Airborne geophysical investigations for landslide risk investigation along the Ångerman River, central Sweden

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Abstract. A study of landslide risks along the Ångerman River in Sweden is currently being performed by the Swedish Geotechnical Institute (SGI) with assistance from the Geological Survey of Sweden (SGU). In this work, knowledge of the distribution of different types of sediment is crucial. The area shows large variations in both sediment stratigraphy and sediment thickness (depth to bedrock) which makes it difficult to describe geotechnical properties for larger areas based on sparse geotechnical field investigations (soundings and sampling). Within the study area, the Ångerman River valley contains numerous fluvial terraces at various elevations separated from the river by steep erosional scarps. Although fluvial sand caps the terraces, their heights are often derived from the underlying silt and clay, which in turn overlies till or glaciofluvial sediment. The thickness of these general stratigraphic units is difficult to determine from existing data. Thus, in 2018, an airborne transient electromagnetic (ATEM) survey was performed along the river and the surrounding river banks with the objective of mapping and characterizing the sediments down to bedrock. The surveyed area is 2 km wide and covers 80 km along the river with a flight line distance of 75 m. From the ATEM data, the 3D resistivity distribution of the ground down to about 100 m below the surface can be determined. The silt and clay show very low resistivity compared to the overlaying sand layers. Therefore, they can be easily distinguished in the resistivity models from the ATEM data. Furthermore, the depth to the more resistive underlaying till and bedrock can be delimited in most areas. The 3D resistivity model derived from the ATEM data was integrated with other geoscientific data such as; geotechnical drillings, information from water wells and surficial deposits maps using 3D modeling software (Geoscene 3D from I-GIS). Based on the modelling results, the area was divided into six different classes based on the soil stratigraphy. The current method of analysis uses detailed geotechnical investigations performed in one location to ground truth the interpretation of geophysical data over a broad area. With the new results based on the ATEM data, the planning of new geotechnical drillings can be better focused on more poorly-understood areas. Furthermore, the number of geotechnical field investigations can be reduced.

1. Introduction

A landslide risk analysis of the Ångerman River valley is currently being performed by The Swedish Geotechnical Institute (SGI). SGI is commissioned by the Swedish government to perform mapping of the risks for landslides along the rivers of Sweden. The mapping also includes an evaluation of how the risk of landslides is affected by climate change. The final product of the mapping is a comprehensive map of landslide risks along the river valley. The map presents the distribution of the risk levels of landslide probability and consequences (in pairs), as well as the impact of climate change on landslide probability in a 100-year perspective. The landslide risk map is used as a basis for comprehensive
planning at the municipal level. Mapping has been finalized for three river valleys in southern Sweden and is currently being performed along 80 km of the Ångerman River in central Sweden [1] [2]. In the first stage of this mapping, the work is being concentrated within a primary study area (figure 1).

The method SGI uses for mapping landslide risk uses detailed geotechnical investigations performed in one section, to define the geotechnical properties for a certain sub-area which has been deemed to have similar geological and geotechnical characteristics [3]. To be able to divide the study area into a number of sub-areas, it is necessary to define the stratigraphy of the sediments along the river valley. Other information that is used includes topography and results from previous geotechnical investigations regarding geotechnical and hydrological characteristics of the soil layers.

In the early stages of the mapping of the Ångerman River an inventory of results from previous geotechnical investigations along the whole river was carried out. In addition to compiling existing geotechnical data, SGI also performed preliminary geotechnical investigations at ten sections along the river [4]. Within the study area, geotechnical data were sparse and existed in only a few areas (figure 2).

A first step towards dividing the study area into a number of sub-areas, was to consider the topography combined with the surficial deposits map. The hypothesis being that slopes with a similar height and slope angle would have similar stratigraphy. However, the geotechnical data did not support the initial working hypothesis. Results from both soundings and sampling showed that grain size as well as thickness of the different sediment layers varied greatly within the suggested sub-areas. To be able to reach a more certain classification of sub-areas would mean a great number of sections with geotechnical investigations. Thus, new data were required in order to delimit new sub-areas.

Geophysical measurements have not been used in the earlier mapping projects. However, in a research project regarding quick clay mapping the ATEM method was tested in four areas in Sweden [5] [6]. One of the areas was a small area in the south part of the Ångerman River valley. The result from this project showed the potential for the method to map the soil stratigraphy along the river.
2. Geological setting

The studied area includes the municipality of Sollefteå and lies along the Ångerman River in the central part of Sweden (figure 2). Deglaciation of the area occurred about 10,500 years ago [7] during a time when the Baltic basin contained a freshwater lake. Due to glacial isostatic depression of the crust, lake level reached to nearly 290 m above current sea level [7]. Thus, deglaciation of the Ångerman River alley occurred in a fjord environment. During this time, a thick sequence of varved silt and clay was deposited above till or glaciofluvial sediments [8].

Subsequent to deglaciation, crustal rebound caused shoreline regression. The uplift caused the Ångerman River to down cut through the varved glacial sediments as they rose above the level of the water in the Baltic basin. The sediment was then transported by the river and re-deposited as fluvial/deltaic sediments. The postglacial deltaic sediments were subsequently uplifted, eroded, transported, and re-deposited as lower level fluvial/deltaic deposits. These processes continue today, albeit much more slowly because the uplift is slower and the river now flows over less erodible sediments, such as till and glaciofluvial sand and gravel [9] [10].

The result of this deglacial and postglacial history is that the lower Ångerman River is flanked by fluvial terraces, which are up to 50 m high in the study area. These terraces are often capped with several meters of fine sand, but below the sand lies either the postglacial and/or glacial silt and clay, which may be susceptible to landslides.

3. Geotechnical data

In the early stages of the mapping SGI performed preliminary geotechnical investigations at ten sections along the river, of which eight are situated within the study area. The location of geotechnical investigations within the study area is shown in figure 2.

The height of the investigated slopes vary between 15 and 50 m. Investigations have normally been conducted at four to five different points within each section. The soundings mainly consisted of CPT and dynamic probing. Sampling consists of disturbed sampling, piston sampling and Shelby sampling, in some points to over 25 m in depth. The soil samples extracted have been investigated in SGI’s laboratory. The investigations have included the determination of soil type and analysis of the soil's geotechnical characteristics. Evaluation of results from soundings and samplings have shown that there are four main characteristic soil layers within the study area. The layers consist of sand, silt/clay with low stiffness, silt/clay with high stiffness and till underlying the sediments [4]. However, the thickness of the layers and their sequence in the stratigraphy varies between the sections. Between these layers there are transition zones.
4. Geophysical measurements

4.1. Ground electrical resistivity measurements
The main objective of the geophysical measurements was to map the distribution and occurrence of different soil types in three dimensions. Clay and silt generally show very low electrical resistivity compared to sand, gravel and till. Therefore, the use of a geophysical technique that maps the resistivity distribution of the ground is appropriate. Ground electrical resistivity measurements like ERT (electrical resistivity tomography) is a well-known and widely-used geophysical technique for subsurface mapping [11]. Measurements with ERT were initially tested along 4 profiles in the Ångerman Valley with positive results. Even though this method is faster than traditional geotechnical methods, it still cannot be used to cover large areas for more regional-scale mapping purposes.

4.2. ATEM measurements
In 2018, an airborne transient electromagnetic (ATEM) survey was performed along the river and the surrounding river banks with the objective of mapping and characterizing the sediments down to bedrock. The ATEM data were collected by SkyTEM Surveys Aps using the SkyTEM 304 system [12]. The system is helicopter based with the equipment carried as a sling load (figure 3). The system was originally developed for ground water applications in Denmark, and it offers resolution nearly as high as ground-based measurements. The surveyed area is 2 km wide and covers 80 km along the river with a line distance of 75 m. The line direction was NE-SW, i.e. almost perpendicular to the river. Three additional lines were flown along the river (figure 2).

![Figure 3. The helicopter carrying the SkyTEM equipment (Photo: SGI).](image)

The collected data were processed using the Aarhus workbench software (Aarhus Geosoftware). All the ATEM data that were contaminated by nearby electromagnetic noise sources, such as power lines and railways, were rejected. The data were then modelled using a spatially constrained inversion [13]. A model with thirty layers (fixed thicknesses) was constructed and the resistivities of each layer were estimated. The resistivity models were then interpolated to a 3D resistivity grid along the river and down to a depth of about 100 m.
5. Results

5.1. Resistivity model and geological interpretation

The resistivity model derived from the ATEM data was integrated with other geoscientific data such as surficial deposits maps and soil stratigraphy from geotechnical drillings and water wells, using the 3D modeling software Geoscope 3D. Several profiles both along and across the river were then selected for more detailed interpretation. Figure 4 shows the resistivity distribution from 3 sections across the river. The location of the sections is shown in figure 2. The large variations in both sediment stratigraphy and sediment thickness (depth to bedrock) along the river are clearly visualized in the resistivity sections.

Section A (figure 4a) coincide with several geotechnical drillings. The resistivity model shows different situations on the two sides of the river. On the north-east side a high resistive top layer is present (corresponding to sand) followed by a low resistive layer (corresponding to silt and clay). On the south-west side the high resistive top layer is absent. The very high resistive layer in the bottom of the model corresponds to till and crystalline bedrock. The results from the geotechnical drillings corresponds well with the resistivity model. The top thin (2 m) sand layer on the south-west side cannot be resolved in the resistivity model.

Section B (figure 4b) shows quite different condition with very high resistivities along the entire section except for the riverbed. The surficial deposits map show silt on the both sides of the river. In the resistivity model the low resistive silt layer is not resolved indicating that the layer is very thin (less than circa 2 to 5 m depending on the resistivity of the silt). Consequently, the bedrock is close to the surface in this part of the river.

Section C (figure 4c) in the eastern part of the study area show again different conditions with very low resistivities at depth indicating larger sediment thickness. The upper high resistive layer corresponding to sand is clearly visible on the south-west side of the river. The resistivity model indicates that the sand layer has a thickness of up to 20 m. The sand is underlain by silt and clay with lower resistivity. The resistivity model indicates a total sediment thickness of at least 40 m along this section. The low resistivities between 200 and 400 m (that corresponds to clay) marks the position of an older riverbed. The lower boundary of the clay layer is not well resolved here due to limitation in penetration depth below the very low resistive clay.

5.2. Geological model

The result from the detailed interpretation described in section 5.1 was then used to divide the area along the river into six different classes based on the soil stratigraphy (figure 5). No classification was done in areas where ATEM data coverage was poor or missing. The different classes are explained below:

1. More than 15 m thick, high resistive sand layer underlain by clay/silt.
2. 10 to 15 m thick, high resistive sand layer underlain by clay/silt.
3. Less than 10 m thick sand layer underlain by clay/silt.
4. Silt at the surface (no sand layer).
5. Thin sand layer (probably less than 10 m) on top of till/bedrock. Bedrock is close to surface.
6. Thin silt layer (probably less than 2 to 5 m) on top of till/bedrock. Bedrock is close to surface.

The depth to bedrock (soil depth) is largest in class 1 and decreases towards class 5 and 6. In class 1 to 3 the resistivity model shows a high resistive layer (sand) on top of a low resistive layer corresponding to silt/clay (like in figure 4a on NE side). Here the resistivity model and selected drillings have been used to estimate the sand thickness within each class. For class 3 (sand layers less than 10 m) the high resistive sand is often not resolved in the resistivity model (see figure 4a on SW side). To separate class 3 and 4 (no sand layer on top) the surficial deposits map was primarily used together with available drillings. For class 5 and 6 the resistivity model shows very high resistivity indicating no (or very thin) silt/clay layer (see figure 2b). Also here the surficial deposits map was used to separate between the two.
Figure 5 clearly show the large variations in sediment stratigraphy along the river. There is often different geology on opposing side of the river. That can also be observed in the topography where opposing terraces are on different elevations. Areas with higher risk for landslides are generally found within class 1 to 3 in combination with very steep terraces.

Figure 4. Resistivity sections with geological interpretation along 3 profiles. The location of profiles is shown in figure 2.
Figure 5. Classification based on the soil stratigraphy along the river. The different classes are described in section 4.2.

6. Discussion and conclusions

The resistivity model obtained from ATEM data correlates well with the data from geotechnical drillings in the area. Especially the low resistive silt and clay layer is very well resolved. Also, the thickness of the top sand layer can be estimated from the resistivity model. On the other hand, very thin sand layers at the surface are not resolved and here the surficial deposits map and available drillings are necessary for the classification.

With the integrated approach using the 3D resistivity model obtained from ATEM data, together with the surficial deposit map and available drillings, it was possible to create a simplified soil model over a large area in a fairly short period of time. The results from the ATEM-data were used to divide the study area into sub-areas based on the six different classes. Geotechnical drillings are now planned in several sections along the river (figure 5). Some sections are also placed in areas with no ATEM data coverage or in areas where data was rejected due to disturbances. The new result from the drillings will then be used to verify the sub-areas and to further refine the model. The new geotechnical data will also be used to evaluate the method and how it can be used in future mapping projects.

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