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Using remotely-sensed paleo-landslide data to assist in locating sensitive clay in Sweden

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INTRODUCTION

An understanding of landslides in the geologic past provides important information for assessing current hazards. In Sweden, paleo-landslide analysis has been used to aid in locating sensitive clay, which is susceptible to landsliding.

Sensitive clay, which forms when salts are leached from uplifted glaciomarine clays by groundwater flow, is susceptible to landslides on very low-angle slopes because its shear strength approaches 0 when remolded. Defining the degree and extent of sensitive clay formation requires geophysical and geotechnical investigations at a local scale (Rankka et al., 2004). Regional-scale estimations of sensitive clays often depend on models that include geological and hydrological conditions as inputs to predict the susceptibility of an area to sensitive clay formation (Quinn et al., 2010). These models have been applied to areas of past glaciomarine conditions, but they generally ignore areas with more complicated late Quaternary histories, such as the Baltic Basin.

During deglaciation, between about 13,000 and 8,000 years ago, the Baltic Basin experienced periods of marine, fresh, and brackish water that changed through space and time (Björck, 1995). This complex geologic history allows for deposition of glacially-derived clay in saline water, a pre-requisite for the formation of most sensitive clays, but it does not lend itself to modeling areas susceptible to the formation of sensitive clay. An alternative means of locating areas of sensitive clay is to locate and identify the distinctive scars left behind by landslides in sensitive clay (Quinn, 2011).

The Geological Survey of Sweden has undertaken such a project and is in the process of inventorying all landslide scars in the country with the aid of a new high-resolution digital elevation model (DEM) acquired using light detection and ranging (LiDAR). Analyses of these data sets provide information about the possible presence of sensitive clay in the geologically complex Baltic Basin.

METHODS

The data used in this study include the LiDAR derived DEM with a vertical resolution of 0.25 m and a pixel size of 2 m^2 (Lysell, 2013). This data set currently covers about 85% of Sweden. Hill-shaded imagery derived from the DEM provided the base for the geological survey to inventory all visible landslides using ArcMap software. The digital inventory includes line features that approximate the scarps as well as information on the sediment type in which each landslide occurred. The sediment type is derived from existing surficial geologic maps produced by the Geological Survey of Sweden.

The landslide inventory includes a total of 3198 features. Of these, 1394 slides were in till and not included in this project. The remaining 1804 landslides occurred in fine-grained sediments (silt-clay) and provide the initial data for this study.

ArcMap tools were used to close the lines that approximated the scarps and create polygon features that included the scarps. The perimeters of these polygons were buffered by 20 m, and then the buffers were erased. What remained were polygons that approximated the landslide scars but did not include the scarps. This step removed many of the smaller landslides in the inventory. A manual cleaning was conducted to remove polygons that did not accurately represent landslide scars because of irregular geometries. The final data set included 765 polygons that represented landslide scars in fine-grained sediments. The mean slope angle within each of these polygons was calculated using ArcMap.

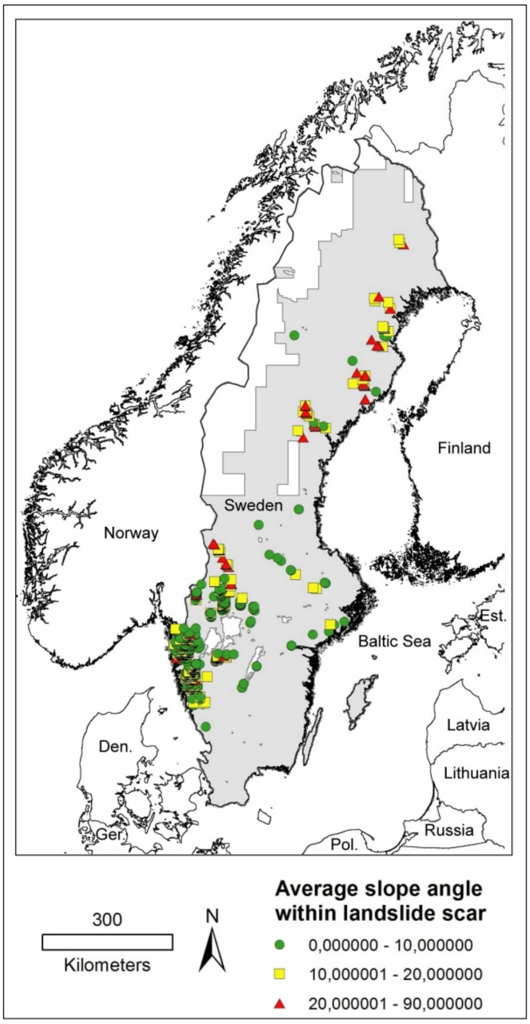

Figure 1. Map of northern Europe. The area currently covered by LiDAR data is shaded in gray.

Slope angle within a landslide scar is not a common metric. Thus, in order to facilitate comparison to other records, scar angles were compared to travel angles (ie the angle from the horizontal of a line drawn from the toe to the crown of a landslide). A subset of 10 large, well-defined, and well-preserved landslides was used for this analysis.

RESULTS

Landslides occur in fine-grained sediments throughout Sweden. Southern and particularly southwestern Sweden has a high number of low-angle landslides (Fig. 1). However, low-angle landslides are not isolated to southern Sweden. In central and northern Sweden there are 19 landslides with scar angles less than 10^o.

The comparison of scar angle to travel angle suggests that for low-angle slides the data sets are similar. Of the ten landslides used in the comparison, the mean scar angle is 3.46^o with a standard deviation of 0.95 o, and the mean travel angle is 2.25^o with a standard deviation of 1.40^o. A t-test indicated that these two datasets do not have statistically different means. Thus, the scar angles reported here are compared directly to travel angles reported elsewhere.

DISCUSSION

The low-angle landslides in southern Sweden occur primarily in areas subjected to marine conditions during deglaciation. In many places, subsequent leaching of salts by groundwater flow has led to the formation of sensitive clay. We do not suggest that all low-angle landslides in this area are in sensitive clay, but the high density of low-angle slides in the southwest suggests that these marine sediments are far more susceptible to landsliding than the fresh and brackish-water sediments along the central and northern portions of the east coast. Thus, the fact that our analysis captures this pattern makes it consistent with previous work that documents the presence of sensitive clay in southern Sweden (Rankka, 2004).

Low-angle landslides in NE Sweden may also indicate the presence of sensitive clay. In areas that never experienced full marine salinity during deglaciation, there are 19 landslides with scar angles less than 10^{o}. Visual inspection of these landslides in the DEM suggests that 4 are particularly flat and broad. Thus, scar length, scar width, and outlet width were measured to compare these dimensions with those of landslides known to have occurred in sensitive clay (Quinn et al., 2011). For these four landslides, the ratios of scar length to outlet width ranged from 0.87 to 5.22; the ratios of scar width to outlet width ranged from 1.00 to 1.75; and the sum of these ratios ranged between 2.20 and 6.96. All of these values are within one standard deviation of the mean values reported by Quinn et al. (2011) for retrogressive earth flows purported to be in sensitive clay in eastern Canada.

While geophysical or geotechnical measurements are required to confirm the presence of sensitive clay, we suggest that these areas are candidates for further investigation prior to any infrastructure construction.

CONCLUSIONS

Paleo-landslide analysis is a useful tool for locating areas that may be underlain by sensitive clay, especially in geologically complex areas like the Baltic Basin. For low-angle ($<10^{o}$) landslides, the mean slope angle within a landslide scars is a reasonable estimate of landslide travel angle, and it is easy to calculate in a geographic information system. Sorting of landslides by scar angle allows for rapid isolation of low-angle landslides for further geometric measurements that may indicate the presence of sensitive clay.

This initial proof of concept opens the door for more rigorous and more automated methods of locating sensitive clays through examination of landslides in the geologic record.

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