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High-resolution reflection seismic investigations of quick-clay and associated formations at a landslide scar in southwest Sweden

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ABSTRACT

We present high-resolution reflection seismic data from four lines (total 1.9 km) that cross a quick-clay landslide scar located close to the shore of the Göta River in southwest Sweden, and compare the results with geotechnical data from boreholes. The seismic data allow the imaging of bedrock topography and normally to weakly consolidated sediments to a subsurface depth of about 100 m. Different types of seismic sources, including sledgehammer, accelerated weight-drop and dynamite were utilized and compared with each other. Analysis of their power spectra suggests that weight-drop and dynamite have higher frequency content and energy than the sledgehammer, which makes these two sources suitable also for waveform tomography and surface-wave data analysis. The shallowest non-bedrock reflector is observed at about 10–20 m below the surface, it overlays the bedrock, and is interpreted to originate from the contact between clay formations above and a coarse-grained layer below. The coarse-grained layer appears to be spatially linked to the presence of quick-clays. It is a regional scale formation, laterally heterogeneous, which deepens to the west of the study area and correlates well with the available geotechnical data. Continuity of the coarse-grained layer becomes obscured by the landslide scar. There may be a link between the coarse-grained layer and landslides in the study area, although this possibility requires further hydrogeological and geotechnical investigations. Reflectors from the top of the bedrock suggest a depression zone with its deepest point below the landslide scar and a bowl-shaped structure in the northern portion of one of the seismic lines.

1. Introduction

Landslides are one of the most commonly occurring natural disasters; the economic cost of the damage caused by them is estimated to be in billions of dollars, and they claim hundreds of human lives every year (Petley, 2011). Sweden is also affected by this natural hazard (Nadim et al., 2008; Fig. 1). This study is about one particular kind of rapid earth flow that is caused by quick-clays, which mainly exist in Sweden, Norway and Canada (Rankka et al., 2004; Rosenquist, 1953; Solberg, 2007). Undisturbed quick-clay resembles a water-saturated gel that accumulated as flocculated silty-clay to clayey-silt sediment in a marine to brackish environment; uplifted above sea-level, and has been leached to low salinity by fresh water flow. The quick-clay liquefies at its natural water content; the flocculated structure collapses if its strength is exceeded, which results in landslides of variable magnitude (Bryn et al., 2005; Kvalstad et al., 2005; L'Heureux et al., 2010, 2012; Lundström et al., 2009; Rankka et al., 2004; Rosenquist, 1953; Solberg et al., 2012; Torrance, 1983). A small block of quick-clay can liquefy due to a stress change as little as the touch of a human hand, while larger deposits are sensitive to greater stress changes, such as increased saturation by excess rainwater (e.g., Vanneste et al., 2012).

Considering the nature of quick-clay formations, application of geoelectrical methods alone to delineate them is a challenge, although they are often used. The presence of thick and conductive marine clay does not allow deep current penetration (Bogoslovsky and Ogilvy, 1977). These thick layers of conductive clay, which can also be fully water-saturated at depth, sometimes already as shallow as 0.5 m, make ground penetrating radar (GPR) techniques inefficient (Annan, 2005). However, each geophysical method has its own advantage and disadvantage for a given site location or problem and for specific geologic target at different depths (Bichler et al., 2004; Bogoslovsky and Ogilvy, 1977; Carpentier et al., 2012; Jongmans and Garambois, 2007). Success is not always guaranteed for a single geophysical method. Therefore, a combination of various geophysical methods and implementing those that can also provide deeper information is needed (Bogoslovsky and Ogilvy, 1977; Jongmans and Garambois, 2007; Solberg et al., 2012). This is particularly important if quick-clays extend to greater depths (e.g., >20 m), such as in this case study.

According to our knowledge, there have been no previous applications of reflection seismic methods for delineation of quick-clays and associated formations in Sweden. Refraction seismic methods have

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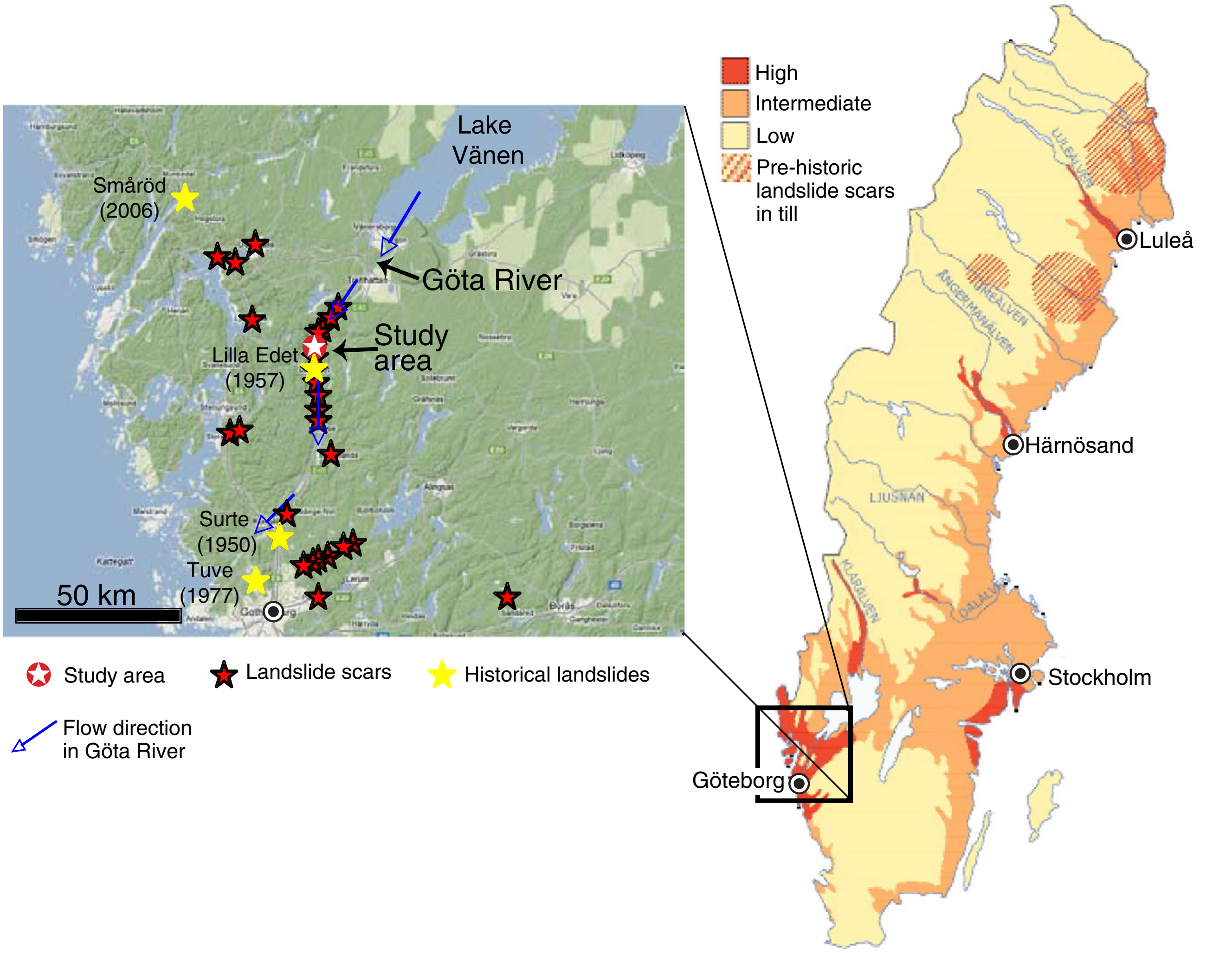

Fig. 1. (right) Landslide risk map of Sweden (from the Geological Survey of Sweden), and (left) showing location of the study area and recent quick-clay landslides in southwest Sweden (e.g., Surte, 1950, Göta, 1957, Tuve, 1977, and Småröd, 2006). Our study area is about 7 km north of the city of Lilla Edet, where the Göta landslide occurred in 1957.

been extensively used for landslide studies (Bekler et al., 2011; Carroll et al., 1972; Jomard et al., 2007; Samyn et al., 2012), however, the use of reflection seismic methods has been limited to countries outside Sweden (e.g., Bachrach and Nur, 1998; Baker et al., 1999a,b; Bichler et al., 2004; Büker et al., 1998; Eichkitz et al., 2009; Kaiser et al., 2009; L'Heureux et al., 2010, 2012; Medioli et al., 2012; Polom et al., 2010; Roberts et al., 1992; Schmelzbach et al., 2005). Reflection seismic methods are more expensive than the traditional geophysical methods for landslide studies, but if properly designed and implemented they can provide high-resolution images of layer boundaries, provided that there is sufficient acoustic impedance contrast (product of seismic velocity and density) between the layers. For example, seismic methods can be used to map bedrock geometry and overlying clays that can sometimes be critical for landslide risk assessments. Integration with other geophysical and geotechnical methods can also be important in modelling and interpreting the data (Eichkitz et al., 2009). Reflection seismic methods experience problems when imaging the top few metres (smaller than one wavelength) of the near surface (<5 m), but this gap can often be filled by geoelectrical and GPR methods (Bichler et al., 2004; Bogoslovsky and Ogilvy, 1977).

Our geophysical investigations of areas prone to quick-clay landslides began in September 2011 over a known landslide scar near the Göta River (Figs. 1 and 2a) in southwest Sweden. Göta River (Fig. 1) is the source of drinking water for about 700,000 people and is used extensively for industrial transportation. Therefore, areas near the river are highly industrialized and populated. The geophysical investigations involved 2D and 3D P- and S-wave source and receiver seismic surveys, geoelectrics, controlled-source and radio-magnetotellurics, Slingram, ground gravity and magnetic surveys as well as passive seismic monitoring (Fig. 2a and b). Prior to our investigations, the Swedish Geotechnical Institute (SGI) studied the site using various geotechnical and hydrogeological methods (Löfroth et al., 2011). Therefore, a wealth of geotechnical borehole data, mainly CPT (cone penetration test with tip friction generated by the rod string; Robertson, 1990), CPTU (cone penetration test with friction sleeve measuring pore pressure data) and laboratory measurements are available from the site. Among geophysical methods, only surface electrical resistivity tomography (ERT) and induced polarization (IP) methods had been carried out by SGI (Löfroth et al., 2011).

An overall assessment of different geophysical methods used in the study area was recently reviewed by Malehmir et al. (in press). Here, we present results and details of high-resolution shallow reflection seismic data acquisition, processing and interpretation along four seismic profiles (lines 2, 3, 4 and 5), some of which cross the landslide scar (see lines 4 and 5 in Fig. 2). Only data along line 5 were presented by Malehmir et al. (in press). The main objectives of this study are (i) to evaluate the performance of high-resolution reflection seismic methods for quick-clay studies in Sweden, (ii) to image a coarse-grained layer