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Geophysical characterization of areas prone to quick-clay landslides using radio-magnetotelluric and seismic methods

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ABSTRACT

Landslides attributed to quick clays have not only considerable influences on surface geomorphology, they have caused delays in transportation systems, environmental problems and human fatalities, especially in Scandinavia and North America. If the subsurface distributions of quick clays are known, potential damages can be mitigated and the triggers of landslides can better be studied and understood. For this purpose, new radio-magnetotelluric (RMT) and seismic data were acquired in an area near the Göta River in southwest Sweden that contains quick clays and associated landslides. High-resolution data along 4 new lines, in total 3.8 km long, were acquired and merged with earlier acquired data from the site. Velocity and resistivity models derived from first breaks and RMT data were used to delineate subsurface geology, in particular the bedrock surface and coarse-grained materials that overlay the bedrock. The latter often are found underlying quick clays at the site. Comparably high-resistivity and sometimes high-velocity regions within marine clays are attributed to a combination of leached salt from marine clays or potential quick clays and coarse-grained materials. The resistivity and tomographic velocity models suggest a much larger role of the coarse-grained materials at the site than previously thought, but they also suggest two different scenarios for triggering quick-clay landslides at the site. These scenarios are related to the erosion of the riverbank, increased pore-pressure and surface topography when close to the river and human activity when away from the river and where bowl-shaped bedrock surrounds the sediments.

1. Introduction

Landslides are natural geohazards that occur all over the world (Fig. 1). They claim hundreds of lives and damage infrastructure every year and may also cause environmental problems (Gregersen and Løken, 1979; AB Svensk Filmindustri, 1957). They are a natural part of landform development (Crozier, 2010) and studies of landslides and areas prone to them are therefore important both to understand the current shape of the landscape and to avoid predictable financial damage and human loss of life, with implications for infrastructure designs and geological storage.

A landslide is generally defined as the movement of rock, debris and soil driven by gravity and preconditioned by the landform (Highland and Bobrowsky, 2008). Landslides can be classified into different categories depending on the types of materials (earth, rocks and debris) involved and the types of movements (fall, topple, slide, spread and flow); for example, rock fall and earth flow (Highland and Bobrowsky, 2008). Landslide triggering mechanisms are varied; they either have a single trigger or multiple sources; a combination of water saturation, seismic, volcanic and even human activities. Examples of human activities triggering landslides are known in Sweden and Norway (Nadim et al., 2008; Gregersen, 1981; Fig. 1b). Steepness of slope, morphology, soil type and underlying geology are the most important factors for causing landslides (Highland and Bobrowsky, 2008). Some of these factors are easier to study while others may not be, particularly due to inaccessibility. Subsurface geology is among those factors that cannot easily be studied or when studied the density of geotechnical boreholes used for this purpose is limited.

Quick-clay landslides, which are classified as earth flows (e.g., Torrance, 2014), are one of the most important geohazards in Northern countries including Sweden (Fig. 1), Norway, Japan and Canada (Geertsema and Torrance, 2005; Torrance, 2012). A small initial slip of quick clay may develop into large landslides that cover a vast area (Rankka et al., 2004) and as a consequence significantly change the terrain shape. Quick-clay landslides in Sweden mostly occur on relatively gentle topographic slopes made up of glacial and post-glacial sediments (e.g., silt and clay) and often bordered by open water such as a river or a lake (Nadim et al., 2008) similar to the example shown in Fig. 1d. For these types of landslides, which are often retrogressive, soil type and underlying geology are more important than the surface topography and morphology and, therefore these factors should be studied together.

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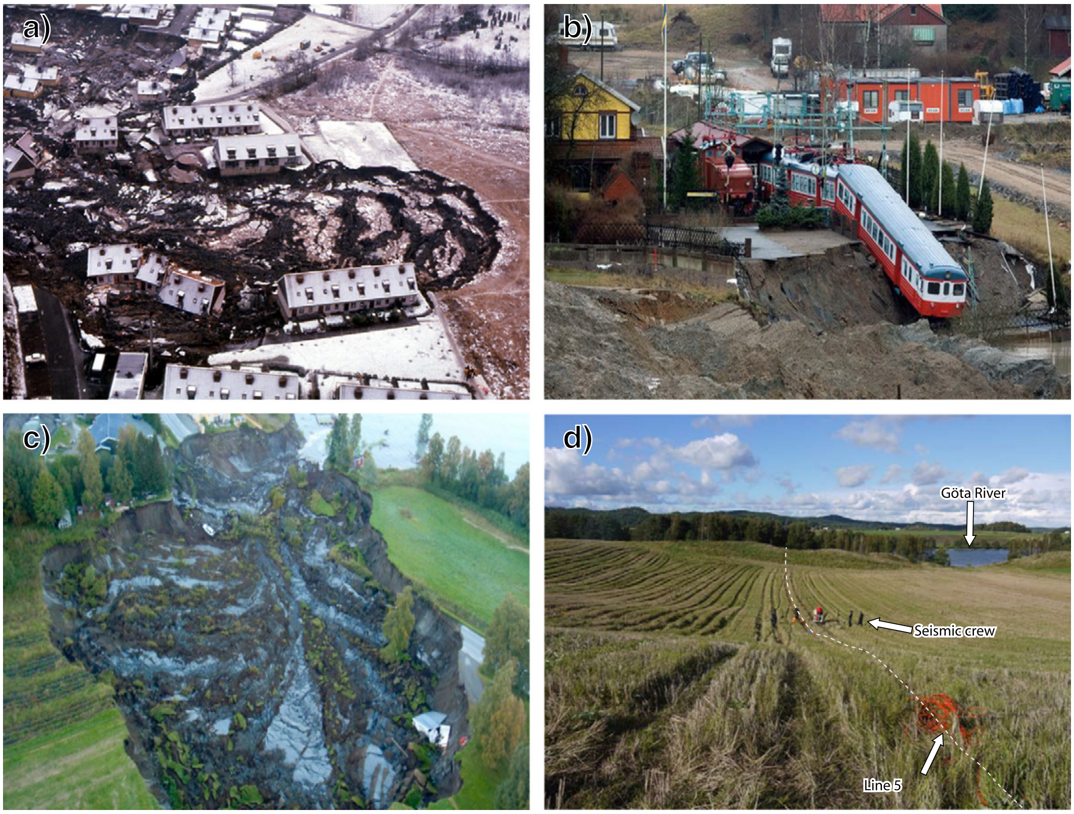

Fig. 1. Example figures showing major quick-clay landslides and their impacts. (a) Tuve landslide, Sweden in 1977 and (b) Småröd landslide, Sweden in 2006 (courtesy of the Swedish Accident Investigation Authority, SHK). (c) Lyngseidet landslide, Norway in 2010; it was likely triggered by loading of materials next to the shoreline (courtesy of the Geological Survey of Norway, NGU, photo: Andrea Taurisano, NVE). (d) Fråstad landslide in our study area next to the Göta River (photo by Alireza Malehmir, 2011).

Based on known sites of quick-clay landslides, geotechnical (and/or geochemical) investigations and assessments have been implemented to understand quick-clay properties (e.g., Gregersen, 1981; Andersson-Sköld et al., 2005a; Geertsema and Torrance, 2005). However, due to the cost-effectiveness and ability to cover a large area and depth, a combination of geotechnical methods (e.g., cone penetration test) and surface geophysical methods is more desirable and has been more or less successfully used to study quick clays and their host environments (Rankka et al., 2004; Andersson-Sköld et al., 2005a; Löfroth et al., 2011; Bazin and Pfaffhuber, 2013; Malehmir et al., 2013a, 2013b; Dahlin et al., 2013; Adamczyk et al., 2013, 2014; Pfaffhuber et al., 2014; Lundberg et al., 2014; Shan et al., 2014; Salas-Romero et al., 2015; Helle et al., 2015; Shan et al., 2016). In this study we use a combination of electromagnetic and seismic methods and focus on an area near the Göta River in southwest Sweden in which quick-clay landslides have occurred (Fig. 1d).

This study complements to an earlier field campaign in year 2011 that covered part of the study area south of the Göta River. It is mainly based on new surface geophysical data acquired in year 2013 to extend some of the earlier geophysical profiles north of the river and west of the study area where a large portion of the area appears to be creeping towards the river (Fig. 2). The 2013 geophysical campaign focused on two geophysical methods that earlier studies have proved to be optimal for the study area, namely seismic and RMT methods (Malehmir et al., 2013a, 2013b). Results from the previous studies have revealed the surface of crystalline bedrock (20–100 m deep) dipping towards the river and layered glacial sediments, including coarse-grained materials (mostly sand) that sandwiched layers of quick clays, requiring a combined use of these methods for their delineation.

The main objectives of our study were (1) to expand our understanding of quick-clay distributions west and north of the area studied earlier and (2) to provide subsurface information about the general structures at the site and evaluate quick-clay landslide potential at various parts of the study area. Given the increased length and area covered by the new geophysical data, the interpretations provided in this study are better constrained near the Göta River where the risk of quick-clay landslides is probably much higher due to the erosion of the foot of the slope (riverbank) and reduction of the lateral support.

2. Quick clays and their formations

Quick clay is defined as a clay with remolded shear strength less than 0.4 and 0.5 kN/m^2 (by fall cone test) and high sensitivity larger than 50 and 30, respectively in Sweden and Norway (Rankka et al., 2004; Donohue et al., 2012). The sensitivity is defined as the ratio between undrained, undisturbed shear strength and the remolded shear strength (Solberg, 2007; Shan et al., 2014). Undisturbed quick clay resembles a water-saturated gel that has formed through flocculation and deposition (Rankka et al., 2004) during and after the last glacial period. Undisturbed shear strength of quick clay is not different from non-quick clay, in other words the in-situ mechanical behavior is the same.

During the last deglaciation, about 11,000 years ago, meltwater from the Fennoscandian ice sheet and its receding glaciers carried suspended materials into marine or brackish waters where clays were deposited. Isostatic land uplift subsequently caused these marine clays to be raised above the sea level and exposed to fresh water infiltration (Brand and Brenner, 1981). Because of this, salt (saline) in the pores of marine clays have been leached out by infiltration of fresh/rain water or through fissures and fractures circulating fresh water from the bedrock (Malehmir et al., 2013a, 2013b; Shan et al., 2014). As a consequence, the bonds between adjacent clay particles become weaker and make the clay sensitive to mechanical disturbance and subject to 'quickness' (Rankka et al., 2004; Torrance, 2012). The reduction in the salt content and change in the structures of the clay imply higher electrical