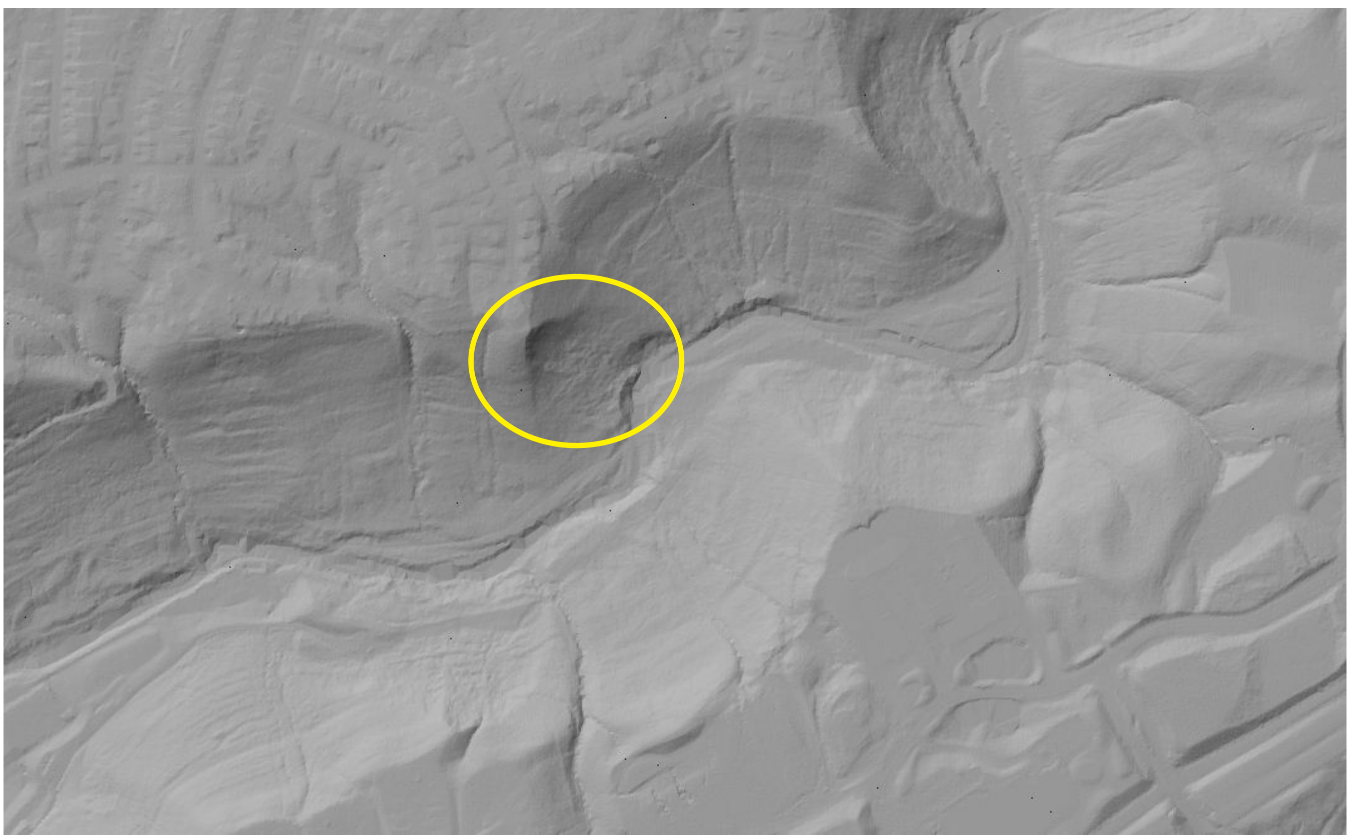
Kentucky Geological Survey
James C. Cobb, State Geologist and Director
University of Kentucky, Lexington

Using LiDAR to Map Landslides in Kenton and Campbell Counties, Kentucky

Matthew M. Crawford



Report of Investigations 24

Series XII, 2012

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General Intermediate Technical

On the cover: Example of a LiDAR hillshade digital elevation model in Kenton County, Ky. A landslide is circled in yellow, identified by the methods described in this report.

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Abstract

The geology and topography of northern Kentucky and Cincinnati make the area susceptible to landslides. Decades of development and slope modification have contributed to the area being prone to landslides and having one of the highest costs per capita in the United States for landslide damage. The slow nature of some landslides and incremental damage that can span several decades often result in lack of awareness of the problem, however. Many of the landslides go unreported, and citizens do not take advantage of resources to become educated about mitigating the problem.

Research at the Kentucky Geological Survey developed a methodology using high-resolution light detection and ranging (LiDAR) data optimal for the terrain of Kenton and Campbell Counties to document landslides and enter them into an inventory. Potential landslide locations were mapped and the resulting new data were digitized. Hillshade DEM maps were the primary data set used. Locations were field verified, where possible.

Continued use of high-resolution LiDAR to identify potential landslides will provide a framework for analyzing landslide data that is crucial to understanding the nature of landslide-prone areas and reducing long-term losses.

Introduction

Landslides have long been a problem in northern Kentucky, so slope stability in the area has been well researched for decades. Steep topography, bedrock geology, and unconsolidated soils make many parts of northern Kentucky susceptible to landslides. A 324-mi^2 area in Kenton and Campbell Counties, Ky., consists of a heavily populated northern part closer to Cincinnati and a more rural southern part (Fig. 1). Many documented landslides in this area have damaged roads, homes, and other infrastructure, causing financial losses for property owners and difficult decisions for government agencies and developers. Data obtained from the Kentucky Transportation Cabinet show that from 2002 to 2010, landslide repair costs to roads exceeded $1.5 million in Kenton and Campbell Counties. In addition to direct costs, indirect costs such as commerce hindered by road closures, devalued property, and environmental effects may exceed direct costs. The slow nature of some landslides, however, many not related to roads, leads to incremental damage that can span several decades, often making people less aware of the problem. Many landslides go unreported, and citizens do not take advantage of resources to become educated about how to recognize and mitigate the problems. The Kentucky Geological Survey therefore undertook a project to provide insight into preexisting landslides and recognize areas with potential for slope failure.

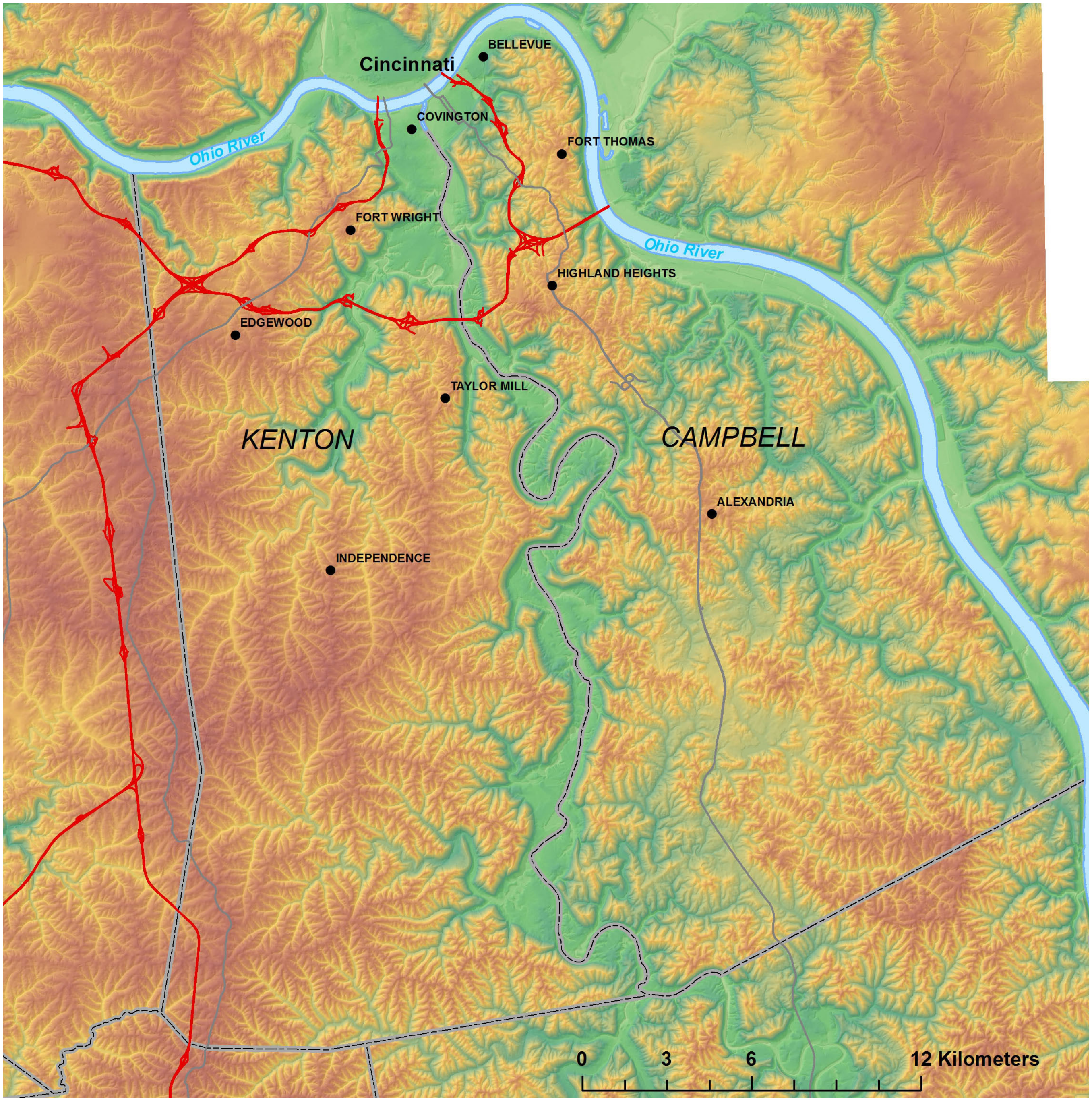

Figure 1. Location of Kenton and Campbell Counties. Elevation contours are draped over the hillshade. Green represents lower elevations and warm colors represent higher elevations. Interstate highways are shown as red lines and major state roads are light gray.

Background

Landslide identification and hazard mapping using light detection and ranging (LiDAR) data have been successful in other landslide-prone areas of the United States, such as Oregon, Washington, and Pennsylvania.

The Northern Kentucky Area Planning Commission contracted to have LiDAR flown and processed for Kenton and Campbell Counties in 2007, which the Kentucky Geological Survey was able to obtain. The planning commission provides many planning and GIS services to these counties, including high-resolution LiDAR imagery.

To better document the distribution and geologic context of landslides in Kentucky, the Kentucky Geological Survey is compiling a landslide inventory. The inventory database is based on inventories and landslide hazard assessment programs in other states. To date, KGS has inventoried 2,236 documented landslides that have accurate locations. Landslide locations come from a variety of sources: geologic maps, current field work, various government agencies, and the public. Using LiDAR to map landslide locations has significantly expanded the KGS inventory with information on slides not reported or detected from other sources.

LiDAR

Light detection and ranging produces high-resolution elevation data that can be used to produce many derivative products for mapping applications. Data are collected from an airplane by a laser pulse that bounces off the earth's surface and returns x, y, and z values for each pulse. GPS locations, the position of the aircraft, and the distance of the laser from the ground are used to produce highly accurate elevation values. Depending on the purpose of the LiDAR acquisition, up to 200,000 points per second can hit the earth. Typical horizontal resolution is approximately 10 times the ground spacing. For example, a 1-m spacing of points should reveal something 10 m wide on the ground. Laser point spacing varies, but 1.4-m spacing is common, leading to 2-ft contours on a map. LiDAR data processing classifies the returned laser pulses and differentiates those that hit the ground surface and those that hit something else, such as a tree branch, a building, or a car. This classification results in bare-earth, hillshade surface models (Fig. 2) as well as other geomorphic derivatives of LiDAR data, including elevation, topographic contours, slope, curvature, roughness, and moisture index. A successful project finds the right combination of these data sets in a multilayered geographic information system and makes an interpretation resulting in useful information.

Purpose

The purpose of this project was to develop an methodology for using LiDAR data in the geologic setting of Kenton and Campbell Counties and to document preexisting landslides to enhance the KGS inventory. Potential landslides were identified using digital elevation models to digitize the data. Using high-resolution LiDAR to identify potential landslides provides a framework for analyzing landslide data that are crucial to understanding the nature of landslide-prone areas and reduce long-term losses from landslides.

Geologic Setting and Landslide Types

Bedrock geology, unconsolidated soils, glacial deposits, and engineering fills are all associated with landslides in Kenton and Campbell Counties. Ordovician bedrock geology consists of, in ascending order, the Kope Formation, Fairview Formation, Grant Lake Limestone, and Bull Fork Formation. Although landslides can occur in any of these units, the Kope Formation is especially problematic and is associated with many of the landslides

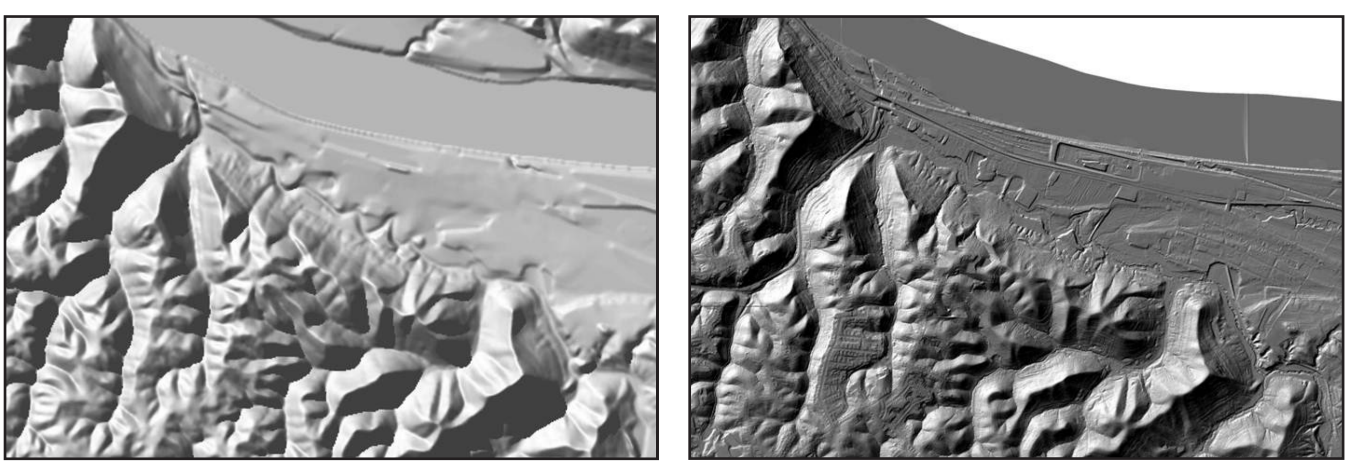

Figure 2. Comparison of elevation models: a 10-m digital elevation model hillshade (left) and LiDAR hillshade (right).

in the area. The Kope consists of approximately 75 percent shale and is 200 to 250 ft thick, primarily cropping out along river valleys and the lower parts of hills. The Kope shale weathers easily, slumping and producing colluvial soils of variable thickness (Fig. 3). Composition of the colluvium ranges from clayey (predominantly illite) to silty to coarse-grained with abundant limestone slabs. Thickness of colluvial soils varies, but they are typically thicker at the toe of a slope. Landslides occur on steep slopes in the colluvium or along the colluvial-bedrock contact. When clay-rich colluvium is mixed with large amounts of water, the soil's pore-water pressure increases, adding to the overall load on the slope. When the pore-water pressure increases, the effective stress decreases, causing a decrease in strength, which can cause landslides (Fig. 4). Other surficial deposits in the area are prone to landslides as well. Pleistocene glaciation in the region produced clayey lake deposits, outwash, glacial drift, and other fluvial deposits that fail and can damage roads or other infrastructure. Artificial fill, particularly above and below roadways, is also susceptible to landslides.

The most common types of landslides are small, thin translational slides and thick rotational slides on steeper slopes (Fig. 5). Less frequent block slides occur in unconsolidated glacial deposits. In a translational slide, thin layers of colluvium move downslope along the underlying bedrock contact. Rotational slides occur in thicker colluvial slopes, artificial fill, and lake deposits where scarps and slide boundaries are more evident but the failure plane is more difficult to identify. Depending on the type of slide, rates of movement range from slow or even imperceptible to meters per day, and damage can be variable as well. Preexisting landslides are generally more susceptible to further slope movement than colluvial slopes that show no sign of displacement and are undisturbed (Agnello, 2009). Landslide movement in colluvium is most common during the spring and winter when precipitation is greater (Agnello, 2009). Many landslides are also associated with some type of human disturbance, such as improper drainage, steepening the slope to build a road or building, or altering the load on a slope.

Methodology

The following steps were taken to identify landslides:

- Applied Imagery's Quick Terrain Modeler software was used to create DEM data sets from LAS files.
- DEM's were imported into ESRI's ArcMap for visualization, spatial analysis, and digitization.
- Digitized landslides were reexamined in 3D in Quick Terrain Modeler (v. 7.1.0).
- Locations were field-checked.

Figure 3. Outcrop of the Kope Formation. Thin to thick, stony, clay-rich colluvial soil covers the slopes. When saturated, the soil can erode rapidly, potentially developing landslides.

Figure 4. Landslide along Ky. 3187. Thick colluvium is shown at the bottom of the photo and a threatened home toward the top.

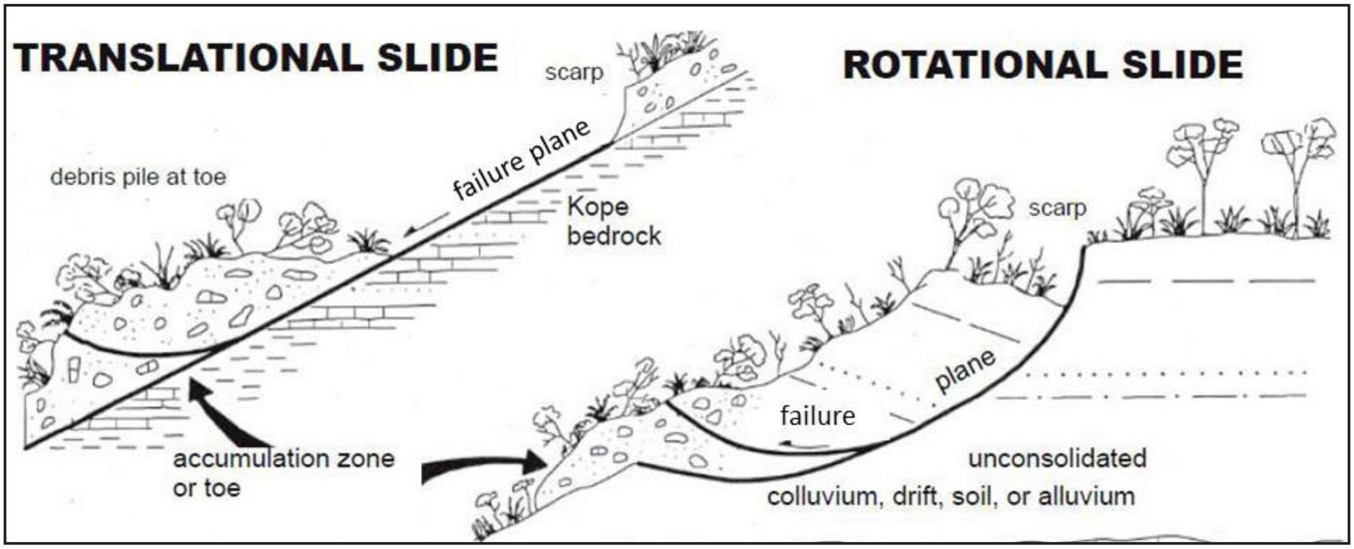

Figure 5. Illustrations of translational and rotational landslides in the study area. From Potter (2007).

Data Sets

Standard LAS files from LiDAR were processed to create digital elevation models, slope maps, and hillshade DEM's. LAS files are binary files that contain the x, y, z data as well as the classifications of the multiple point returns (ground, trees, buildings, vehicles, powerlines, and bridges). Only the points classified as ground were used to create the bare-earth model. LiDAR bare-earth elevation models prepared as hillshade DEM maps were the primary data set used for visualization and landslide mapping. The horizontal resolution of the data was 1 m. The LAS files were imported into Quick Terrain Modeler to create the hillshade, bare-earth digital elevation models. Hillshade DEM's of various extents were created, with a sun angle of 45° and an azimuth of 35° specified. The models were exported as hillshade DEM's (georeferenced TIF files) that could be used in a geographic information system with other spatial data sets. Other data sets used were topographic contours (2- and 4-ft intervals), 2-ft-resolution color aerial photography (taken during a season without leaves on trees, allowing better views of the ground and structures—referred to as leaf-off), and 1:24,000-scale geologic map data.

Visualization and Analysis

Potential preexisting, previously undetected landslides were identified by visual examination of slope morphology at different scales. The hillshade DEM's were used in ArcMap to map potential landslides. ArcMap allows for other data sets (contours, aerial photography, geology, etc.) to be used in conjunction with the LiDAR. The hillshade DEM's were systematically panned at various scales to identify and digitize the areal extent of potential landslides. Draping the topographic contours over the hillshade was important for accentuating the slope geomorphology. A reference grid was used to help organize the panning and zooming across the DEM's. Examination occurred at 1:10,000, 1:5,000, and 1:2,000 scales. All digitizing of potential landslide extents was done at a scale of 1:2,000.

Potential landslides were primarily identified and mapped based on geomorphic expression on the hillshade models. Steep scarps, hummocky terrain, concave and convex areas, and thick toeslopes were possible indicators of landslides (Fig. 6). Changes in contour spacing helped accentuate thick toeslopes where the landslide deposits had spread out, creating a gentler slope. The geology and leaf-off aerial photography were also used in the visualization and analysis process. Evidence of landslides, such as repaired roads and leaning trees, was occasionally seen in the aerial imagery.

Potential landslide extents were digitized and assigned general confidence levels. Confidence levels assigned to digitized polygons were "con-

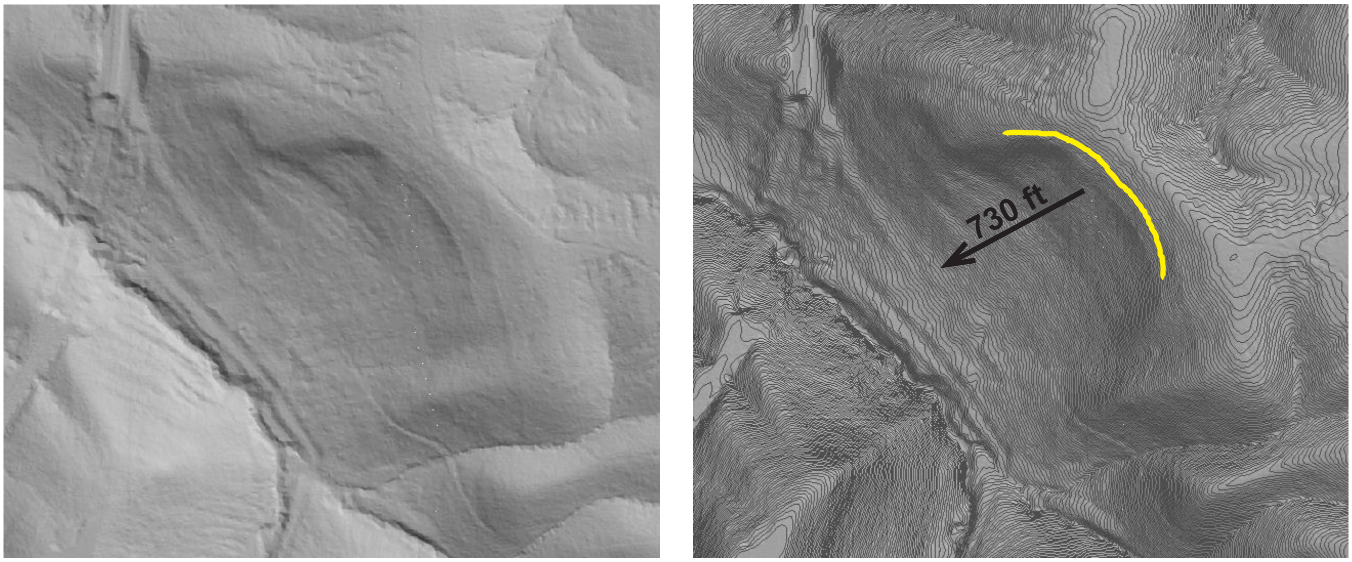

Figure 6. LiDAR hillshade DEM without contours (left) and with contours (right). The 2-ft contours accentuate the slope morphology: scarp (in yellow), concavity, landslide flanks, and hummocky terrain.

fident," "moderately confident," and "questionable," based on the visual clarity and geomorphic signature on the LiDAR hillshade model. Some of the questions dictating the confidence level included: How visible is the scarp? How visible is the toeslope? How much concavity or convexity is shown? Is the hummocky terrain actually a landslide or is it a modified surface that was forested? A standard rating system was not used to classify confidence; instead, it was a subjective decision by the mapper.

Distinguishing between hummocky landslides and a general "roughness" in the LiDAR hillshade (Fig. 7) was a challenge. ("Roughness" refers to the hillshade quality and local landscape variability. The roughness may represent actual landscape ruggedness and discrete features, or a "false topography" because of sun angle, azimuth, resolution, and bare-earth derivation of actual landscape.) The data-processing algorithms that produce bare-earth models can also create false ground-surface roughness (McKenna and others, 2008). Roughness appears to be more prominent on forested slopes, particularly slopes with many cedar trees. Southwest-facing slopes also exhibited more roughness than other slopes of similar land use. This would most likely change if hillshade DEM's were created with different azimuths. Mapping landslides in the more urban areas of Kenton and Campbell Counties was also a challenge. Densely populated neighborhoods with altered landscapes and abundant fill areas can be deceiving in a bare-earth surface model. Many of these areas appear to have landslides, but usually are artificially contoured terrain, not a landslide. The color, leaf-off, 2-ft-resolution aerial photography helped clarify questionable geomorphology in urban areas.

Knowing where the geologic contacts between formations are also helped in the analysis of slope geomorphology. Bedrock controls how hummocky some slopes are. Many places initially thought to be a landslide scarp or to have ques-

Figure 7. LiDAR hillshade exhibiting hummocky slopes and roughness. Although these slopes may be creeping, the roughness is probably an artifact of forested slopes, aspect, and geology.

tionable geomorphology were actually the contact between the Fairview Formation and the underlying Kope Formation. The Fairview is interbedded limestone and shale with about 40 percent limestone near the base increasing to about 65 percent near the top. The Kope is interbedded shale and limestone, shale comprising about 80 percent of the formation. The transition of a more resistant limestone to weaker shale shows up very well in the LiDAR hillshade (Fig. 8). The breaks in slope in the Fairview are probably limestone beds that extend in a more continuous fashion along the slope than a landslide scarp would.

Reexamination of Surface Models

After initial identification of potential landslides in ArcMap, selected digitized features were reexamined in Quick Terrain Modeler for verification. This software allows for the rapid change of azimuths and sun angles. Different lighting and perspective on slope geomorphology and potential landslides help with assigning the confidence level (Figs. 9–10). Scarps or concavity observed with one sun angle may appear completely different with other lighting orientations. In addition, Quick Terrain Modeler allows for 3D visualization, whereas ArcMap is best for 2D map view of data sets. Using rapid zooming and panning tools with 3D was very helpful in assigning confidence to the digitized landslide extents, confirming well-defined scarps, flanks, or thick toeslopes. The areas focused on were the landslides digitized in ArcMap. Approximately 25 percent of the slides (about 50) were viewed with different lighting and viewed in 3D. For about half of those, the confidence was changed from questionable to moderately confident, and the other half were left as questionable. Potential landslides that were initially attributed as questionable and not viewed in 3D were left as questionable.

Field-Checking

Field-checking was attempted for approximately 20 percent of the landslides whose extents were digitized. A strict project timeframe and inaccessibility controlled how much field verification was possible. Clusters of landslides were visited to try to verify as many as possible. Separate attributes were assigned to the field-checked landslides: "confirmed"—landslide deposits and geomorphic features were observed in the field, "likely"—the actual deposit was not observed, but a landslide is likely based on proximity to other slides or other telling geomorphic features, "observed but could not determine"—the deposit was accessible but further field investigation was required, and "no access"—the landslide was on private property, inaccessible terrain, or could not be seen.

Many of the confirmed landslides could be seen from the road, and road damage was usually associated with them (Figs. 11–13). Recent scarps were also present in many slides, and deposition was active toward the toe of the slide (Fig. 14). Determining that potential landslides were likely was a subjective process. For example, a potential landslide might have been identified on a slope, and slumping in the road below it provided field verification, but it was not clear whether there was ac-

Figure 8. Geology (left) compared to the LiDAR hillshade image (right). The break between the more limestone-rich Fairview Formation and the shale-rich Kope Formation is evident in the LiDAR image.

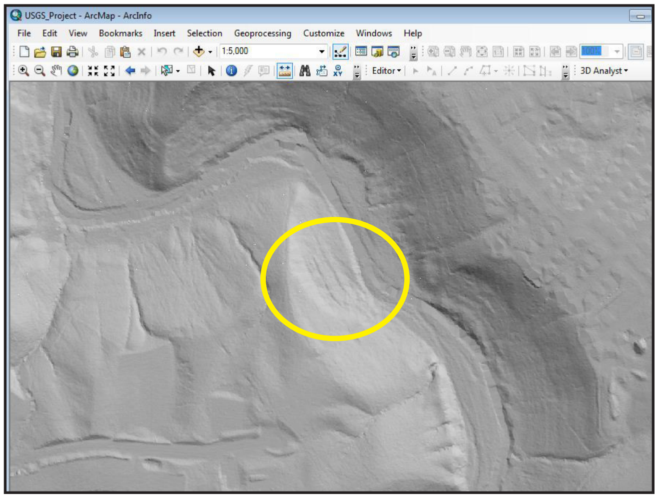

Figure 9. Image of a potential landslide (circled), viewed in ArcMap. Azimuth and sun angle were 45° when hillshades were created.

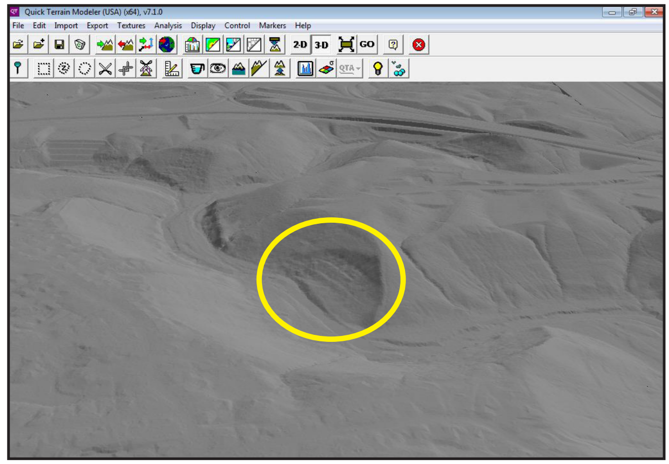

Figure 10. Three-dimensional view of the same landslide shown in Figure 9 in Quick Terrain Modeler. Changing the sun angle and azimuth can make the scarp and flanks stand out. The image was rotated in 3D and the azimuth was changed to 225°. This landslide was termed confident after it was viewed with Quick Terrain Modeler.

tive sliding above the road or if there was geologic control on the geomorphology of the slope. Many of these slopes are creeping, but distinguishing between active creep and relict, nonactive movement makes attribution difficult.

Results

Two hundred thirty-four potential landslides were detected in Kenton and Campbell Counties, and their extents were digitized. Twenty landslides (approximately 9 percent) were initially attributed as confident (Fig. 15). The other slides were attributed as questionable or moderately confident (Figs. 16–17). The LiDAR hillshade geomorphology, geology, and proximity to urbanized areas dictated the initial classification. Reexamination in Quick Terrain Modeler changed the initial classification (i.e., from questionable to confident or vice versa) of some of the slides. Landslides were not deleted from or added to the inventory after Quick Terrain Modeler was used.

Forty-five landslides (approximately 20 percent) were field-checked. Of those, 20 were confirmed, 18 were likely or observed but could not be determined, and seven were not accessible. Landslide type (translational or rotational) was not de-

Figure 11. An old I-beam pier retaining wall in the grass suggests previous slope failure, and a leaning telephone pole suggests the slope is actively creeping.

Figure 12. Evidence of landslide activity: The road is benched into the middle of the slope and the landslide stretches above and below the road. There is significant offset in the pavement.

Figure 13. Recently repaired I-beam piers and leaning telephone poles along Ky. 8 are evidence of landslide activity. Ky. 8 is in constant need of repair because of landslide damage.

Figure 14. A scarp (outlined in yellow) from a recent landslide. Identification of offsets like this using LiDAR can flag these areas as highly susceptible to future failure.

termined by LiDAR visualization. If landslide type could be determined in the field, then it was noted. Many of the landslides mapped were not associated with roadways and are in rural, wooded areas that are private property.

Using airborne LiDAR for detailed inventory mapping significantly improves awareness of landslide locations not previously known, especially in forested and suburban landscapes.

Discussion and Future Work

This study successfully used LiDAR to map landslides in Kenton and Campbell Counties. Although there were some limitations, the methodology provided here can be a precedent for future studies. Potential landslides were identified that would not have been identified with traditional, lower-resolution GIS data. One of the strengths of using LiDAR is being able to map potential landslides in areas not accessible by roads. Much of the landslide data in the existing KGS landslide inventory is from road-related slide activity, and are too small to see in the LiDAR or were repaired before the LiDAR was flown. Mapping landslide locations on slopes unrelated to roads or other human activity can provide a better understanding of landslide activity within a natural geologic and geomorphic context.

In addition to revealing inaccessible and small slides, this methodology can indicate future failure. Many of the landslides mapped are old, creeping slides that may not yet have been a problem. A heavy rain or other trigger could cause these existing landslides to move again, potentially quickly and unexpectedly (Figs. 18–19).

Hazard mitigation efforts continue across the state to help citizens facing landslide problems. Although mitigation projects provide solutions, obtaining funding is often difficult, and the process can take years to implement.

This study was limited by time and ability to field-check identified landslides. Urbanization in parts of Kenton and Campbell Counties also made landslide identification with LiDAR challenging. Extensive neighborhoods, large industrial areas, and Interstate highways can mask the natural slope geomorphology. Using Quick Terrain Modeler helped with the initial confidence level of landslide identification. Using software specifically designed for processing large amounts of LiDAR data and having the capability to view the data in 3D is very effective. Although ArcMap was effective for 2D mapping, many traditional GIS programs cannot process large data sets with the speed needed for detailed slope visualization.

The amount of LiDAR data available for Kentucky will increase in the future. High-resolution data sets will become available for other landslide-prone counties, and studies similar to this one can provide precedent for future landslide inventory mapping. An automated program that completes the image analysis part of landslide mapping

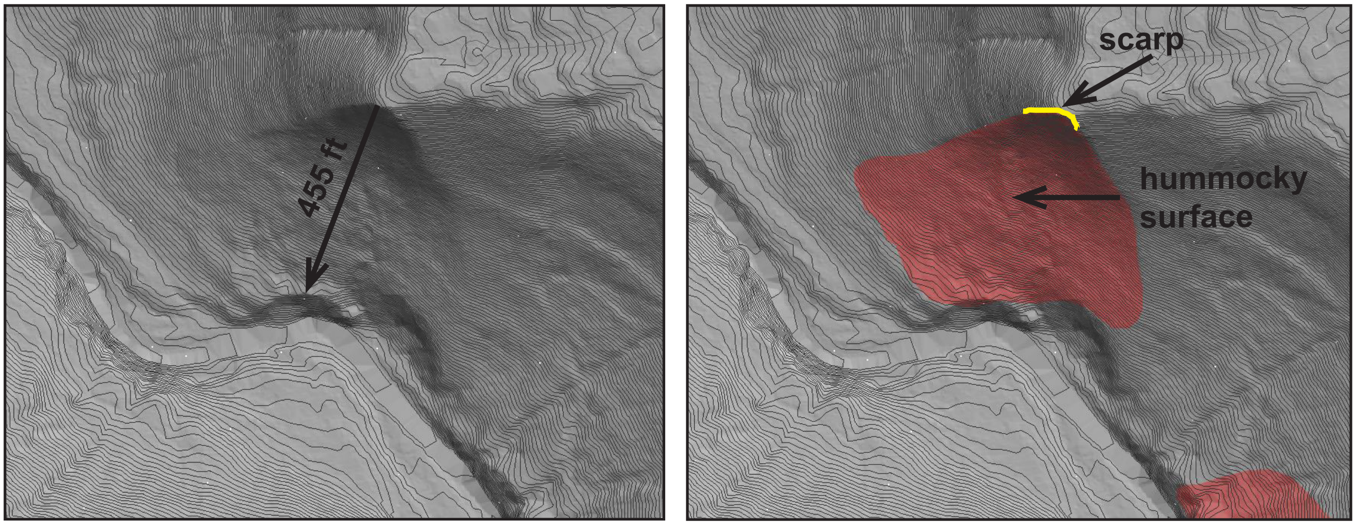

Figure 15. Example of a landslide identified on the LiDAR image (left) and the digitized polygon (right). Note the scarp (dashed yellow line) at the steep top part of the slide, boundary flanks, and hummocky surface. The contour interval is 2 ft. The steep scarp along the cutbank of a stream eroding the toe of the slope probably contributed to the landslide. This slide initially was attributed as confident.

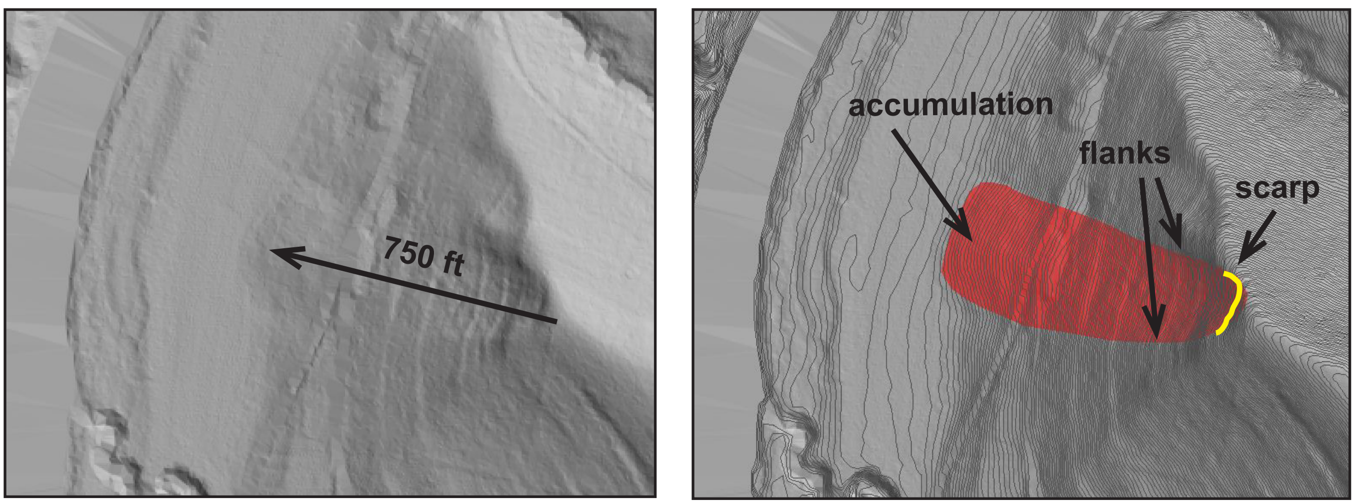

Figure 16. Example of a landslide identified on the LiDAR image (left) and the digitized polygon (right). Note the steep scarp, boundary flanks, hummocky surface, and accumulation at the toe. The contour interval is 2 ft. This slide was attributed as moderately confident.

would be very beneficial. Future mapping will greatly enhance the existing KGS landslide inventory, which is a foundation for effective hazard and risk analysis.

Additional Resources

- Kentucky Geological Survey landslide page: www.uky.edu/KGS/geologichazards/landslide.htm
- Kentucky Geological Survey geologic map information service: kgs.uky.edu/kgsmap/kgsgeoserver/viewer.asp
- Carey, D.I., Hounshell, T.D., and Kiefer, J.D., 2008, Geologic hazards in Kentucky: Kentucky Geological Survey, ser. 12, Map and Chart 187, scale 1:750,000 (kgs.uky.edu/kgsweb/olops/pub/kgs/mc185_12.pdf).

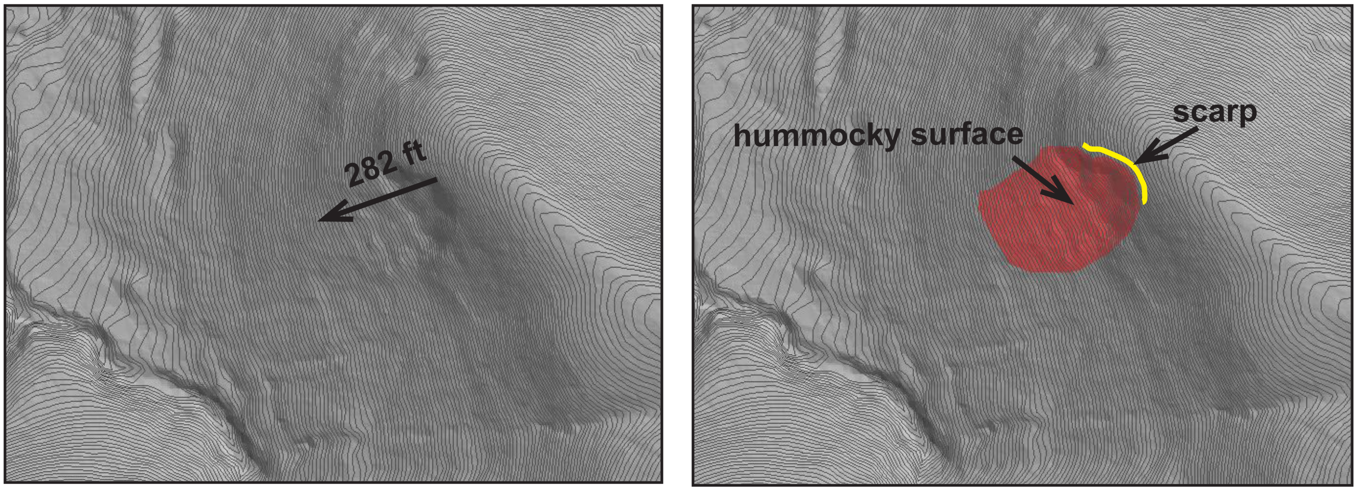

Figure 17. Example of a landslide identified on the LiDAR image (left) and the digitized polygon (right). Note the steep scarp, boundary flanks, and hummocky surface. The contour interval is 2 ft. This is a good example of a slide not associated with a road and occurring on a natural slope. The slide was attributed as questionable.

Figure 18. A small translational slide in November 2011 is indicated by debris and leaning trees at the toe and the neighborhood above the scarp. The greater slope area was predicted using LiDAR beforehand.

Figure 19. A large translational slide in December 2011 brought debris downslope into two condominiums. The greater slope area was predicted by LiDAR beforehand.

Acknowledgments

I would like to thank Paula Gori and Peter Lytle with the U.S. Geological Survey Landslide Hazards Program, which provided funding for this project. I also thank Sarah Johnson with Northern Kentucky University, who assisted with field work and provided valuable discussion of landslide activity in the area. Finally, I would like to thank William Andrews, Jerry Weisenfluh, Jackie Silvers, and Meg Smath of the Kentucky Geological Survey, who helped with the proposal, deliverable report, and making this project possible.

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