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A fast and efficient algorithm to map prerequisites of landslides in sensitive clays based on detailed soil and topographical information

Ari Tryggvason [a,*], Caterina Melchiorre [a], Kerstin Johansson [b]

[a] Department of Earth Sciences, Uppsala University, Villavägen 16, SE-752 36 Uppsala, Sweden
[b] Swedish Geological Survey, Box 670, SE-751 28 Uppsala, Sweden

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ABSTRACT

We present an algorithm developed for GIS-applications in order to produce maps of landside susceptibility in postglacial and glacial sediments in Sweden. The algorithm operates on detailed topographic and Quaternary deposit data. We compare our algorithm to two similar computational schemes based on a global visibility operator and a shadow-casting algorithm. We find that our algorithm produces more reliable results in the vicinity of stable material than the global visibility algorithm. We also conclude that our algorithm is more computationally efficient than the other two methods, which is important when we may want to assess the effects of uncertainty in the data by evaluating many different models. Our method also provides the possibility to take other data into account. We show how different soil types with different geotechnical properties may be modelled. Our algorithm may also take depth information, i.e. the thicknesses of the deposits into account. We thus propose that our method may be used to provide more refined maps than the overview maps in areas where more detailed geotechnical/geological data have been acquired. The efficiency of our algorithm suggests that it may replace any global visibility operators used in other applications or processing schemes of gridded map data.

1. Introduction

Landslides in sensitive clays are the major mass wasting processes in Sweden in terms of loss of human lives and of economic costs (Nadim et al., 2008). Significant landslide risk exists in many areas of Sweden, and Southwest Sweden is one of the areas in Scandinavia with the highest risk. The presence of high sensitive clays or quick clays implies that a major landslide hazard can exist even with moderate slopes (Osterman, 1963; Torrance, 1983, 2014; Viberg, 1984; Berggren et al., 1991). Similar conditions occur in e.g. Canada, Norway, Finland and Alaska (Brenner et al., 1981; Lebuis et al.,1983; Hilmo, 1989; Rankka et al., 2004). The term 'quick' refers to a clay for which the internal structure collapses when disturbed. Technically, clays are classified as quick if the sensitivity (defined as the ratio of the undrained and the remoulded shear strength) is at least 50, and its remoulded shear strength is below 0.4 kPa (Osterman, 1963; Viberg, 1982; Karlsson and Hansbo, 1989). Quick clays are predominantly found in sediments deposited in shallow seawater during the last deglaciation that have been uplifted by isostatic rebound. On land, fresh water leaching changes the ion concentration in the pore water reducing the quick clay's remoulded strength (Osterman, 1963; Torrance, 1983, 2014). The highly sensitive clays are rarely – if at all – visible at the surface, often they have been covered by more recent (e.g., fluvial, deltaic) sediments.

In Sweden, the most used method to obtain clay sensitivity is using undisturbed and remoulded shear strength measurements from laboratory tests (i.e., cone fall tests) performed on undisturbed soil samples. Because of the cost of undisturbed samplings, geotechnical and geophysical methods have been developed to investigate the presence of sensitive clays in soil deposits as an alternative to laboratory analysis. Geotechnical soundings (e.g., CPT – cone penetration tests) have been widely used in Scandinavia for decades (Lundström et al., 2009 and references therein) to identify areas with sensitive clays, since sounding resistance is correlated to clay sensitivity. Geophysical techniques based on electrical resistivity have recently shown potential for detecting clay sediments leached by fresh water and for understanding the environment they are situated in (Solberg et al., 2008; Malehmir et al., 2013). The accuracy and time efficiency of these geophysical techniques vary significantly, and their operational costs are generally high. Therefore methods to assess landslide hazard in Sweden, Canada, and Norway usually use only geological and topographic information (Lundström and Andersson, 2008) to

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[*] Corresponding author.
E-mail addresses: Ari.Tryggvason@geo.uu.se (A. Tryggvason), Caterina.Melchiorre@geo.uu.se (C. Melchiorre).

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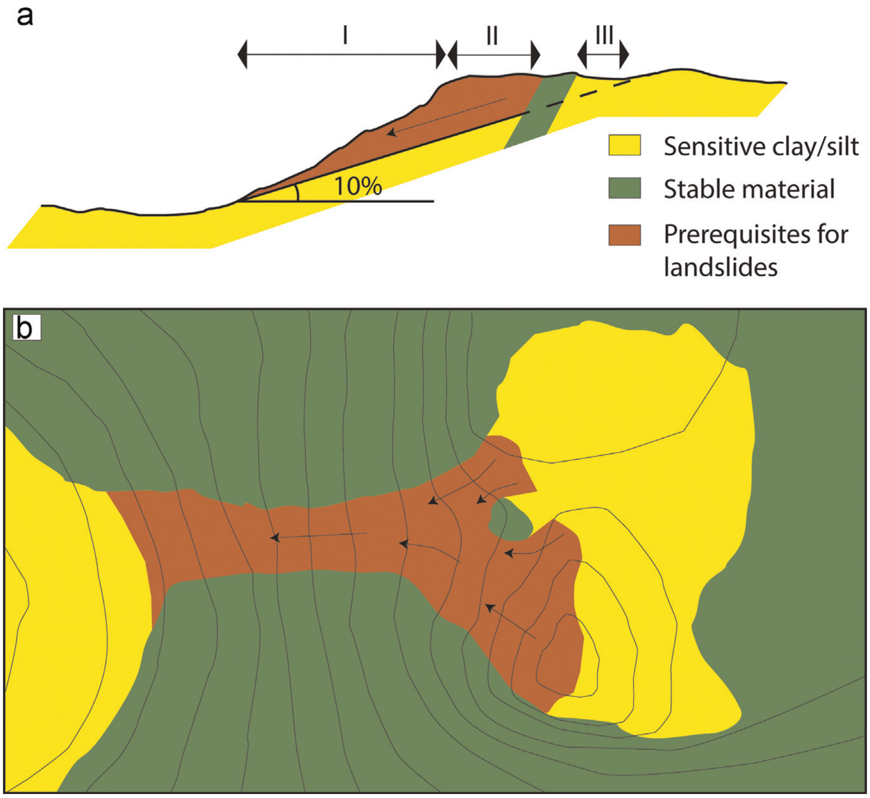

Fig. 1. Schematic view of how areas prone to landslides are identified. Panel (a) shows the one-dimensional case. The area marked I covers the slope that exceeds the stability criterion (here 10%), area II does not slope very much, but is situated above the critical cross-sectional angle within sensitive clay. Area III is also above the critical cross-sectional angle but is shielded by stable material. Panel (b) shows a schematic view of a more complicated three-dimensional case. Thin lines are elevation curves, increasing elevation to the right in the figure. Arrows show the direction of a potential landslide, which is not necessarily along a straight line.

identify areas for detailed geotechnical investigation. The methodology used in Sweden to map landslide hazard in sensitive clays (Berggren et al., 1991) involves computing cross-sectional angles rather than slope surface angles (see Fig. 1a) and, therefore, specially designed tools.

Below we describe an algorithm that, based on surface topography and Quaternary soil information, is used in Sweden to identify areas prone to landslides (Swedish Geotechnical Institute, 2001; Fallsvik, 2007). Including some recent refinements, we describe a novel method which:

1) is computationally fast and efficient,
2) provides more reliable results close to stable areas,
3) can model deposits with laterally varying geotechnical properties, and
4) takes the thickness of the deposits into account.

The algorithm performance is demonstrated using simulations and it is compared with implementations of other computational schemes used today for producing overview maps of landslide susceptibility.

2. Algorithm

Because of the difficulties in directly mapping sensitive clays, topographic and geological criteria are extensively used in Sweden as a first step in the analysis of landslide hazard (e.g. Fallsvik, 2007). The use of digital elevation data and detailed information on marine deposits allows identification of areas prone to landslides. The topographic criterion is based on analysis of historical data from Sweden, Norway and Canada, which shows that landslides in sensitive clays have not occurred in slopes with a height-length ratio below 1:10 or 10% (Viberg, 1982; Lundström and Andersson, 2008). This ratio does not represent the surface slope angle, but a cross-sectional angle (Fig. 1). Identifying areas above a given cross sectional angle is straight forward in one dimension (Fig. 1a), but may be slightly more complicated in two dimensions (b), because the path a slide may take is not along a straight line, or there may be barriers of stable soil blocking certain paths etc. In this context a barrier simply represents material that is classified as not susceptible to landslides (either bedrock or Quaternary material with a low clay content), and (as far as is known) not underlain by sensitive clay.

2.1. *Methodology*

A computer algorithm, commonly called the “visibility approach”, was first developed mimicking the established, originally manual approach, i.e. stepping through a map position by position checking if any other positions are above a certain cross-sectional angle from the source position. Computing visibility on a geographical grid is a rather slow procedure, as the number of computations is proportional to N^2 where N is the total number of nodes in the investigated area. For a typical area under investigation, 25×25 km^2 sampled at 5 m, $N=25$ million nodes. The visibility approach thus requires on the order of 10^{15} computations. Even with modern computers, run time can therefore be an issue, especially if high level applications packages, such as ArcGIS (www.esri.com), with their in-built overheads, are used. Computational geometry is a well-studied subject (e.g. Goodman and O’Rourke, 1997) and the number of methods and optimizations are numerous, depending on – among other things – the model representations (e.g. discrete objects, lines, or pixels). For slope stability assessment standard GIS tools, e.g. looking only at