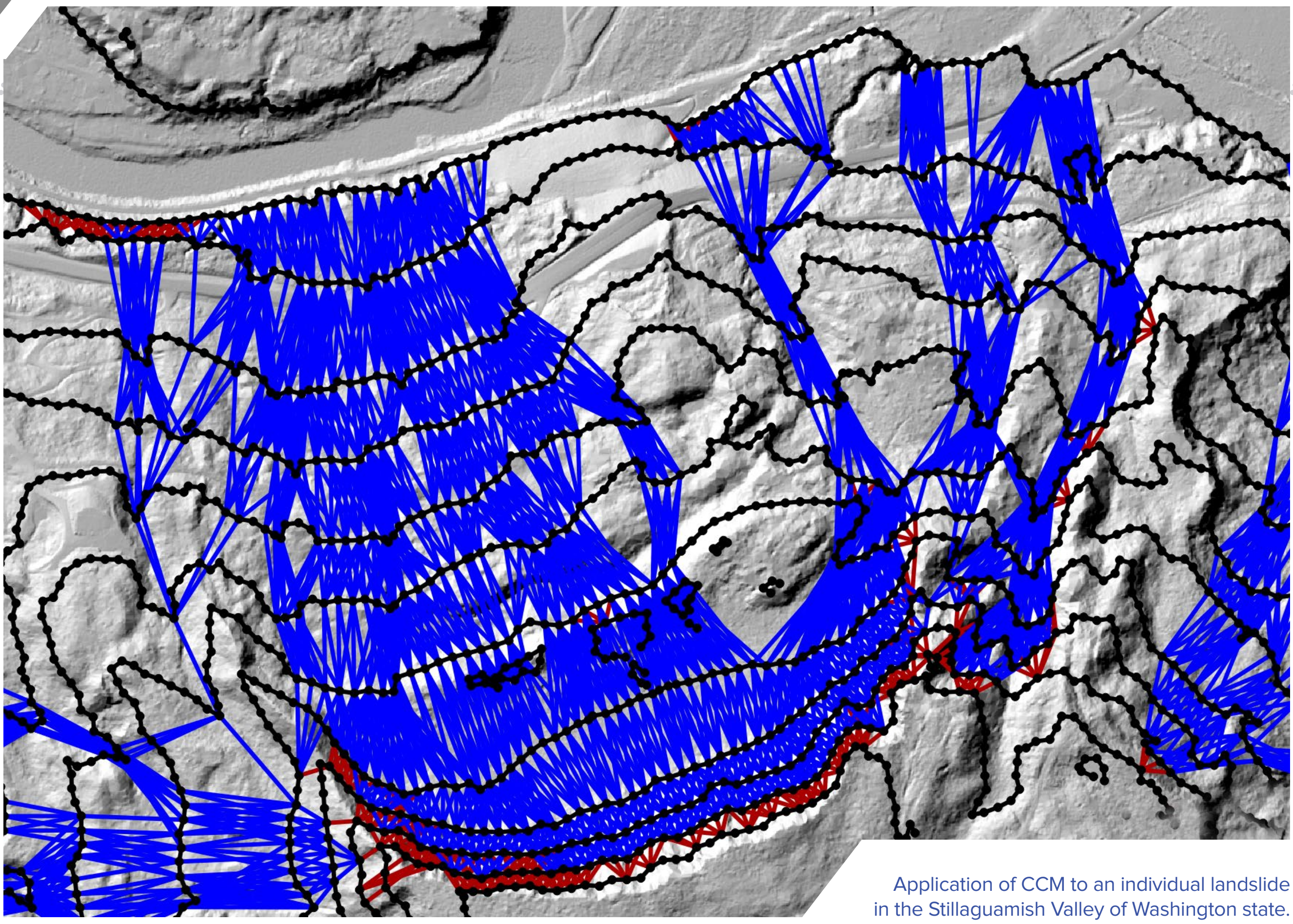


Application of CCM to an individual landslide in the Stillaguamish Valley of Washington state.

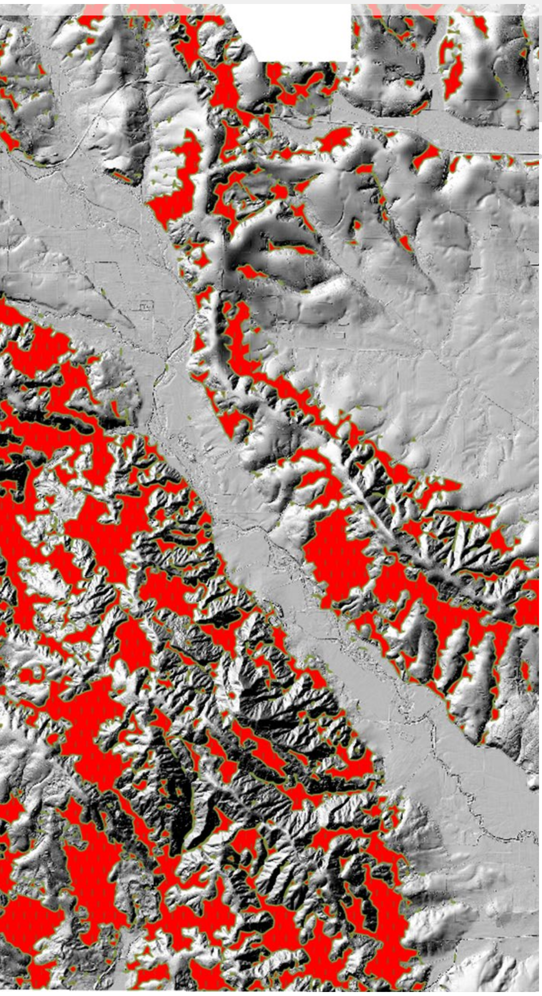
The Contour Connection Method

Inventorying and Classifying Landslides using Bare Earth Lidar

It was a sunny weekend morning on the North Fork of the Stillaguamish River when suddenly, the surrounding hills started moving. At 10:37AM, a landslide of approximately 7 million cubic yards of soil, rocks and trees swept across the Stillaguamish Valley, tragically taking the lives of 43 residents. In the aftermath of this disaster, colloquially known as the Oso Mudslide, a renewed interest in inventorying existing landslides was brought to the public eye. Many of the affected homes sat on the deposits of earlier large landslides.

A comprehensive, manual inventory of existing landslides in the valley had been performed, yet many of the local residents were unaware of the subtle, yet ominous features of the surrounding geology. The Oso mudslide presents a disaster where improved awareness of existing landslide hazards may have minimized the tragic loss of life. Many populated regions of the world are unaware that they too may be in the shadow of moving earth. The common hazard of landslides result in major economic, environmental and social impacts, yet despite their devastating effects, inventories of existing landslides are scarce or hard to find. The need for inventorying becomes apparent in the wake of the Oso disaster, yet current inventorying approaches are a challenging, time-consuming, and expensive process.

BY BEN **LESHCHINSKY**, MICHAEL **OLSEN**, BURAK **TANYU** AND JOSEPH **WARTMAN**



Landslide inventory resulting from a polygonised CCM analysis that was applied to an entire quadrant of BE lidar in NW Oregon.

Despite the impacts of landslides, knowledge of existing landslides where we live, work, or play is limited. It may not always be obvious that the convenient, flat grade we select to build a house is actually located on ancient landslide deposits. It may seem appropriate to build a highway that traverses a steep mountain on the opportune bench that exists on its flanks, but unknowingly may be the headscarp of an ancient landslide. Often these decisions seem unwise in retrospect, but it is difficult to know where past slope failures have occurred, especially with dense vegetative cover (e.g., a forest canopy). Fortunately, the challenges of inventorying these features are becoming more manageable with the development of remote sensing and surveying technologies, namely lidar.

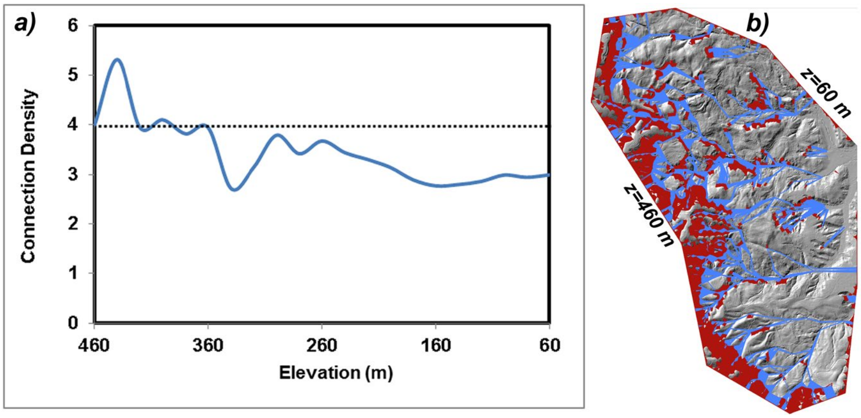
Current landslide mapping techniques include field inventorying, photogrammetry, and use of bare-earth (BE) lidar Digital Elevation Models (DEMs) to highlight regions of past instability. However, many of these techniques do not have sufficient accuracy, resolution or consistency for inventorying landslide deposits on a landscape scale, except the use of lidar bare earth digital elevation models (DEMs). These DEMs can reveal the landscape beneath vegetation and other obstructions, highlighting landslide features, including scarps, deposits, fans and more.

Current approaches to landslide inventorying with lidar include manual delineation, where a geologist must painstakingly mark hundreds, perhaps even thousands of landslide features using GIS tools, only identifying slope failures in a small area of land. Statistical or machine learning approaches have been used to "train" computers to use complex parameters to find landslides using a DEM, but this often requires experience or complex parameters. These approaches are important to defining an inventory, yet there are drawbacks—manual inventorying is extremely time-consuming and subjective; machine-learning approaches are not necessarily intuitive or simple to apply. Despite current collaborative efforts between computer scientists, geographers, engineers and geologists to expediently inventory current landslides, we are at a bottleneck. That is, in the wake of the Oso tragedy, the public sees the importance of inventorying past landslides, the same way flood maps or tsunami zones are widely available.

A new algorithm, called the Contour Connection Method (CCM), utilizes bare earth lidar to consistently detect landslide deposits on a landscape scale in an automated manner. This approach requires simple user input, and focuses on general landslide geometry—requiring input of the slopes of landslide scarps and deposits. The CCM algorithm functions by applying contours and nodes to a map, and using vectors connecting the nodes to evaluate gradient and associated landslide features. Connections having slopes greater than that defined as a scarp activate a downslope highlighting of deposits. These cascading vector connections are terminated when the gradient between contours is less than that of the slope defined as a deposit. Thus, the deposits of landslides can be bracketed by these two parameters.

CCM has shown strong agreement with manually inventoried landslide maps provided by the Oregon Department of Geology and Mineral Industries (DOGAMI), which serves as a leader in using BE lidar to delineate landslide features throughout the state of Oregon—a daunting task. Comparisons of manually delineated quadrants have shown up to 90% agreement (pixel-pixel) with geologist-inventoried landslides in a matter of minutes, presenting a means of expediting the important process of inventorying the ghosts of past landslides that surround all hilly or mountainous terrain. This presents a promising tool to help geologists consistently inventory existing landslides, especially in consideration of a federal effort to map all of the United States with high-resolution, aerial lidar, known as the 3D Elevation Plan (3DEP).

This process not only highlights deposits, but it yields a unique signature for each landslide feature that may be used to classify different landscape features. Each landslide feature has a distinct set of metadata—specifically,

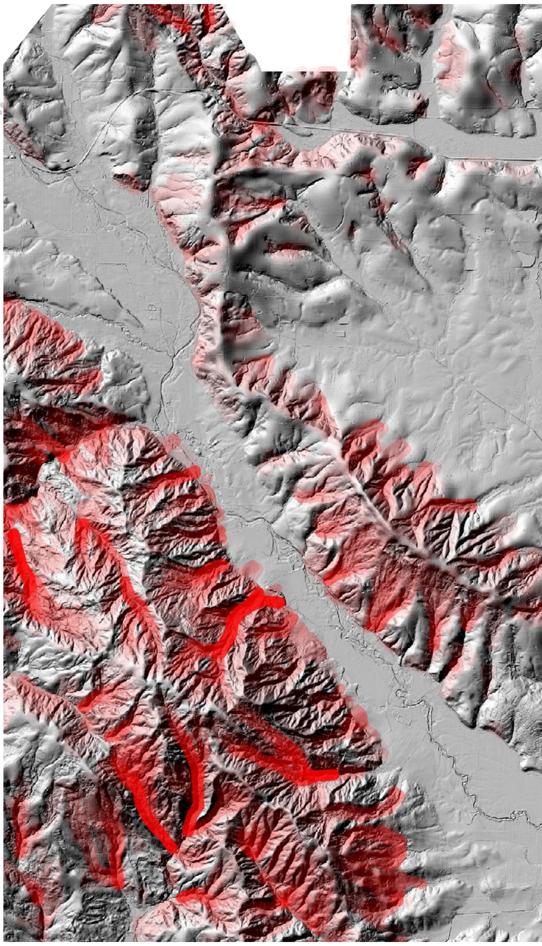


Individual landslide signature resulting from CCM analysis and density of connection vectors on each respective contour.

density of connection vectors on each contour—that provides a unique signature for each landslide. The given change in connection density over layers can be indicative of a landslide's progressive change in shape (e.g. concavity, convexity, and slope). Concurrently, an erratic signature is indicative of surface roughness (i.e. "hummocky" terrain), which is associated with younger features or specific landslide types. The features of this signature present a new means for classifying existing landslides within a consistent framework. That is, it presents a potential quantitative approach to differentiating between what would be considered an "earth flow", "translational slide", "debris flows" and more. With further refinement, this simplified approach presents an automated framework for not only highlighting landslide deposits, but classifying the type of slides and their respective ages consistently, an important component of assessing risk of reactivation and public risk.

In the wake of tragic events such as Oso, it is evident that inventories of past landslides should be public information and deserve greater attention. Current databases of landslides are limited and fragmented since they are based on a variety of inventories/geologic maps and have been mapped sporadically over time. This is not the fault of public agencies, but often results from a lack of resources allotted to these essential organizations as well as hazard mapping research. Often, when large landslides occur, little to no information exists, whether it is a reactivated landslide or a new slope failure. Moreover, an inventory of existing landslide hazards is critical, so a baseline quantity of existing landslides can be established—especially those of which are ongoing. Such knowledge is crucial to public safety, especially in the wake of significant precipitation or seismic activity. This insufficient availability of information is due to an enormous landscape that presents significant logistical challenges to geologists and engineers for manual inventorying. With the help of lidar and use of landslide inventorying tools like CCM, geologists may be able to cover the ground needed to continue this battle.

Details of the CCM algorithm and case studies can be found within a peer-reviewed article recently published in *Computers and Geosciences*:



Rasterized landslide deposit polygons applied to four quadrangles in western Oregon.

Ben A. Leshchinsky, Michael J. Olsen, Burak F. Tanyu, Contour connection method for automated identification and classification of landslide Deposits, Computers & Geosciences, ISSN 0098-3004, http://dx.doi.org/10.1016/j.cageo.2014.10.007. http://www.sciencedirect.com/science/article/pii/S0098300414002301

Ben Leshchinsky is an Assistant Professor of Geotechnical Engineering at Oregon State University.

Michael Olsen is an Assistant Professor of Geomatics at Oregon State University.

Burak Tanyu is an Assistant Professor of Geotechnical and Geological Engineering at George Mason University.

Joseph Wartman is the H. R. Berg Associate Professor of Geotechnical Engineering at the University of Washington.