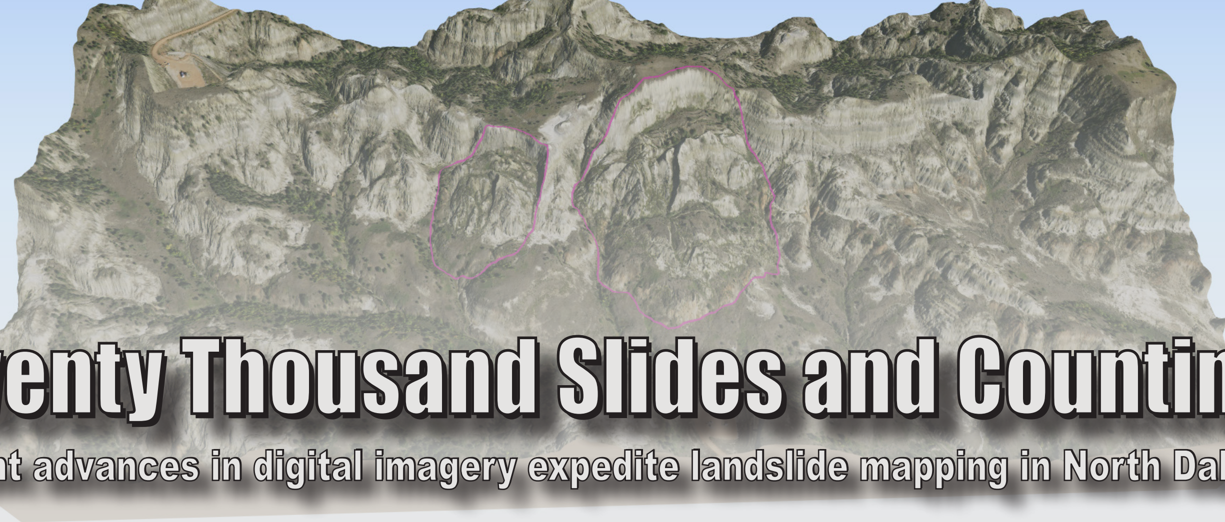

Twenty Thousand Slides and Counting

Recent advances in digital imagery expedite landslide mapping in North Dakota

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Introduction

The North Dakota Geological Survey's (NDGS) landslide mapping program continues to put on paper what experienced engineers and long-term residents of western North Dakota have suspected for a long time: many of North Dakota's slopes are unstable. Since 2003, NDGS landslide maps have provided the local observational landslide inventory necessary to understand the regional geologic context of these failures (Murphy, 2017). Documenting existing slope failures is the most pertinent data in furthering our understanding of which slopes are at risk of future failure. As the program approaches coverage of half of the state, that regional picture has never been clearer. Over 22,000 distinct earth flows, slumps, and areas of soil creep have been delineated, a number that will only increase as mapping continues.

Focused efforts since 2017

Mapping efforts have concentrated in areas of the most active development, and the program will have completed initial 1:24,000-scale coverage of North Dakota's oil and gas fields by early 2019 (fig. 1). This region will continue to be a focus for updates and monitoring as new mapping shifts to areas of wind turbines, pipelines, and other energy infrastructure, especially where it transects major river valleys.

Table 1. Updated statistics of the NDGS landslide identification program since 2017. 2017 data from Murphy (2017).

	Percentage of North Dakota Mapped	Number of Landslides Identified	Total Landslide Area (acres)	Average Landslide Size (acres)
January 2019	**49%**	**22,543**	**200,983**	**8.9**
January 2017	25%	11,077	116,500	10

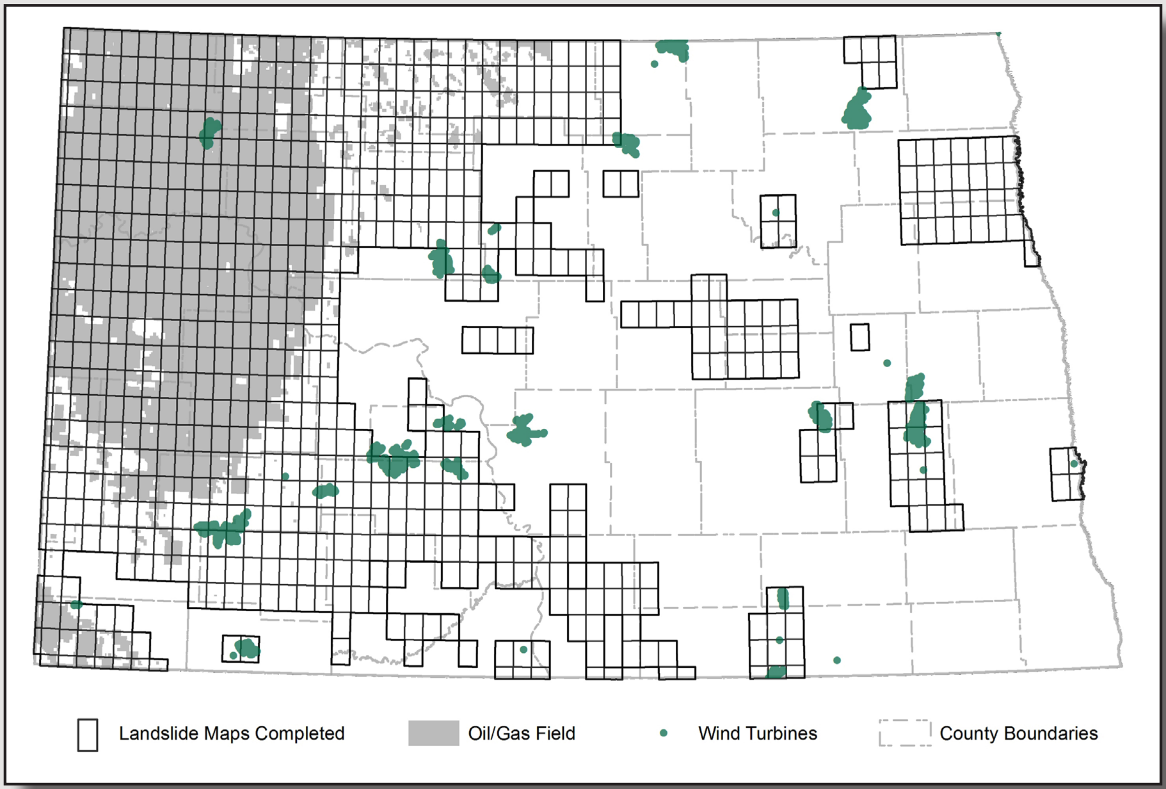

Figure 1. Coverage of 1:24,000-scale landslide maps relative to major energy infrastructure in North Dakota. Landslide data can be downloaded as polygons overlain on a topographic map (.pdf) or as GIS shapefiles (.shp) at www.dmr.nd.gov/ndgs/landslides/.

More landslides have been identified by the program from 2017 to 2018 than the previous 13 years of mapping combined (table 1). Average landslide density increased despite recent coverage including low-relief areas of Divide, Burke, Ward, Renville, and Bottineau counties, where the glaciated topography features fewer slopes steep enough to fail. The size of the average landslide also decreased by over an acre, suggesting a higher number of smaller slope failures are being identified. This is not a surprising outcome given the recent rapid advancement in the quality of surface imagery made available, especially over the past two years.

15 Years of Increasing Clarity

The NDGS collection of 1:20,000-scale aerial photographs viewed in stereo pairs continues to be the primary dataset from which failed slopes are identified. These photos sets, collected by the United States Department of Agriculture (USDA) from low-flying aircraft as early as the 1930s, provide a detailed picture of North Dakota in three dimensions. The expression of mature landslides can be overprinted by development, especially by urban expansion along major river valleys and oil and gas infrastructure in badlands terrain. In many instances these historical images record the pre-development surface of areas that face the highest potential impact by slope failure.

Supplementing the Survey's statewide collection of historical aerial photography is a continually increasing supply of modern digital imagery. Reviewing the most recent imagery available allows the identification of the newest landslides and provides a multi-decade view of which slopes have stabilized and which may be active. Since the NDGS first began mapping landslides in 2003, the USDA's National Agriculture Imagery Program (NAIP) digital aerial orthophotography coverage of North Dakota has increased in resolution more than tenfold; from 2-meter resolution in 2003 (fig. 2A) to 60-cm resolution for 2016-2018 coverage (fig. 2B) (USDA, 2018). Recent updates by programs such as Google Earth have made comparable-quality satellite imagery freely accessible, a marked improvement over the 15-meter resolution LANDSAT and Copernicus satellite imagery from just a few years ago. Equally noteworthy is Google's efforts to upload and host historical aerial photography, offering users largely instant and seamless projections that reduce the time and computational power required to process. This wealth of two-dimensional imagery can

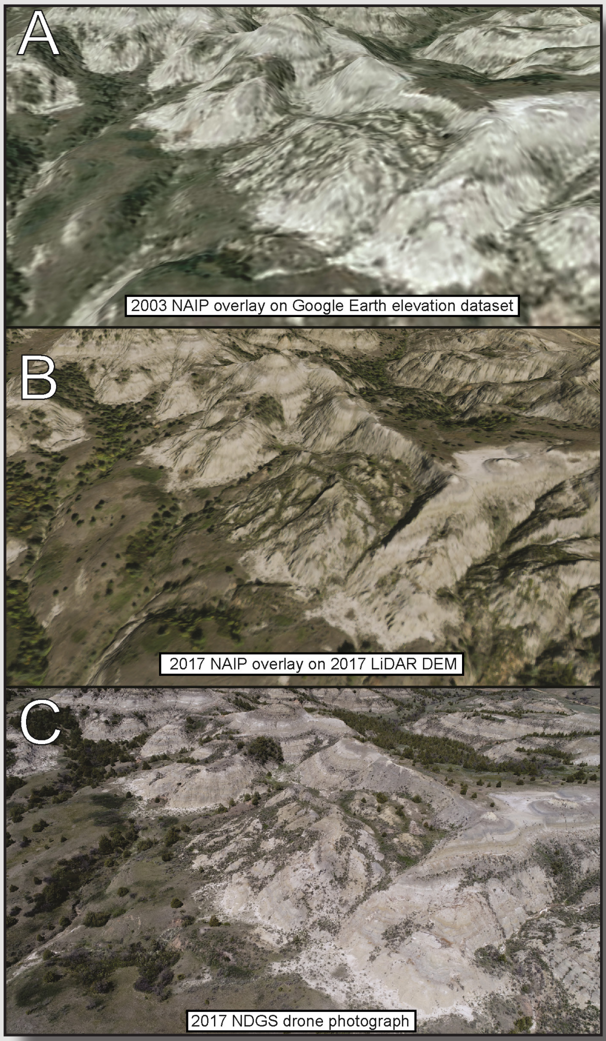

Figure 2. Oblique aerial imagery of the smaller western slide outlined in figure 3. NAIP image quality has increased greatly from 2003 (A) to 2017 (B), and modern elevation models allow detailed 3D renderings only surpassed by dedicated drone photography (C). NDGS drone photograph by Chris Maike.

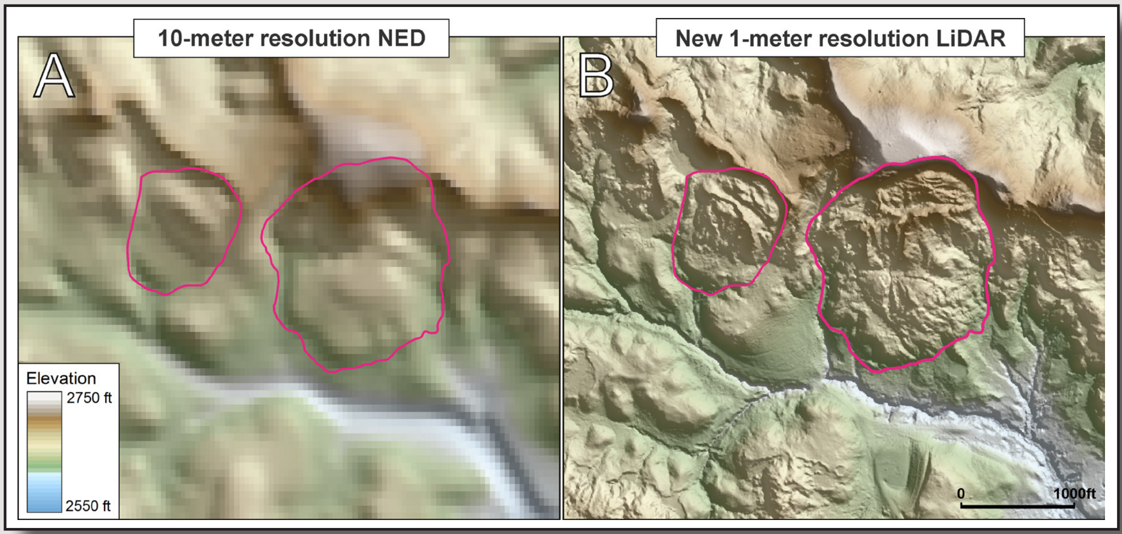

Figure 3. Two slumps (pink outline) in northern Billings County viewed on digital elevation models (DEMs) produced from (A) 10-meter resolution data from the USGS's National Elevation Dataset and (B) LiDAR data published in 2017.

now be instantly projected on the program's elevation dataset, producing a digital 3D model that is detailed enough to provide a useful secondary reference during mapping.

New elevation datasets may be the most significant advancement of the last 15 years in regards to landslide mapping applications. The United States Geological Survey's National Elevation Dataset (NED) has included statewide 1/3 arc-second (10-meter resolution) coverage of North Dakota since 2011 (FGDC, 2011). Although significantly higher-resolution than the 1 arc-second (30-meter resolution) NED it replaced, it was still too coarse for large-scale landslide identification (fig. 3A). New Light Detection and Ranging (LiDAR) data (fig. 3B), made available through the North Dakota State Water Commission and compiled into 7.5-minute quadrangles by the NDGS, now provides bare earth (vegetation removed) elevation data approaching 1-meter resolution for the entirety of North Dakota. Vegetation can provide clues to the disruption of drainage patterns by mass movement, but it can also interrupt or completely obscure the surface expression of slides (fig. 4A). Shaded relief imagery produced from bare-earth LiDAR data can dramatically increase the accuracy of landslide identification in these areas (fig. 4B).

Much of the LiDAR data published since 2017 includes coverage of western counties containing landslide-prone badlands topography. This conveniently coincides with the recent NDGS effort to map areas of oil and gas infrastructure, which has heavily utilized LiDAR during new landslide mapping and updates of existing maps. High-resolution LiDAR coverage now includes all of North Dakota with the release of Stark County data in February of 2018.

Beyond Passive Mapping

Landslides in close proximity to or directly effecting developed areas can often require a more detailed view than even the most modern aerial imagery can provide. Since 2017 the NDGS has had the ability to capture landslide-specific oblique aerial imagery with the use of unmanned aerial vehicle (fig. 2C) (Anderson & Maike, 2017). As mapping coverage expands and failed slopes are identified near oil and gas pipelines, well pads, federal and state highways or other infrastructure, the NDGS has responded to collect data and consult with industry and other state agencies (Maike, 2019). Mapping priorities are shifted as new projects such as windfarms are proposed, and existing maps are reviewed and updated in response to industry requests to review proposed pipeline corridors.

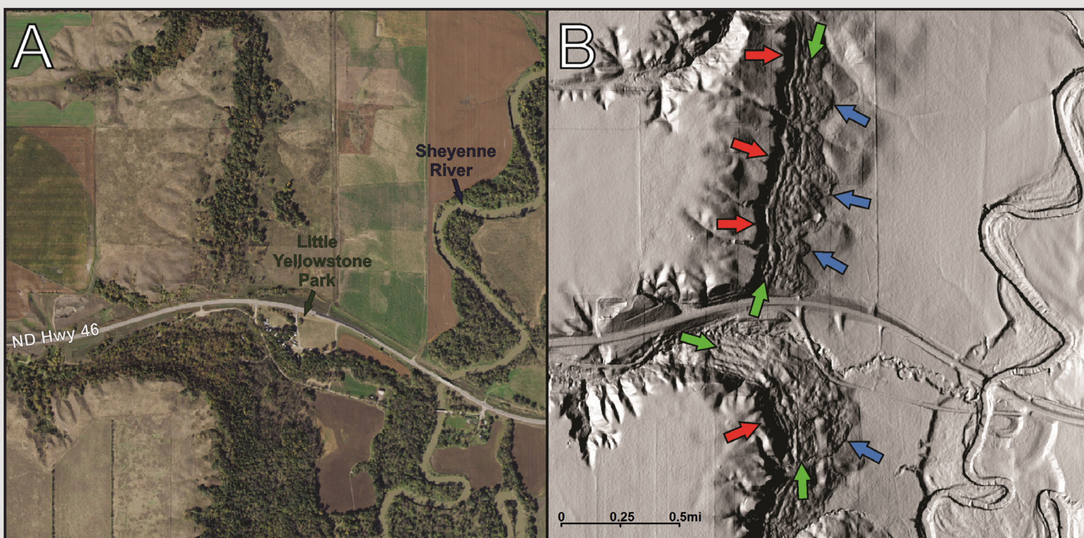

Figure 4. The western slope of the Sheyenne River Valley along the border of Barnes and Ransom counties. The Pierre and Niobrara Formations that comprise the valley walls are weak Cetaceous shales prone to flows and slumps. The ground surface is obscured by heavy forest cover in 2015 NAIP aerial imagery (A), but slide features such as scarps (red arrows), transverse ridges (green arrows), and toes (blue arrows) are strongly expressed in the shaded-relief image produced from LiDAR (B).

Although a 1:24,000-scale landslide inventory of the state cannot be a substitute for project-specific geotechnical site analysis, it has exponentially increased our understanding of landslide distribution in North Dakota. These data can now be utilized in the earliest phases of planning by public policy makers, utility providers, the energy industry, and private developers. Perhaps more importantly, the program has already increased communication between industry and regulators, and between state agencies in a mutual effort to share data and get a handle on the nature of landslides in the state: all 22,543 of them.

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