Zonation and landslide hazard by means of LS DTM – Deliverable 7

JAN FALLSVIK
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Deliverable 7 – Zonation and landslide hazard by means of LS DTM
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Task: 1.1.1: In-situ and remote monitoring techniques
Sub-task 1.1.1.1 – Application of Laser scanning digital terrain model (LS DTM) in landslide hazard zonation

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PREFACE

This deliverable reports the development of a method for application of airborne Laser scanning to accomplish a detailed digital terrain model for landslide hazard zonation purposes.

The development, which is performed by the Swedish Geotechnical Institute (SGI-SW), is included as the Sub-task No 1.1.1.1 in the Sub-project Landslide Monitoring and Warning Systems/In-situ and remote monitoring techniques in the LESSLOSS-project in the EU 6th Frame Work Programme.

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Linköping, February 2006

Jan Fallsvik
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LIST OF SYMBOLS AND ABBREVIATIONS

\[ F \] = Factor of stability
\[ F_{\text{Undrained}} \] = Factor of stability calculated by undrained parameters
\[ F_{\text{Combined}} \] = Factor of stability calculated by both undrained and drained parameters, the lowest shear strength is chosen in each section of the slide surface
\[ F_\phi \] = Factor of stability calculated by drained parameters
1. Summary

In regions covered by glaciers during the latest Ice Age, many areas are covered by fine-grained soils. Slopes in these soil layers can be unstable, and in some cases prone for devastating landslides in built-up areas. In several countries, such as Canada, Estonia, Norway and Sweden, nation-wide overview hazard mappings are performed to identify areas with prerequisites for landslides.

In this LESSLOSS-project sub-task, topographic models (digital terrain model DTM) produced by means of helicopter born laser scanning (LS) have been tested and incorporated in the Swedish landslide hazard mapping method.

The laser scan digital model (LS DTM) has proven to be an interesting tool in landslide hazard mapping. It can not only replace elevation data from national topographic maps but also be used for detection and analysis of objects of interest for the hazard mapping. It has the potentiality to complete or even replace air photo interpretation.

LS DTM gives a very detailed picture of the topography. Topographic maps can be produced in both small and large scales to give overview and details of the ground. Trees can be replaced by a virtual ground and thereby revealing features such as small landslide scars, ravines and ditches which are even difficult to detect from ground.

In Sweden the landslide hazard mapping is carried out manually, i.e. is not computer based, which means that the mapping is time consuming and expensive. However, a computer based mapping prototype is developed by the Swedish Geotechnical Institute in cooperation with the Geological Survey of Sweden, Swedish Rescue Services Agency and the Swedish Land Survey. This prototype has been used in this project.

The LS DTM has been used in two test sites in Sweden.

The LS DTM has been successfully incorporated in the Swedish method.

Pilot studies of landslide hazard mapping revised from the Swedish manual mapping method has been carried out at two sites in Sweden, where rivers are floating through landslide prone areas.

For the requested input data a digital soil map database and detailed topography information have been used. The latter is achieved by Laser scanning (LIDAR) on land and multi-beam echo sounding of the bottom of the rivers. Maps based on this very detailed topographical information are excellent tools to finding old landslide scars, erosion etc.

An ArcGIS algorithm has been developed to perform calculations based on the local soil and topographical conditions. The algorithm performs assessments on the landslide prerequisites based on empirical criteria. The criteria can be adjusted to different soil regimes, so the method could be implemented for overview mapping in other countries. As output data the ArcGIS-method delivers a digital landslide hazard map dividing the terrain in three zones indicating the local landslide hazard variety. The zones indicate sub-areas where further detailed stability investigations must be performed, and vice versa, where for prevailing conditions no sliding is estimated.
Primarily, the method is planned to be used in future overview mapping of the stability conditions in built-up areas. The results will be a necessary basis for the identification of risk areas, which are important for planning of new urbanisation and infrastructure. In addition, as the output data is in a digital form, it can easily be used as input overlay data in further GIS-processing for land-use planning.

In the Deliverable Report the developed method is described and the results of the mapping of the two test sites is presented.
2. Scope

Laser scanning of the terrain from an aircraft is of special interest as it can deliver a detailed digital terrain model (DTM). The accuracy in the x-, y-, and z-measurements is less than 10 cm, which is much better than the accuracy of existing national topographic maps. In Sweden, these maps have contour lines with equidistance not smaller than 5 m.

Further, a digital image registered simultaneously as the Laser scanning is performed can be layered on the scanned DTM, providing a new tool for stability mapping and planning. In forest areas, the ground in between the trees can be measured. Scars from old landslides, gullies, small erosion, and other morphological and hydrological features can be detected and mapped.

The laser scanned digital terrain model (LS DTM) with a photo image overlay, as described above, offers a new way to mapping landslide hazards. Its potential is explored in this sub-task to the LESSLOSS-project. The today in Sweden and other countries used, methods for overview landslide mapping are performed manually by time-consuming comparisons between and measurements in different categories of maps.

The cost of laser scanning is rather high, but the benefits are also high; they can be used for other categories of planning than landslide mapping.

In this LESSLOSS-project sub-task, one test area in Sweden with slopes in clay layers is selected. The site chosen is Lilla Edet Town situated in the northern part of the Göta Älv River valley. However, as laser scanning optionally already was carried out in another site, Eskilstuna, for other purposes, a pre-study could be performed, also offering the possibility to carry out a comparison of the usefulness of the method in slight different types of landscapes.

The content in the following sections of this deliverable report is as follows:

- In Section 3, a background is given, indicating the philosophy behind the overview landslide hazard mapping.
- In Section 4, the Overview Landslide and Erosion Hazard Assessment in Slopes in Clay and Silt is described – an existing method for a national survey in Sweden.
- In Section 5, the Swedish computer based prototype for a national digital map data base on landslide prerequisites is described. The philosophy and the GIS-algorithm developed and used in that prototype were further developed in this LESSLOSS sub-task.
- In Section 6, the theoretical basis for the Laser based method for scanning of the topography is briefly described.
In Section 7, the GIS-algorithm for construction of stability zones is described.

In Section 8, the performed pre-study along the shores of the Eskilstuna River is reported.

In Section 9, the work carried out for the LESSLOSS sub-task, along the Göta Älv River in the Lilla Edet Town, based on Laser scanning, multi-beam echo sounding and GIS-processing is reported.

In Section 10, studies and use of the digital images and results of field check is described for the LESSLOSS sub-task test site in Lilla Edet.

In Section 11, the advantages and possibilities of the studied methods are discussed.

In Appendix A, the Swedish overview landslide hazard mapping method is described.

In Appendix B, reports an example of a manually performed stability mapping, as a background.

In Appendix C, the production of the SGU digital Quaternary Soil Map is described.

In Appendix D, the bathymetrical survey of the Göta Älv River bottom topography by Multi-beam Echo Sounding is described.

In Appendix E, the studies and use of the digital images and maps and results of field check is reported.

In Appendix F is given a description of the region around Lilla Edet and the test-site.
3. Background

In regions covered by glaciers during the latest Ice Age, many areas are covered by fine-grained water laid sedimentary soils (clay and silt). Slopes in these soil layers can be unstable, and in some cases prone for devastating landslides in built-up areas. In several countries, such as Canada, Estonia, Norway and Sweden, nation-wide overview hazard mappings are performed to identifying sub-areas with prerequisites for landslides. In Sweden the mapping is carried out manually; hence it is time consuming and expensive.

Previously, landslides were difficult to predict, but research during the last decades has improved slope stability diagnosis. However, detailed stability calculations must be performed, which are expensive to carry out, especially if wide areas are in concern.

Statistics from previous landslides indicate that landslides in slopes in soft clay and silt soils have not occurred in Scandinavia and Northern America if the slope inclination is below 1:10. This can be used as mapping criteria that divide clay and silt areas into sub areas with no prerequisites for landslides and sub areas with such prerequisites. The latter should be further investigated. For a stratigraphy with other type of geology, corresponding criteria could be developed.

Typically, landslides occur very seldom, and therefore they have a surprising and shocking effect. Locals, who are not informed in the nature of landslide risks, often suppose a certain slope to be stable of the simple reason that they are used to the existence of a slope in that very spot – “this slope has always existed here”. However, the meaning of “always” is often the same as the so-called “living memory”. The length of the “living memory” is personal, and it differs from around 20 to 100 years, while the time lap between two landslides occurring locally along the same slope typically exceeds such a period of time. As an example, a landslide that occurred 80 years ago (1926) can therefore be forgotten, and further, the poor slope stability conditions are still more forgotten if the last local landslide occurred around 700 years ago (AD 1300). Furthermore, for an unskilled eye, scars of landslides are difficult to detect in the landscape only after some years, because of hiding growing vegetation.

As a basis for municipal and/or infrastructure planning before exploitation, the slope stability conditions must be investigated. To be able to perform the right decisions, planners must be informed about the slope stability conditions, first overview and later more detailed information.

In previous planning, more than 2-3 decades ago, normally the level on information on landslide stability conditions was low. Therefore, from a slope stability point of view, homes, schools, service areas, factories, roads, railroads, etc., could have been localised on unsuitable land.

To gather information on the stability conditions needed both for planning for new development as well as control of already built up areas, it would be too expensive to perform detailed investigations of the total areas in concern. In Sweden built-up areas on slopes with inadequate stability conditions are detected by a four step strategy. The methodology is also a suitable tool for finding and judging new areas for further development.
1. An overview mapping is performed indicating sub-areas with prerequisites for initial slope failure where detailed investigations are needed.

2. Slope stability investigations are performed with a suitably selected level of detail in the areas indicated by the overview mapping. Areas with adequate level of safety will be approved for existing load condition.

3. If the detailed investigations show insufficient level of safety according to the chosen level of detail, the investigation is completed to increase the level of detail.

4. If the level of safety still is too low, further stability investigation may be required to fulfil the demands for design of stabilising and/or preventive measures.

The methodology is further described below in Section 4, Table 4.1, and the required calculated safety factors are listed in Appendix E, Table E.1. The required calculated safety factors differ in various investigation stages, with different level of investigation detail and with respect to the present or intended land use, Swedish Commission on slope stability, (1995).

Dependent on the slope soil stratigraphy, two different early stage landslide hazard zonation methods are developed in Sweden:

A) Early stage landslide and erosion hazard assessment in slopes in clay and silt

B) Early stage landslide, erosion and debris flow hazard assessment in slopes and gullies in till and coarse sediment soils

Here, only the former, early stage landslide and erosion hazard assessment in slopes in clay and silt is considered.
4. Early stage landslide and erosion hazard assessment in slopes in clay and silt – an existing method for a national survey in Sweden

4.1 INTRODUCTION

4.1.1 Background and purpose

In Sweden, sporadically, infrastructure, constructions and buildings are constructed on, or close to, slopes in clay and silt with an inadequate level of safety. Every year, there are a number of landslides, in addition to movements and cracks indicating slopes, which are at a high risk. Following the landslide catastrophe at Tuve in 1977, where nine people were killed and about 70 homes destroyed, the Swedish Government appointed a commission, which proposed a governmental finance of a national mapping programme to identify built up areas with inadequate safety concerning landslides. The Swedish Rescue Services Agency (SRSA) was given the responsibility to administrate the mapping.

A mapping method was developed by SGI-SW in the late 1970-ies and used in a first landslide hazard mapping of a number of municipalities, especially in the south-western Sweden but also some other areas. The mapping method was used in the national mapping program and has been developed successively. SGI-SW has carried out this development in cooperation with Swedish Rescue Services Agency and Department of Geotechnics and Foundation Engineering at Chalmers Technical University.

The developed landslide hazard mapping method has been adopted by the Swedish Rescue Services Agency, in the Swedish national mapping programme for landslide risk reduction, see Table 4.1.

This section of the report provides a description of the hazard mapping method, Stage 1-3.
Table 4.1 Stability investigations carried out in the different stages of the Swedish national mapping programme for landslide risk reduction

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<th>Sub-stage</th>
<th>Financing</th>
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<td>1 Landslide hazard mapping</td>
<td>1a Mapping of soil conditions and topographic conditions</td>
<td>Government Administrator: The Swedish Rescue Services Agency</td>
</tr>
<tr>
<td></td>
<td>1b Overview assessment of stability conditions</td>
<td></td>
</tr>
<tr>
<td>2 Detailed stability investigations</td>
<td></td>
<td>Responsible party / problem owners, i.e. municipalities, real property owners, or other</td>
</tr>
<tr>
<td>3</td>
<td>If required, extended investigations, and supplementary stability investigations completing the basis for selection, design and realisation of preventive measures</td>
<td>Grants from the Swedish Rescue Services Agency based on application from responsible party</td>
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</table>

4.1.2 Scope

The general landslide hazard mapping is carried out nation-wide, however comprises only existing built up areas. When the mapping is finished, normally the municipalities have the responsibility to proceed carrying out detailed stability investigations, Stage 2, within areas indicated by the mapping. When the detailed investigations indicate that strengthening measures are required, Stage 3, the municipalities can apply for Governmental grants for partial financing. The annual total of the grants is 25 million Swedish Crowns (ca. 2.8 M€), this sum being allocated among the most urgent projects in Sweden.

4.2 THE SLOPE LANDSLIDE HAZARD MAPPING METHOD (STAGE 1)

4.2.1 Introduction

The landslide hazard mapping is carried out individually for each municipality. For purchasing reasons, a pilot study is carried out to get an idea of the investigation volume within each municipality. After the pilot study, and selection of consultant, the mapping is carried out divided into two sub-stages – Sub-stage 1a and Sub-stage 1b.

4.2.2 The pilot study

The pilot studies are carried out nation-wide and successively in the totally 21 Swedish provinces.

The pilot study identifies a number of built up sub-areas in each municipality, which are considered to be in need of a general mapping of stability conditions. The pilot study is based on contact with municipalities, examination of geological and topographical maps, and an overview field inspection.
Each municipality is contacted and interviews are held with officials of the engineering department. Also inventories of aerial photographs and relevant earlier geotechnical investigations stored in municipal archives are done.

4.2.3 Sub-stage 1a – Mapping of soil conditions and topographic conditions

In Sub-stage 1a, a division of the land is made into areas with and without prerequisites for initial slope failure in clay and silt.

Areas where landslide hazard could not be neglected are divided into the two Stability Zones, I and II, whereas the Stability Zone III comprises land with other soils than clay and silt:

- The Stability Zone I comprises land where there are prerequisites for spontaneous or proceeding landslides in slopes containing clay or silt soil layers, e.g. areas which may be primarily affected by an initial slide or slip. Many slopes in Zone I could have a satisfactory stability; however, this has to be investigated.

- The Stability Zone II comprises areas containing clay or silt soil, which have no prerequisites for initial slope failure, but may be affected secondarily by landslides in Zone I acting backwards or forwards. After changes of the conditions by human activities (e.g. construction work, land filling, excavation, change of ground water conditions etc., and after landslides in adjacent Zone I areas etc., the stability conditions in Zone II could change. In these cases, the stability may have to be investigated.

- The Stability Zone III comprises areas with bedrock outcrops or where the soil layers do not contain clay or silt. Before activities as blasting, piling or other vibration creating activities and change of the ground water conditions etc., are performed within Zone III, their influence on the stability conditions within adjacent Zone I or II areas must be investigated.

The dividing of the land into the stability zones is based on soil type and topography as well as information obtained from earlier geotechnical investigations carried out in the area or nearby, aerial photo interpretation and field inspections.

The criteria for division into stability zones are shown schematically in Table 4.1.
The ground for the criteria is as follows:

1. The objective of the mapping of soil conditions and topographic conditions in Sub-stage 1a is to finding slopes in clay or silt soil layers in urbanised areas being steep and high enough so the stability conditions must be further investigated.

2. According to the literature, in the former glaciated regions in Norway, Sweden and Canada, see Figure 4.1, landslides have not occurred in natural clay slopes where the slope inclination is roughly below 1:10, Inganäs & Viberg, (1979). Therefore, the inclination 1:10 was chosen as the upper limit criteria for clay slopes. This means that many slopes in Zone I have a satisfactory stability, however, this has to be controlled.

![Image](https://via.placeholder.com/150)

Figure 4.1 Areas covered by Inland Ice during the latest ice age in North America and Europe respectively, after Flint (1971).

3. In addition, in slopes with superficial silt layers under-bedded by clay layers the inclination 1:10 was chosen as the upper limit criteria.

4. In silt slopes (with no underlying clay layers) the limit inclination is stated to be 1:2.5, on the assumption that the pore pressures in the soil-layers in an overview estimation can be estimated to be low (dry slopes with no signs of springs, ponds, creeks etc). The limit inclination 1:2.5 is derived with an angle of friction $\varphi > 28^\circ$ and the effective cohesion $c' > 2$ kPa in Scandinavian silts, and with a factor of safety $F > 1.35$.

5. In silt slopes, with no underlying clay layers, where the pore pressures can not be supposed to be low, the limit inclination is stated to be 1:5.

The division into stability zones is presented in colours on maps, scale of 1:5000. In addition to the stability zones, the maps also show other data of interest for slope stability, such as:

- scars from old slides,
- ongoing erosion, and
− presence of quick clay as indicated in old geotechnical investigations

Criteria and legend for stability zone division and corresponding demands on the performance of stability investigations are presented in Appendix A.

Observations made during the field inspections are documented according to a given standard structure, see Appendix B. Also photos of inspected sites are analysed and presented.
4.2.4 Sub-stage 1b – Overview assessment of stability conditions under prevailing conditions

Sub-stage 1b comprises an overview assessment of the stability under prevailing conditions. The same investigation areas as in Sub-stage 1a are assessed. The assessment is carried out with the aid of survey calculations according to the “Directives for Slope Stability Investigations” issued by the Swedish Commission on Soil Stability (1995). The calculations are based on information obtained from earlier stability investigations, if such exist, together with overview field and laboratory investigations in a selected number of sections. In addition to calculations in these investigated sections, calculations are also carried out in a necessary number of complementary sections, however only based on map data and geotechnical information from adjacent sections.

Sections where stability calculations have been performed in earlier stability investigations, and sections where overview field investigations have been carried out in Stage 1b, are marked on the map by a continuous drawn line. Sections where only rough calculations are performed are marked by a hatched line. On the map the section are marked with the accurate length and direction. By each section line, the lowest calculated factor of safety and the type of analysis method is specified; see principle in Figure 4.2 below.

Figure 4.2 Principle. The figure describes how the sections where stability calculations have been performed are marked on Map 1b (see the text).

Each section line is identified by a code (letter + identity number), which is a reference to a corresponding line in a table, where more information about the section is documented:
Sections, belonging to stability investigations performed earlier in the area, are marked with the letter ‘T’.

Sections, where overview field investigations are performed in Stage 1b, are marked with the letter ‘K’.

Sections, where only rough calculations are carried out, are marked with the letter ‘Ö’.

The reference table for elderly performed investigations contains information about date, geotechnical consultant, the consultant’s reference number, the municipalities’ reference number and the lowest factor of safety calculated by using different theories of analysis, c.f. example Table B.1 in Appendix B.

The results of Sub-stage 1b consist of areas considered to have satisfactory stability and areas considered having unsatisfactory stability. The latter are marked by shading on a map to a scale of 1:5000. Areas where a detailed investigation is judged to have high priority are marked on the map, together with a comment. The legend describing how different areas are judged is presented in Appendix A, Table A.2. Other information of interest, such as calculated sections, scars of old landslides, erosion in progress and the presence of quick clay are shown on the same map.

The produced maps, Map 1a and Map 1b respectively, are exemplified in Appendix B, from a hazard mapping performed in the Bollebyggd town situated in south-west Sweden about 50 kilometres Northeast of Gothenburg. In Appendix B also the field control form for a selected section (Bbd-Ö9.1) is filled in. There is also presented a photo of the inspected site.

4.3 The further stability investigation stages

The objective of the landslide hazard mapping, Stage 1, is to indicate areas where further stability investigations should be carried out. According the Swedish programme for stability investigations, these investigations are carried out in the following stages 2 and 3 are described in Appendix F.
5. Prototype for national digital map data base on landslide prerequisites in clay and silt areas in Sweden

5.1 Background and scope

As described in Section 4 above, a national survey investigation of the landslide hazard in built up areas in clay and silt soils has been going on in Sweden since the nineteen eighties. However, there is also a demand for landslide hazard maps outside built up areas as a tool for

- city and infrastructure planning,
- planning and executing of rescue actions and
- judgement of landslide hazard for existing constructions outside built up areas.

Therefore, in 2000-2001, The Swedish Geotechnical Institute, SGI, was commissioned by the Swedish Ministry of Environment to develop a prototype landslide hazard map produced by GIS-technique. This work was carried out in co-operation with the Swedish Geological Survey, SGU, Lantmäteriet, LMV (the Swedish land surveying authority), and the Swedish Rescue Services Agency. The project “National digital map data base on landslide prerequisites in clay and silt areas in Sweden” is abbreviated the NAKASE-project, (2001).

5.2 Needs and benefits

Costs for landslide damage are described in Swedish Geotechnical Institute (1995). In Sweden, the annual cost for landslide damage and remedies could be estimated to several tens of millions of Euros. The cost/benefit ratio for prevention measures versus damage is 1/10 to 1/100, Swedish Rescue Services Agency (1996).

There has been a need for development of a landslide hazard mapping method based on database and GIS-technique.

It is beneficial if information on landslide hazard is available and easily accessible in early planning phases. The database format makes it possible to combine information on landslide hazard with other hazards, for example like flooding, in further processing.

5.3 Stability classification model

The stability classification model, described in Section 4 is used. However, yet only the criteria 1:10 for slopes in clay is applied.
5.4 DEVELOPMENT OF THE DATABASE

The development work was applied to a river valley in the Sundsvall municipality, Medelpad County, in the middle part of Sweden, see Figure 5.1. The database is based on soil map data and topographical elevation data in digital format.

The soil data was furnished by Swedish Geological Survey, SGU. The source data was a soil database, which had to be reclassified to fit the soil classes forming the basis for the stability zonation, Table A.1 and Figure A.1 in Appendix A. As the original soil data was in digital database format, the reclassification work was rather easily done.

The topographical data source was a set of standard altitude contour lines (elevation iso-lines), furnished by Lantmäteriet, LMV. These lines had x- and y- coordinates and had to be furnished by elevation data (z-coordinates) to form the basis for the creation of a digital elevation terrain model.

The soil and height data were fed into GIS software (ArcGIS). The GIS classification was proceeded in raster format with a cell side length of 5 m.

An algorithm was designed to process the data and classify the terrain into the Stability Zones I, II and III. Theoretically, it is a simple problem to solve, but the number of calculations is high even for moderately large areas. The created database is named “survey map database on landslide prerequisites in clay and silt soils”. A printout from the database is shown in Figure 5.1. Figure 5.2 illustrates the principle of the stability zonation.
Figure 5.1  Example of printout from the database on landslide prerequisites in clay soils (Swedish Geotechnical Institute, 2001). Legend, see Figure 5.2. From the NAKASE-project (2001).
5.5 PROPOSED PRODUCTION

The working group have proposed to the Swedish Ministry of Environment, that the classification should comprise all Swedish municipalities where prerequisites for landslides in clay and silt is at hand, e.g. areas with high and moderate frequency of landslide scars according to Figure 5.3. In total, these areas correspond to about 300 map sheets 25×25 km in the scale of 1:50,000.
Generalised map on relative landslide frequency in Sweden. (From Swedish Geological Survey, homepage www.sgu.se)
6. LASER based scanning of the topography

6.1 DESCRIPTION OF THE LASER BASED ZONATION PERFORMED IN THE LESSLOSS SUB-PROJECT

The laser scanning included in the LESSLOSS sub-project was performed in April 2005 by using the TopEye™ airborne topographic survey system, to capture topography and high-resolution digital images with high precision and in near real time, based on scanned laser and digital images.

6.2 TOPEYE Mk II – LiDAR SYSTEM WITH INTEGRATED DIGITAL CAMERA

TopEye Mk II introduces an industrial fibre laser technology to full control of the transmitted laser pulse’s properties, Sterner (2006). The emitted laser pulse has a wavelength of 1064 nm, shape of the pulse as well as the length and amplitude is tuned to height, divergence and the properties of the receiver. This combined with a dual channel receiver that gives sub centimetre range resolution with outstanding dynamics produces consistent centimetre accuracy with minimized noise. Complemented with an innovative Palmer scanner – a tilted plane mirror rotating at constant speed that provides:

- An elliptic scan pattern,
- Always full receiver aperture
- Minimized transmission losses
- No acceleration and de-acceleration
- Precise determination of scan angles.

TopEye Mk II:

- PRF 50'000 Hz
- Pulse length 4 ns 1064 nm wavelength.
- Range resolution – sub centimetre
- Echo’s – First, last and strong echo’s between first and last; i.e. unlimited number of echoes.
- Full waveform
- Intensity – 16 bit resolution
- Palmer scanner – 20/14 degrees. Results in a gross swath that is 0.7 multiplied with the Altitude Above Ground (AAG). The net swath is typically set to be ½ the AAG to ensure sufficient side lap and thus full ground coverage.
- Operational Altitudes Above Ground (AAG): 60 – 1000 meter.

The system consists of the following modules:
• A vibration isolated sensor frame holding the Laser unit with receiver optics, inertial system (Honeywell 764 laser ring gyro) and a digital camera.
• Control systems in the cockpit; power and signal distribution unit, receiver electronics, laser computer with encoder and digitizer, GPS receiver and a computer for images capture and flight management.

The data capture on the Lila Edet project was performed April 9, 2004. The flight was done at approx 400 m AAG and the raw point density was between 7-10 points per m². The crew that made the data capture was one person setting up GPS receivers on survey points (used to capture correction data for the GPS processing as well as a physical ground control signal), one operator that through the flight management system provides a real-time feedback to the pilot. The operator can if needed make adjustments in flight modification of the flight plan.

Besides the data captured during the flight did we use other available data from terrestrial surveys in the area; aerial photo signals, control points surveyed for another project in the areas with significantly more demanding precision requirements (better than 5 cm).

The ground penetration in vegetated areas was deemed to be good. This is normally only a problem were the tree vegetation is sparse and the “ground vegetation” thus very dense – typically the situation in areas far north.

The data qualification procedure is based on control of each individual step in the processing. The trajectories are calculated using GPS and INS data. The trajectories are verified in an isolated process. There after is the point cloud – raw data – processed using the trajectories and observations from the Laser Range Finder (slant range), INS (attitudes) encoders giving the direction of the scanner at the time of each individual laser pulse.

The standard output is coordinates for each laser point identified by time with additional information as point intensity and waveform structure.

When merging the GPS, INS and LRF-data that results in the point cloud data-set is it possible to have systematic shifts between the survey flight trajectories, mainly due to the variation in the GPS positioning quality. The allowed shift is pending the requirements of the final product. The eventual systematic shift between the survey trajectories is verified by checking data from overlapping flight lines. This is done in software TerraMatch that is a part of the TerraSolid OY suite of LIDAR processing tools.

For projects with extremely high precision requirements TerraMatch can be used to match the trajectories together and generate an even more homogeneous dataset with improved internal integrity.

6.3 Use of known points and ground survey measurements

As an independent check on the processed laser point clouds and ortho imagery was done in order to verify the laser data and imagery against known points and surfaces. This was done on the Lilla Edet project by using ground data from a high precision survey done in the same area and this control serves the need to have an independent verification of the data set.
6.4 **ESTIMATION OF THE REAL GROUND SURFACE**

The laser scanning achieves echoes from the ground surface as well as vegetation, and buildings, etc. To avoid the echoes from the latter objects hiding the real ground surface, the achieved data was processed by using algorithms developed to identifying the typical geometrical shapes of obstacles. There obstacles is found (trees, bushes, houses, etc.), the algorithm “neutralises” them, by replacing the obstacles with a virtual ground surface normalised to the neighbouring ground surface, see Figure 6.1.

![Figure 6.1](image)

Figure 6.1 Where obstacles are found like trees, bushes, houses, etc., which are hiding the ground surface, an algorithm “neutralises” them, by replacing the obstacles with a virtual ground surface normalised to the neighbouring ground surface.

6.5 **ACCURACY IN X-, Y- AND Z-DIRECTIONS**

The accuracy in estimation of heights is ± 0.1 m. In x- and y-direction the accuracy is achieved by the point density which is between 7-10 points per m².
7. GIS-algorithm for construction of stability zones

The GIS-algorithm was developed in ArcInfo in the NAKASE-project, (2001), by Ari Tryggvason, Swedish Geological Survey (SGU), based on the revised original idea by Jan Fallsvik and Leif Viberg, Swedish Geotechnical Institute (SGI).

The algorithm uses two types of in-data:

- Information on the soil conditions, e.g. the digital soil map
- Information on the topographical conditions, e.g. height data

In the computations the algorithm uses a given “critical angle” applicable for fine grained soils, which equals the criteria for estimating if there exist prerequisites for initial landslides. Within each sub-area containing fine-grained soils, all pixels which are located above a critical line inclined by the given “critical angle”, are classified as a sub-area having prerequisites for an initial landslide.

The following pre-processing of in-data must be carried out:

7.1.1 Soil conditions

The different soil conditions, are classified in two classes with respect to their disposition to sliding in low or moderately inclined slopes:

<table>
<thead>
<tr>
<th>Class</th>
<th>Soil conditions</th>
<th>Disposition to sliding in low or moderately inclined slopes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fine-grained soils containing clay, silt and/or organic components.</td>
<td>Yes</td>
</tr>
<tr>
<td>2</td>
<td>Till, gravel, cobbles or blocks or bedrock and also bedrock outcrops</td>
<td>No</td>
</tr>
</tbody>
</table>

7.1.2 Topographical conditions

When using topographical information produced by Laser scanning, “disturbing effects” from vegetation, buildings and infrastructure must be neutralised to get a “natural surface”.

39 (133)
Within areas covered by water, e.g. rivers, creeks, lakes, ponds and in the sea, the weight of water as a counterweight is taken into account. This is done by setting the water depth to half the real depth, see Figure 7.1 and 7.2. By this the water is approximated as soil layer having roughly half the density of an ordinary soil.

**Figure 7.1.** The weight of the water along a shore line acts as a counterweight against a presumptive sliding surface.

**Figure 7.2.** Estimation of the water depth to be half the real depth

### 7.1.3 Methodology

In principle, the algorithm is based on the procedure of lowering all pixels that are situated above the “critical line”, down to this line, see Figure 7.3.

The procedure is performed iteratively, using all of the pixels inside the sub-areas with fine-grained soils, as starting points. Each pixel which successively is found in a position above the critical lines, drawn from each starting point, will be marked to belong to an area where there are prerequisites for initial landslides. Each pixel that is marked in this way is compared to its neighbouring pixels according to the “Analysis Window” in Figure 7.4. When the analysis is performed for all the pixels in the Analysis Window, the window is moved one step aside and the comparisons start again. The process proceeds until all pixels in the sub-areas with fine-grained soils are investigated and adjusted to the critical line. All pixels within the fine-grained soil areas, which originally had a position over the critical inclination line, are classified to belong to an area with prerequisites for landslides.
Figure 7.3  Pixels situated above the critical inclination line are lowered to a level on that line.

Figure 7.4  The “Analysis Window” (the “scrolling box”). Pixels neighbouring the starting pixel (grey), which will be analysed in each step. The pixels surrounding the starting point pixel indicates the 16 discrete directions in which the search is performed.
7.1.4 Favourable factors

The algorithm can detect areas hidden “behind corners”, e.g. clay or silt areas behind hills composed by coarse soils as till or gravel or behind bedrock outcrops, see Figure 7.5.

![Figure 7.5 Detection of areas “behind corners”](image)

7.1.5 Unfavourable factors

- The algorithm cannot lower all pixels exactly to the critical inclination, because only the 16 discreet directions governed by the scrolling box can be analysed. The highest value of the inclination, which the algorithm failed to adjust, was 10.6% instead of the correct value 10.0%.

Example: If the difference in height along a slope is 10 m the error is less than 6 m in horizontal direction, see Figure 7.6. The error is in the same magnitude as the width of one pixel, 5 m.

![Figure 7.6 If the difference in height along a slope is 10 m the fault is less than 6 m in horizontal direction](image)

- Barriers (soil classed as 2) as narrow as one pixel, 5 m, is at present invisible for the algorithm. This implies that an area “protected” by coarser soils or bedrock may be erroneously classified as having prerequisites for landslides.

7.1.6 Post processing

Because the Laser scanned height information is sampled down to 0.1 m accuracy, also topographical objects like ditches, minor road banks, and other very small height variations in many cases will be classified as having prerequisites for landslides. To avoid a large number of small and scattered risk areas, a post-processing is performed. A GIS-algorithm has been developed which analyses each isolated area having prerequisites for landslides. If the area or the maximum elevation differ-
ence within the area is less than a given number, the area will be neutralized. For the Lilla Edet test site the following criteria was chosen:

- Difference in height < 4 m
- Area < 100 m²

In practice, the described post-processing GIS-algorithm works well when applied on small and well-defined objects like ditches and road banks. However, if a ditch, or a road bank, connects to a large slope, the algorithm cannot regard the ditch as a separate entity, hence it will not be neutralized. However, the geometrical data on road banks, and their parallel road ditches, could be obtained from the digital topographical map, therefore also these areas could be identified and sorted out (assumed they are located outside larger slopes).
8. The Eskilstuna River Pre-study

8.1 Basis

In a project called KRISGIS (2004) the topography in the surroundings of the Eskilstuna River in central Sweden was scanned with LIDAR mainly with purposes to estimate the risk for flooding. However, as the achieved detailed information on the topography also can be used for an overview landslide hazard map according to Stage 1a as described above, there was an opportunity to test the possibility to construct the Map 1a by using:

- The detailed Laser scanned information on the topography
- The digital quaternary soil map, locally available
- The GIS-algorithm developed for the NAKASE-project, described above

We could use the information from the performed Laser scanning freely.

8.1.1 Performed LIDAR scanning

The topography in the surroundings of the Eskilstuna River including a major part of Eskilstuna city was Laser scanned by the TopEye airborne topographic survey system described above. The river, which is around 20 km long, dewateres the lake Hjälmaren to the lake Mälaren. The laser equipment was mounted on a helicopter, which scanned the area from 150 m altitude; see Figure 8.1. The LIDAR-system delivers 5-10 measurements per square meter and the accuracy in z-direction is ±10 cm.
So, compared to the NAKASE-project described above, in the Eskilstuna River project the Laser scanned topographical information could be used in stead of the height contour lines from the topographical map, which meant a good improvement in detail.

### 8.1.2 The river bottom topography

The Eskilstuna Municipality performed ordinary simple echo sounding of the river bottom from a small boat (multi-beam echo sounding was not performed). When sounding, the prevailing water level of the river was registered, and the position of the boat was estimated by GPS.

Within areas covered by water, e.g. rivers, creeks, lakes, ponds and in the sea, the weight of water as a counterweight is taken into account. This is done by setting the water depth to half the real depth, see Section 7, Figure 7.1 and 7.2. By this way, the water is approximated as soil layer having roughly half the density of an ordinary soil. This simulates a “new bottom topography”, which is used as in-data.

### 8.1.3 The SGU Digital Quaternary Soil Map

The SGU Digital Quaternary Soil Map is available for the Eskilstuna area, see 8.4. In Appendix C, the construction of the digital Quaternary soil maps is described.

### 8.2 GIS-PROCESSING

The GIS-algorithm, originally developed for the NAKASE-project, see Section 5, was adjusted to also fit the LASER-scanned information on the topography, and a GIS-processing was performed creating a overview landslide hazard map along the Eskilstuna River. The processing was based on the following parameters:

- The topographical conditions on land achieved from the laser scanning
- The river bottom topography achieved from the echo sounding. The water depth was adjusted to its half value, see above
— The soil conditions achieved from the SGU Digital Quaternary Soil Map, adjusted in respect to eventual underlying layers of clay or silt, see Appendix C.

The Laser-scanning was originally performed to fit as in-data for prediction of flooding, hence with a very high demand on the degree of detail. However, when using it for the hazard mapping, it appeared to be too detailed. The GIS-algorithm, originally created for the NAKASE-project, was fitted to be based on the coarse topographical information from the 5 m topographical iso-lines. When the original GIS-algorithm was applied, only using the chosen criteria based on the inclination 1:10, it indicated even small variations in the topography as small Zone 1 areas with prerequisites for landslides, for example road ditches, and even furrows in a farmers field and pavement kerbs. Therefore, in the Eskilstuna pre-study we introduced a “filter” to sort out areas to be too small if their areas were smaller than 15 m².

Laser scanning cannot be performed with a lower accuracy than the achieved. However, it does not matter because of the possibility to using a “filter” as described above. Moreover, information from the Laser scanned topographical measurements will be useful in the further detailed stability calculations, which should be performed in segments of the slopes indicated to be necessary by the overview hazard mapping – and of course for other needed municipal planning.

8.3 RESULTS

An extract of the result from the GIS-processing in Eskilstuna is shown as a map in Figure 8.2 and 8.5. Legend, see Figure 8.6.

As a comparison, an extract of the earlier manually performed mapping, Räddningsverket/Bohusgeo (1996), for the same sub-area as in Figure 8.2 and 8.5 is shown in Figure 8.3. Because the surroundings of the Eskilstuna river is rather flat, in the manually performed mapping, only a 50 m wide Zone I was outlined along the river. (Legend, see Appendix A, Table A.1 and Figure A.1.)
Figure 8.2 Map 1a based on GIS processing by the algorithm described above also regarding influence from the river bottom topography. The dots in the magnified map indicates where echo sounding has been performed. Legend, see Figure 8.6.
Figure 8.3  Comparison. The "manually performed" map performed earlier for the same sub-area as in Figure 8, Räddningsverket/Bohusgeo (1996), extract. Because the surroundings of the river is rather flat, in the manually performed mapping, only a 50 m wide "restriction zone" was outlined along the river. (Legend, see Appendix A, Table A.1 and Figure A.1.)
Figur 8.4  Extract from the SGU digital quaternary soil map for Eskilstuna.

Figure 8.5  Extract from GIS-based overview hazard mapping, Map 1a. Overlay between inclination and soil conditions. The same sub-area as in Figure 8.2 and 8.3 above. Legend, see Figure 8.6.
Figure 8.6 Legend for the maps in Figure 8.2 and 8.5 presenting the result of the overview landslide hazard mapping along the Eskilstuna River.
9. The Lilla Edet test site

9.1 The Southwest Region of Sweden – A Geotechnical Problem Area

The Southwest region of Sweden around and north of the Gothenburg area – especially the Göta Älv River Valley – has long been well known for a large number of landslides in clay, for example the Tuve landslide in 1977 attracting particular attention.

9.2 The Lilla Edet Town

In the history, particularly many landslides have occurred in the town Lilla Edet, which is situated on the banks on both sides of the Göta Älv River. Therefore, the site is well investigated through performed detailed stability investigations. In selected parts of the town also a manually performed overview landslide hazard mapping has been carried out, according to the Swedish nation wide programme, see Appendix A. The town was selected to become the LESSLOSS sub task test site of three reasons.

- The site is prone for landslides providing much substance to study, like old landslide scars, active erosion, etc.
- The site is previously well investigated, providing possibilities to comparison
- The topography of the Göta Älv River bottom had previously in another project been investigated by detailed Multi-beam Echo Sounding, see below and Appendix D.

A detailed description of the region around Lilla Edet and the test area can be found in Appendix F.

9.3 Performed Laser Scanning of the Topography on Land

In the same way as in the Eskilstuna River pre-study, the topography in the surroundings of the Göta Älv River through the Lilla Edet Town was Laser scanned by the TopEye airborne topographic survey system. The laser equipment was mounted on a helicopter, which scanned the area from 150 m altitude, the helicopter routes see Figure 9.1. The LIDAR-system delivers 5-10 measurements per square meter and the accuracy in z-direction is ±10 cm.
9.4 THE BOTTOM TOPOGRAPHY OF THE GÖTA ÄLV RIVER

The laser scanning provides detailed information on the topography on land. However, in the task to analyse the slope stability conditions, detailed information on the bottom topography in the river is also essential.

For the purpose of creating a detailed terrain model of the bottom topography of selected sections of the Göta Älv River, bathymetric measurements earlier have been performed by Marin Mätteknik AB (2004). These measurements were commissioned by the SGI and financed by the Swedish Road Administration, Banverket (the Swedish National Railway Administration) and the municipalities Lilla Edet and Ale.

One of these measured sections involves the river through Lilla Edet town, and could therefore form one important basis for the LESSLOSS sub-task.
The bathymetric measurements were carried out by Marin Mätteknik AB by using Multi-beam Echo Sounding, see Appendix D.

The multi-beam echo sounding could only be performed where the water depth exceeds 1 m under the keel of the measuring vessel. Therefore, the river bottom topography could not be measured within a narrow shallow zone close to the shores.

9.5 COMBINATION OF THE LASER SCANNING AND THE MULTI-BEAM ECHO SOUNDING

The data from the Laser scanning and the multi-beam echo sounding was combined in a Digital Terrain Model (DTM). As an example, an out print from the Lilla Edet DTM is presented in Figure 9.2, (oblique view).

![Figure 9.2 Out print from the Lilla Edet DTM. Oblique view, direction from south](image)

The lack of data within the narrow zones along the shores was overcome, by estimating the river bottom inclination as a tilted straight line in the gap between the shoreline and the closest measured points on the river bottom.

9.6 RESULTS OF THE MAPPING IN LILLA EDET PERFORMED BY LASER SCANNING, ECHO SOUNDING AND GIS-PROCESSING

As a summary, the overview landslide hazard mapping in Lilla Edet was performed as described in Table 9.1.
Table 9.1  Summary of landslide hazard mapping in Lilla Edet in the LESSLOSS-project sub task.

<table>
<thead>
<tr>
<th>Effort</th>
<th>Method</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>The topography on land</td>
<td>Helicopter borne Laser scanning (LIDAR)</td>
<td>Section 6</td>
</tr>
<tr>
<td>The soil conditions on land</td>
<td>Overlay achieved from the SGU Digital soil map, revised with reference underlying sited fine grained soils</td>
<td>Appendix C</td>
</tr>
<tr>
<td>The Göta Älv River bottom topography</td>
<td>Multi-beam Echo Sounding</td>
<td>Appendix D</td>
</tr>
<tr>
<td>The soil conditions below the river bottom</td>
<td>Overlay achieved from the SGU’s classification based on information from side scanning sonar images</td>
<td>Appendix C</td>
</tr>
<tr>
<td>The stability zones</td>
<td>GIS processing by overlay technique involving the information above and by using the GIS-algorithm revised and extended from the Swedish NAKASE-project</td>
<td>Section 5-9, Appendix A and B</td>
</tr>
<tr>
<td>The field control</td>
<td>Evaluation of the Laser scanned digital terrain model with respect to analysis results of field check. Studies of the detailed digital topographical information.</td>
<td>Section 11</td>
</tr>
</tbody>
</table>

The result of the LESSLOSS overview landslide hazard mapping along the Göta Älv River through Lilla Edet town, based on Laser scanning, is available as a digital database, and is illustrated in the maps in Figure 9.3, 9.4, and 9.5.

The LESSLOSS result is interesting to compare with the result of the manually performed landslide hazard mapping done by Räddningsverket/GF Konsult AB (2002) in parts of the Lilla Edet test area, see Appendix F, Figure F.6. It is obvious that the LESSLOSS result has a higher level of detail and that it also is influenced by achieved information on the topographical conditions on the river bottom.
Figure 9.3  Map presenting the result of the overview landslide hazard mapping along the Göta Ålv River through Lilla Edet town. Note the very high level of detail, which gives the image a three dimensional impression. In Figure 9.4, a magnification of the area indicated with the
northern hatched line is presented. In Figure 9.5, a magnification of the area indicated with the southern hatched line is presented. The blue lines indicate the shorelines of the river and other watercourses. Legend, see Figure 9.6.

Figure 9.4  Map presenting the result of the overview landslide hazard mapping along the Göta Ålv River trough Lilla Edet town. Magnification of the area indicated with the northern hatched line in Figure 9.3. The blue lines indicate the shorelines of the river and other watercourses. Legend, see Figure 9.6.

The dotted black line indicates a scar of an ancient landslide. The hatched black line indicates the scar of the 1759 landslide. Note the Zone 1 areas on the bottom of the river, indicating zones with prerequisites for initial underwater landslides.
Figure 9.5  Map presenting the result of the overview landslide hazard mapping along the Göta Ålv River trough Lilla Edet town. Magnification of the area indicated with the southern hatched line in Figure 9.3. Legend, see Figure 9.6.

The dotted black line indicates a scar of an ancient landslide. Note the Zone 1 areas on the bottom of the river, indicating zones with prerequisites for initial underwater landslides. The blue lines indicate the shorelines of the river and other watercourses.
Legend for the maps in Figure 9.3, 9.4, and 9.5 presenting the result of the overview landslide hazard mapping along the Göta Ålv River through Lilla Edet town.
10. Evaluation of LS DTM with respect to landslide information

10.1 General

One of the purposes of this project is to evaluate the LS DTM with respect to landslide information. The detailed topographical data in the DTM can be used to detect and analyse objects of importance for the landslide hazard mapping. By combining the topography with the photos taken simultaneously with the laser scanning we have an interesting tool for landslide hazard mapping. The photos are mainly used for orientation.

The equidistance can be chosen at will, but must not be less than the accuracy in z-coordinate. We have used an equidistance of 0.2 m, which gives very detailed topographic information. However, a rather large map scale, 1:1000, is required to get high enough resolution. In this study the detailed topographical map was used without photos.

10.2 Detailed Topographical Maps

Detailed topographical maps based on the Laser scanning as well as the multi-beam echo sounding were constructed. Maps with varying equidistance between the height iso-lines were compared.

The map in Figure 10.1 with 0.5 m equidistance gave a good overview for detection of large objects like old landslide scars, gullies, erosion, and human activities. Small objects could not be detected. On that map the iso-lines were printed as an overlay on a background achieved from the mosaic of digital high resolution photos of the ground surface (the vertical views).

The map in Figure 10.2, with 0.2 m equidistance, gives a good guidance for detection of large as well as small objects like old landslide scars, gullies, erosion, ditches, fill, erosion protection, and human activities. On that map only the iso-lines were printed as an overlay on a background indicating land (grey) and water (white). The red markings were made in the office when planning the field control, and the blue notes were performed during the field control.
Figure 10.1  Extract from a map where the iso-lines are printed as an overlay on high resolution photos. The map gave a good overview for detection of old landslide scars, gullies, erosion, and human activities. Hence, it can be used when planning the field control included in the overview landslide hazard mapping, Stage 1a. (Equidistance, 0.5 m)
10.3 DIGITAL PHOTO IMAGES

Together with the Laser scanning equipment, the helicopter was also supplied with a high resolution digital camera. So, simultaneously as the Laser scanning was performed, also high resolution photos of the ground surface were taken (vertical views). These photos were processed and fitted together covering the entire Lilla Edet investigation area, extract see Figure 10.3. The accuracy in the high resolution photos is ±0.4 m.

10.4 THE ANALYSIS AND FIELD CONTROL

The analysis of the detailed topographic maps and the field control is reported in Section 11.
10.5 CONCLUSIONS

The detailed topographical maps achieved by GIS-processing of the high resolution Laser scanning as well as the detailed photo images taken from the helicopter are good tools for finding and overview evaluating eventual landslide hazard signs in the landscape. These tools where also very informative for planning and performing the field control.

Elevation data from laser scanning, LS DTM, is a powerful tool for detection of both large and small objects of interest in landslide hazard mapping.

It is surprising that even features covered by rather dense vegetation are revealed. Small features like ditches only some half meter deep and with tree and bush vegetation are imaged.

In our study the LS DTM seems to be reliable giving very few false features. These have certain “artificial” forms and give rise to suspicion.

The LS DTM tool have the potentiality to be a strong complement to 3D air photo interpretation and can probably replace it in the future. The LS DTM has several advantages to air photo interpretation: It gives a 3D impression without instrument, it is easy to analyse, several people can watch it simultaneously, it reveals tree covered features, it is digital and it can be produced in large as well as small scales with different contour interval.
The analysis of LS DTM has the potentiality to be computer based in the future.

One important drawback of LS DTM is the cost.
11. **Evaluation of LS DTM with respect to analysis results of field check**

11.1 **BACKGROUND**
The field control was carried out in November, 2005. The ground was snow free.

Trial with different prints of the maps having different contour interval lead to the conclusion that an interval of 0.2 m was optimal for detection of large as well as small morphological forms. We found that 0.5 m did not reveal the small forms and 0.1 m produces too many lines. We also found that the map scale should be 1:1000 in order to get an appropriate separation of the contour lines for steep slopes.

The map was inspected by the naked eye for interesting features and areas were marked for field check, see extracts of these maps below. On these maps the red markings were made in the office when planning the field control, and the blue notes were performed during the field control.

11.2 **THE INVESTIGATED AREAS**
The Lilla Edet test area was divided in seven areas, AREA 1-7, which all were visited during the field control. The results of the studies performed during the field control were reported as follows:
AREA 1

Name: Holmen

Sub area 1a

The form consists of an about 4 m deep depression resembling a landslide scar with a mouth ending into Göta River. The form is very pronounced on the contour map. (PHOTO 1-3)
However, this feature is not a landslide scar. The abruptly ended valley is a result of an old idea to relocate the Göta River by digging out a canal. The excavation, which was not fulfilled, reached further north of what is seen today, but was refilled up to the present straight back-slope. The morphology of the area adjacent to the river is also affected by this excavation. The reason for the canal project was that the water in the river was shallow and this caused troubles for the ships. The problem was solved by deepening the river by excavating the bottom instead of digging a new canal. (Information from the present farmer). (PHOTO 3)
Sub area 1b

The terrace in the slope in the south is caused by a house. (PHOTO 4)

PHOTO 4

Sub area 1c

A ditch parallel to the road is about 40 cm deep. The ditch is revealed by elongated contour lines.

Benefits/drawback for landslide risk mapping

The morphologic depression resembles a landslide scar, although the rectangular shape of the back slope may raise suspicion. Manmade forms like this are misleading. Forms that do not look natural should be further checked, e.g., people who live close to such landscape forms should be interviewed.
AREA 2

Name: South Lilla Edet

Sub area 2a

A wide ravine is crossed by a highway. The road embankment with its slopes stands out clearly. On the west side the height of the embankment can be calculated to be 3.6 m high (18 contour lines).

PHOTO 28

Seen from south the road surface, in the centre of the ravine, is gently inclined to the left (westwards). The maximum tilt is about 20 cm. The road crossing is straight so it is unlikely the surface was designed with this inclination. A possible cause is settlement in the underlying clay (and in the embankment).

The road is stabilized by counterweight berms on both sides. They are clearly visible on the map, especially the berm on the west side. On the west side the berm is 2,2 m high (11 contour lines). (PHOTO 28, 30)
The drainage pipe under the road is clearly evident on the east side (inlet). On the west side the outlet is not very evident, but is indicated by a vague incision between the road slope and the stabilising berm.

A ditch is seen in the natural slope on the east side is around 50 cm deep. The contour lines straighten out and form a shallow valley.

The natural slope on the south side of the ravine is covered by dense tree vegetation. The computer “clear cutting” reveals the major geomorphological forms of the slope. Some troughs are seen and especially the trough in the east is pronounced. All the troughs are of course important water ways during and after rain storms. No landslide scar is detected. (PHOTO 28-30)
Sub area 2b

A steep slope with dense tree vegetation. On slope crest there are rectangular terraces, which are house sites. (PHOTO 31-32)

PHOTO 31

A ditch is very well depicted in area c. (PHOTO 33)
PHOTO 32

PHOTO 33
Benefits/drawback for landslide risk mapping

The marked ravine in sub area 2a in combination with counterweight berms are strong indications of soft clay. Add to this high and steep slopes it is evident there are conditions for landslide. However no landslide scars are detected by the contour lines. The trees in the slope are a stabilising factor at least against erosion and shallow slides. Manmade forms like house sites are revealed by unnatural (rectangular) forms. The underlying orthophoto shows the houses.
AREA 3

Name: Strandbacken

General

The slope stability has been too low in the area why unloading by excavation has been executed. The excavated area is clearly seen as a terrace.

There is a pattern of bended lines along the western shore. This pattern is not found in the field. It is evident that the pattern is due to some systematic error in the LIDAR registration or at the data processing. A similar pattern is seen on the eastern side in the south part. The contour lines are jagged in these areas even between the bends.

Sub area 3a

Description

The slope is densely covered by trees. The erosion protection along the shore line is laid out as berm with a 2-3 m wide horizontal surface. It consists of crushed rock. The horizontal surface is not revealed everywhere. However, looking along the shores on both sides of the river it is seen that the horizontal part of the erosion berm is revealed at very long stretches. (PHOTO 7, 8)
Sub area 3b

Description

The slope is result of the excavation mentioned above. Despite dense tree cover the slope seems to be rather well described by the contour lines. (PHOTO 9)

Sub area 3c

Description

The form consists of a shallow ditch, about 0.3 - 0.5 m deep, densely overgrown by trees and bushes. It is remarkable that the ditch is so well described by the contour lines. (PHOTO 10)
Sub area 3d

Description

A ravine about 6 m deep is partly filled over and the water is drained by a pipe through the bottom of the filling. The surface of the filling consists of two plateaus. The filling forms are well described by the contour lines. (PHOTO 11)

On the map, the site of a pump house is manifested by a horizontal surface.
Benefits/drawbacks for landslide risk mapping (Sub area 3a-d)

The rather good imaging of the erosion protection is of great value e.g. for inspection of the berm condition. Probably rather small damages as fallouts may be detected.

The detection of small ditches covered by dense vegetation is of great value for hydrological mapping.

The detailed description of the filling in the ravine is also of great value in order to disseminate manmade forms from natural forms.

The existence of the bended pattern may cause interpretation problems if only one or a few lines show up. When many repeated bands occur as in this case it is rather evident that the bands do not represent natural features.
AREA 4

Name: Ström

Sub area 4a:

The entrance down to a garage in basement of a house is depicted. You drive down from east to west. The contour pattern on the opposite side is caused by the computer removal of the house and is a false pattern.

Sub area 4b:

There are three terraces below the natural sediment plane. The terrace close to the river is the erosion protection berm, consisting of crushed rock, which is clearly depicted here. The next two terraces are caused by excavation in order to unload the slope and increase its stability. The slopes are well represented despite dense tree vegetation in the slopes. The terrace plateaus are covered by grass. (PHOTO 12)
In the south a ravine is cut into the slope. It is densely covered by trees, but is clearly depicted.

Sub area 4c:

The slope of the stabilizing berm is very steep and the contour lines come so close together that they can not be separated at this scale. Two ravines covered by trees are seen in this area.

Sub area 4d:

A vertical stone wall borders the river. The south part of it is not correctly represented as vertical wall, but as a steep slope. Further north the steepness is fairly well represented. (PHOTO 13).
On the map, the inward bend of the slope in the south is caused by a house.

**Sub area 4e:**

The river bank consists of a quay with a horizontal ground surface supported by a vertical stone wall towards the river. There are three similar depressions in the quay, which are false forms. They are probably caused by data processing. The vertical quay wall is rather well depicted.

**Benefits/drawbacks for landslide risk mapping (Area 4a-e)**

The good depiction of slopes and ravines that are covered by trees is of great value. False forms like the ones on the quay may be wrongly interpreted as landslides. The existence of three similar features, however, calls for suspicion. In this case a check in the field is necessary.
AREA 5

Name: “Opposite Smörkullen”

Sub area 5a

The form looking like a filling in the slope could not be found in the field. It is evidently a false form.

The form at the ravine mouth could neither be found in the field. There is a wooden bridge (PHOTO 14) across the small brook in the ravine bottom.

Sub area 5b

The large scar of the 1759 landslide appears well. Its border in the south consists of a clay ridge where the driving force decreased and the landslide stopped. (PHOTO 15-19)
PHOTO 15
In the northern landslide slope a small depression is depicted. It is a small slide. It is overgrown by trees and bushes and is hard to detect from the landslide bottom. It is well represented by the contour lines. (PHOTO 16).

The ditch in the landslide bottom is only a few decimetres deep, however, detectable on the map. (PHOTO 19)
The landslide bottom north of the ditch is covered by high grass, namely sedge. This may be the reason why the contour lines are jagged. South of the ditch there is regular grass and the contour lines are a somewhat smoother.

**Benefits/drawbacks for landslide risk mapping (Sub area 5a-b)**
The very nice depiction of landslides such as this and small slope features is of great value for landslide risk mapping. The false forms in Sub area 1a could not be explained in the field. They are probably caused by data processing.

AREA 6

Name: Bonde-Ström

Sub area 6a

An old food cellar dug down into ground is depicted. It is the entrance down to the cellar that is seen. (PHOTO 21)
Sub area 6b

A scar of a landslide with gently sloping bottom. (PHOTO 22) The ravine south of the slide stopped its progression southwards. The remaining original ground surface is seen as a broad ridge along the ravine.
Sub area 6c

Two nice ravine arms are very well depicted despite tree vegetation. (PHOTO 23) A bank of crushed rock – about 0.5 m high - in the ravine mouth is not detected by contour lines. Water is present in the mouth. (PHOTO 26)
Sub area 6d

The steep part in the north is due to stone wall. (PHOTO 24)

PHOTO 24

Sub area 6e

The shallow ditch – about 0.5 m deep – is well depicted. (PHOTO 25)

PHOTO 25

Sub area 6f

A private grass air field is laid out on the ground. This is of course not detectable by contour lines.
Benefits/drawbacks for landslide risk mapping (Sub area 6a-f)

The good representation of the large landslide and the tree covered ravines in combination with the detection of small features like ditches is positive for landslide risk mapping. The detection of small human objects like the cellar in this area has no effects on landslide risks but is a good proof of the LIDAR ability.
AREA 7

Name: Directly N Lilla Edet
Sub area 7a

A crack in the road. The form is too small to be detectable by LIDAR. (PHOTO 37)

Sub area 7b

The ravines are densely covered by trees and bushes, but stands out very fine on the contour map. (PHOTO 39)

Sub area 7c

The rock slope is too steep to separate the contour lines. The rugged nature of the rock slope is well depicted. (PHOTO 41)
Benefits/drawbacks for landslide risk mapping (Sub area 4a-e)

Steep rock slopes are well depicted by the contour lines.
12. Advantages and possibilities of the studied methodology

12.1 The performed study

In the LESSLOSS project sub task 1.1.1.1, we have combined information from the following sources by using ArcGIS applied on the Lilla Edet test site:

- Detailed laser scanning (LIDAR) on land
- Simultaneous photographing with a digital camera (vertical views)
- Multi-beam echo sounding of the Göta Älv River bottom
- The digital Quaternary soil map

The GIS-algorithm developed for the NAKASE project, Swedish Geotechnical Institute (2001), was further developed to fit the very detailed topographical information achieved.

The pre-study performed in Eskilstuna showed that the method is fruitful.

When applying the method on the Lilla Edet test site, it is obvious that the method of GIS-processing (combining) the different overlay of information generates good improvement compared to “manual mapping”:

1. An improvement of the quality of maps – much higher level of detail of the local topography. These maps are very informative for the viewer, hence implying the possibility to carry out studies giving implications of old landslide scars, active or old erosion, human activities, the state of eventual stabilisation measures, etc. The properties of the found objects can be stored digitally in the GIS-system as so-called attributes.

2. Information about the influence on the zonation from the river bottom topography.

3. A possibility to GIS-process a combination the information to achieve new information, as tested in the sub-task the zones of the overview landslide hazard mapping. To performing these zones manually in the original way, by measurements in topographical a maps and comparisons to soil maps, is very time-consuming and the result tends to be inexact.

4. The result (the digital maps, attributes, etc) of the GIS-processing is stored digitally. Therefore, it can be used as in-data in GIS-processing in further physical planning, e.g. municipal planning, road and rail-road planning, environmental planning, planning of measures against flooding etc.

To gather topographical information by Laser scanning or Multi-beam measurements is expensive. However, not only landslide hazard mapping and related problems need this information. In the near future, physical planners will perform these gatherings for other reasons, and hence the costs can be shared between different categories of users.
12.2 **Possible Further Development**

The HawkEye System is a new further development of the Laser scanning technique based on both infrared (IR) and green light Laser waves. The green light can also penetrate through water, which makes it possible to measure the water depth. However, the HawkEye measuring depth is limited to 2.5 times the so-called Secci depth\(^1\).

As the water in rivers in many cases is very muddy, the Secci depth is small. In the Göta Älv River the Secci depth is normally around half a meter, so the penetration depth for the HawkEye green Laser light could not be more than 1-1.5 m. However, having this limitation in mind, the landslide hazard mapping methodology based on Laser scanning could be further developed by combining the TopEye and Multi-beam sounding measurements with HawkEye measurements. This combination could perform the measurements of the topography as follows:

- TopEye measurements of the ground surface on land
- HawkEye measurements of the shallow water areas, with depths less than 2.5 times the Secci depth (e.g. the gap with no multi-beam sounded water depth data close the river shores, see Section 9)
- Multi-beam measurements of the deeper water areas, with depths exceeding 2.5 times the Secci depth

\(^1\) Secci depth = the water depth which is visible by the eye
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Sub Task 1.1.1.1 – Zonation and landslide hazard by means of LS DTM


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SGU, (2005), Swedish Geological Survey, digitaliserad del av jordartskarten (digitalized part of the Quaternary soil map), SGU Ser. Ae nr 48


APPENDIX A. Swedish overview landslide hazard mapping
(Stage 1a)

Criteria and legend for stability zone division and corresponding demands on the performance of stability investigations

Contents

Table A.1 Criteria and legend for stability zone division and corresponding demands on the performance of stability investigations on Map 1a (during Stage 1a)

Figure A.1 Criteria for the division and description of stability conditions in clay

Figure A.2 Criteria for classification and documentation of the stability conditions in areas containing soil layers of silt and sand on firmer soil materials (i.e. gravel, till) or bedrock

Figure A.3 Criteria for classification and documentation of the stability conditions in areas where profound layers of clay could be found (verified or suspected) under layers of sand or silt. In Sub-stage 1a, there are difficulties to judge if profound layers of clay exist under layers of sand or silt

Table A.2 Legend, presentation of the judgement of the different assessed areas on Map 1b (during Stage 1b)
Table A.1 Criteria and legend for stability zone division and corresponding demands on the stability investigations during Stage 1a

<table>
<thead>
<tr>
<th>Stability Zone</th>
<th>Criteria for Classification of Areas into Stability Zones</th>
<th>Demands on Performance of Stability Investigations when the Loads are Changed</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZONE I CLAY (yellow lined) (Figure A.1)</td>
<td>Area within the distance of 10 × slope height measured from the foot of the slope or a shoreline of the sea, lakes and major rivers Area within the distance of 50 m measured from a shoreline of the sea, lakes and major rivers Area within the distance of 25 m measured from a shoreline of minor creeks and ditches</td>
<td>Normally the stability conditions must be judged based on investigations and calculations</td>
</tr>
<tr>
<td>ZONE I SILT/SAND (orange lined) (Figure A.2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No groundwater outflow in the slope</td>
<td>Area within the distance of 2,5 × slope height measured from the foot of the slope or a shoreline Groundwater outflow in the slope</td>
<td>Area within the distance 5 × slope height measured from the foot of the slope or a shoreline</td>
</tr>
<tr>
<td>ZONE I SILT/SAND ON CLAY (yellow lined) (Figure A.3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No groundwater outflow in the slope</td>
<td>Area within the distance of 10 × slope height and n × slope height, where n is the factor of inclination for silt or sand. The applied value of n is 2,5 or 5, see below.</td>
<td></td>
</tr>
<tr>
<td>ZONE I SILT/SAND ON CLAY (yellow lined and dotted) (FIGURE A.3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No groundwater outflow in the slope</td>
<td>Area within the distance of 2,5 × slope height measured from the foot of the slope or a shoreline Groundwater outflow in the slope</td>
<td>Area within the distance 5 × slope height measured from the foot of the slope or a shoreline</td>
</tr>
</tbody>
</table>

(The table is continued on the next page.)

Table A.1 cont. Criteria and legend for stability zone division and corresponding demands on the performance of stability investigations
<table>
<thead>
<tr>
<th>Stability Zone</th>
<th>Criteria for Classification of Areas into Stability Zones</th>
<th>Demands on Performance of Stability Investigations when the Loads are Changed</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZONE II</td>
<td>CLAY (yellow) (Figure A.1)</td>
<td>Normally an experience-based judgement performed by a geotechnician is sufficient. In some cases however, investigations and calculations must be carried out.</td>
</tr>
<tr>
<td></td>
<td>Area situated on longer distance than 10 × slope height measured from the foot of the slope or a shoreline, however, by minimum 50 m from a shoreline</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SILT / SAND (orange) (Figure A.2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Area situated on longer distance than 5 alt 2,5 × slope height measured from the foot of the slope or a shoreline</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SILT / SAND ON CLAY (yellow) (Figure A.3)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Area situated on longer distance than 10 × slope height measured from the foot of the slope or a shoreline, however, by minimum 50 or 25 m from shorelines/gullies/ditches</td>
<td></td>
</tr>
<tr>
<td>ZONE III</td>
<td>FIRM GROUND (green) (Figure A.1)</td>
<td>The stability conditions within neighbouring areas containing loose soil layers shall be considered before activities within firm ground areas are performed, which could have influence on the neighbouring areas – i.e. blasting, artificial groundwater infiltration etc. Otherwise, there are no restrictions in regard to stability conditions.</td>
</tr>
<tr>
<td></td>
<td>Outcrop, till, coarse glacifluvial deposits etc.</td>
<td></td>
</tr>
</tbody>
</table>
Sub Task 1.1.1.1 – Zonation and landslide hazard by means of LS DTM

Figure A.1 Criteria for the division and description of stability conditions in clay

Figure A.2 Criteria for classification and documentation of the stability conditions in areas containing soil layers of silt and sand on firmer soil materials (i.e. gravel, till) or bedrock. For slopes in sand or silt the inclination $1 : n$ is applied, where the value of $n$ is depending on the local groundwater conditions:

- No groundwater outflow in the slope: $n = 2.5$
- Groundwater outflow in the slope: $n = 5$
Figure A.3 Criteria for classification and documentation of the stability conditions in areas where profound layers of clay could be found (verified or suspected) below layers of sand or silt. In Sub-stage 1a, there are difficulties to judge such conditions. If there are geological conditions for presence of profound clay layers, the area shall be marked as in the figure, i.e. both the lines $\frac{1}{10}$ and $\frac{1}{n}$ are applied. For slopes in sand or silt the inclination $\frac{1}{n}$ is applied, where the value of $n$ is depending on the local groundwater conditions:

- No groundwater outflow in the slope: \( n = 2.5 \)
- Groundwater outflow in the slope: \( n = 5 \)

Table A.2 Legend, presentation of the judgement of the different assessed areas on Map 1b

<table>
<thead>
<tr>
<th>Description</th>
<th>Symbol</th>
</tr>
</thead>
</table>
| Areas, which in older stability investigation have been classified to be satisfactory stable, or areas where stabilising measures have been carried out, however, not in correspondence with the rules of today according to the directions of the Swedish Commission on Soil Stability. It is recommended that old stability investigations and eventual stabilising measures will be judged, and, if needed, revised and modified. | ![Yellow]
| Areas, where judgement and/or revision of old stability investigations and modification of eventual stabilising measures is of special importance. | ![Yellow lined and dotted]
| Areas, which after overview judgement have been classified to be unsatisfactory stable or unsatisfactorily investigated. A detailed stability investigation is recommended. | ![Yellow lined]
| Areas, where a detailed stability investigation is particularly recommended. | ![Yellow lined and dotted]
APPENDIX B. Bollebygd Municipality – Example of a Manually Performed Stability Mapping

Hazard mapping according to the Swedish manual method was performed by Swedish Rescue Services Agency/SWECO VBB (2004) in the Bollebygd municipality situated in south-west Sweden around 50 kilometres Northeast of Gothenburg. The result maps from the mapping, Map 1a (Figure B.1) and Map 1b (Figure B.2) respectively, are exemplified in this appendix, as well as information on the carried out overview stability calculations, Table B.1, and the filled in Field Control Form, Table B.2.

Figure B.1  Map 1a – Sub-stage 1a, example. Hazard mapping performed manually in Bollebygd town, south-western Sweden. Legend, see Table A.1 in Appendix A. The red arrows indicate field observation points and the direction of photos.
Figure B.2  Map 1b – Sub-stage 1b, example. Hazard mapping performed in Bollebygd town, south-eastern Sweden, the same area as in Map 1a. Legend, see Appendix A, Table A.2. To the map belongs a table, “Table 1b”, which reports the results of the carried out stability calculations indicated by the marked sections on the map. In Table B.1, the text in that table is translated to English.
Table B.1  The table referring to Map 1b, translated to English, which reports the results of carried out stability calculations along the marked sections on the map. Bollebygd town, south-eastern part of Sweden.

<table>
<thead>
<tr>
<th>Reg. No.</th>
<th>Type of investigation</th>
<th>Method of analysis</th>
<th>Calculated stability factors, $F$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$F_{Undrained}$</td>
<td>$F_{Combined}$</td>
</tr>
<tr>
<td>Bbd-K4.0</td>
<td></td>
<td>1.67</td>
<td>1.24</td>
</tr>
<tr>
<td>Bbd-O4.1</td>
<td></td>
<td>1.69</td>
<td>1.39</td>
</tr>
<tr>
<td>Bbd-O4.2</td>
<td></td>
<td>1.04</td>
<td>1.01</td>
</tr>
<tr>
<td>Bbd-K5.0</td>
<td></td>
<td>1.08</td>
<td>1.04</td>
</tr>
<tr>
<td>Bbd-O5.1</td>
<td></td>
<td>1.11</td>
<td>1.00</td>
</tr>
<tr>
<td>Bbd-O5.2</td>
<td></td>
<td>1.36</td>
<td>1.31</td>
</tr>
<tr>
<td>Bbd-T7</td>
<td>Overview</td>
<td>1.00</td>
<td>1.37</td>
</tr>
<tr>
<td>Bbd-T8</td>
<td>Overview</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Bbd-T13</td>
<td>Overview</td>
<td>1.60</td>
<td>1.64</td>
</tr>
</tbody>
</table>

Comments:

1 The first three letters indicate the place where the stability investigations have been performed. In this case, “Bbd” is an abbreviation of “Bollebygd”.

Bbd-Tx indicates a section from a stability investigation carried out earlier

Bbd-KX.x indicates an overview calculated control section, based on field control or alternatively archived material

Bbd-ÖX.x indicates a roughly calculated overview section, based on adjacent sections

2 The different types of stability calculation methods are described in section 3.4 below

REFERENCE

Swedish Rescue Services Agency/SWECO VBB (2004), Bollebygds kommun, Översiktlig stabilitetskartering, Västra Götalands län, Uppdragsnummer KD14156 (SWECO 2305 078)
### SURVEY MAPPING OF STABILITY CONDITIONS

#### FIELD CONTROL FORM

- **Municipality:** Bollebygd
- **Place:** Section Bbd-O5.1
- **ID NO:** Bbd-Op5.1
- **Photo(-s) NO:** Fo5.1 (see below)

#### Indications of Erosion

<table>
<thead>
<tr>
<th>Indication</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exposed (naked) soil</td>
</tr>
<tr>
<td>Type of damage - morphology (e.g. washed shoreline or river bank)</td>
</tr>
<tr>
<td>Inclined trees</td>
</tr>
<tr>
<td>Bent trees (with vertical top)</td>
</tr>
<tr>
<td>Holes in the coverage of undergrowth</td>
</tr>
<tr>
<td>Exposed location in the terrain</td>
</tr>
<tr>
<td>Fallen trees</td>
</tr>
</tbody>
</table>

#### Parts of the Slope Influenced by Erosion – Extent

<table>
<thead>
<tr>
<th>Extent</th>
</tr>
</thead>
<tbody>
<tr>
<td>The entire slope</td>
</tr>
<tr>
<td>Only the lower parts</td>
</tr>
<tr>
<td>Only the upper parts</td>
</tr>
<tr>
<td>Varying</td>
</tr>
</tbody>
</table>

#### Type of Erosion

<table>
<thead>
<tr>
<th>Type of Erosion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landslide - fall (silt, sand or coarser)</td>
</tr>
<tr>
<td>Creep (clay, silt)</td>
</tr>
<tr>
<td>Landslide - slump (clay or silt)</td>
</tr>
<tr>
<td>Difficult to estimate</td>
</tr>
</tbody>
</table>
### Intensity of Erosion

<table>
<thead>
<tr>
<th>Grade</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>Large activity (large areas without ground growth; many inclined or fallen trees)</td>
</tr>
<tr>
<td></td>
<td>Moderate activity (small areas without ground growth; a few inclined trees)</td>
</tr>
<tr>
<td></td>
<td>Small activity (small areas without ground growth)</td>
</tr>
<tr>
<td></td>
<td>Regenerated damage (old erosion, not active anymore)</td>
</tr>
<tr>
<td></td>
<td>Erosion impossible to estimate</td>
</tr>
<tr>
<td></td>
<td>No erosion</td>
</tr>
</tbody>
</table>

### Soil conditions

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>X Clay</td>
<td>Boulders</td>
</tr>
<tr>
<td>Silt</td>
<td>Till</td>
</tr>
<tr>
<td>X Sand</td>
<td>Bedrock outcrop(-s)</td>
</tr>
<tr>
<td>Gravel</td>
<td>Organic soil</td>
</tr>
<tr>
<td>Cobble</td>
<td>Fill</td>
</tr>
</tbody>
</table>

### Slope Inclination

<table>
<thead>
<tr>
<th>Inclination</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>X Steep</td>
<td>(&gt;30°, 1:1.5)</td>
</tr>
<tr>
<td></td>
<td>Moderate inclination, (15-30°, 1:4-1:1.5)</td>
</tr>
<tr>
<td></td>
<td>Small inclination, (&lt;15°, &lt;1:4)</td>
</tr>
</tbody>
</table>

### Height of the Slope

<table>
<thead>
<tr>
<th>Height</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 5 m</td>
<td>15 - 20 m</td>
</tr>
<tr>
<td>5 - 10 m</td>
<td>20 - 30 m</td>
</tr>
<tr>
<td>10 - 15 m</td>
<td>X Higher: ...35...... m</td>
</tr>
</tbody>
</table>

### Vegetation on Land and in Water

<table>
<thead>
<tr>
<th>Vegetation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>X Adult forest</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Young forest</td>
</tr>
<tr>
<td>X Herbs, bushes and young trees</td>
<td></td>
</tr>
<tr>
<td></td>
<td>A few large trees</td>
</tr>
<tr>
<td></td>
<td>A few small trees</td>
</tr>
<tr>
<td></td>
<td>Bushes</td>
</tr>
<tr>
<td>X Grass and herbs</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Water loving vegetation on land</td>
</tr>
<tr>
<td></td>
<td>Vegetation along shoreline or riverbank (reeds, etc.)</td>
</tr>
<tr>
<td></td>
<td>Other type of vegetation: ................................</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Activity of Eventual Gully

<table>
<thead>
<tr>
<th>Passive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active</td>
</tr>
</tbody>
</table>

### Observed "Human Activity"

| Erosion shelters of high quality |
| Erosion shelters of low quality |
| Erosion shelters of a quality difficult to estimate |
| Underground installations (pipes, cables, etc.) |
| Cesspools, sinks |
| Fill of earth |
| Fill of waste, waste deposit |
| Retaining wall, sheet piles (rabbet) |
| Houses, dams and other constructions |
| Human activity in general, wear, traces of vehicles |
| Felling of forest of larger magnitude |
| Quay |
| Excavation |
| River or creek in underground culvert |
| Fill of blast stone |

### Groundwater Conditions

| Spring, well |
| Estuary of ditch |
| X Estuary of underground water pipe or covered drain |
| Covered drains |

### Constructions for Ground Improvement

| (Type and condition) |
Example of a documentary photo, Sub-stage 1a, field control in Bollebygd town, Section Bbd-Op5.1
APPENDIX C. Production of the SGU Quaternary Soil Maps

The information in this Appendix is based on personal communication with Engdahl (2006).

The soil layers on land

The geological soil map (the Quaternary Map) is based on stereo interpretation of aerial photos combined with field verification. The field verification was performed using a hand-held probe, auger, and shovel. Complementary information on the soil layer stratigraphy and thickness has been collected from open cuts and by borings performed by the Swedish Geological Survey (SGU) and others.

In general, the SGU soil mapping is of soil conditions at a depth of 0.5 m below the ground surface. In the LESSLOSS-project, clay layers deeper than 0.5 m below the ground surface are also included on the map, even if coarser superficial soils exist above the clay, such as washed deposits, fluvial deposits or peat.

The soil layers on the river bottom

The Göta Älv River bottom has been scanned with side scanning sonar. The river fairway was used as a reference line for mapping. The resulting sonar image looks like a greyscale aerial photo. Generally, darker shades on the sonar image indicate coarse-grained soils,
whereas lighter shades indicate fine-grained soils, such as clay. The resulting soil assessment based on the sonar images was verified by studying seismic profiles, and by probing.

REFERENCE

Engdahl, M., (2006), Personal communication with Mats Engdahl, Swedish Geological Survey (SGU), Gothenburg
APPENDIX D. Bathymetrical survey of the Götä Älv River

Performed by:

Marin Mätteknik AB

Nya Varvet Byggnad 84, SE- 426 71 Västra Frölunda, Sweden

Tel.: +46 (0)31 695280 Fax: +46 (0)31 695290 E-mail: info@mmtab.se

(The text in this Appendix is reviewed by Ola Arvidsson, Swedish Geotechnical Institute)
INTRODUCTION

On commission by the Swedish Geotechnical Institute (SGI), Marin Mätteknik AB (MMT) has performed a bathymetric survey in the Göta Älv River for acquiring a high-resolution terrain model of the river bottom topography, (bathymetry). The survey was carried out using a multi-beam echo sounder to establish a bathymetric model of different sections of the Göta Älv River fairway through the Ale and Lilla Edet municipalities. MMT is a survey company specialised in high-resolution marine survey, to supply the industry with detailed information for seafloor constructions and installation.

The task was financed by Vägverket (the Swedish Board for Road Administration), Banverket (the Swedish Board for Railway Administration), and the SGI and the Ale and Lilla Edet municipalities respectively.

PERFORMANCE OF THE MEASUREMENTS

The survey was executed after the following planning:

- Delimitation of river sections to be measured
- Calibration of the equipment and an acceptance test

Marin Mätteknik AB performed the survey between November 9th and November 22nd, 2004. Because the equipment is very sensitive and vulnerable, as a safety margin the measurements could not be performed where the water depth under the vessel was below 1.0 m, which corresponds to 2.0 m total water depth.
EQUIPMENT

Device
To fulfil the demands to carry out high performance resolution mapping of the river bottom topography the following main device was used:

- Multi-beam echo sounder: Simrad EM 3000, dual head 300 kHz, 254 beams
- Positioning: Network RTK + Ashtech Z12
- Track data: Gyro HS50
- Marine motion sensor: MRU
- Navigation system: ARON 2000 / Transas
- Sound velocity profiler: AML SVP
- Processing software: Cfloor, Neptune, Point Edit
- Reporting: AutoCAD 2000

Vessel
The equipment was mounted on the vessel M/V Ping, see Figure D.1.
Figure D.1   M/V Ping, carrier of the multi-beam echo sounder equipment

<table>
<thead>
<tr>
<th>Hull</th>
<th>Aluminium</th>
<th>Draught:</th>
<th>0.5 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight:</td>
<td>2600 kg</td>
<td>Machinery:</td>
<td>2 x Iveco 82 HP</td>
</tr>
<tr>
<td>Length:</td>
<td>7.30 m (24')</td>
<td>Speed:</td>
<td>20 knots</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Speed when measuring:</td>
<td>2-10 knots</td>
</tr>
</tbody>
</table>

**POSITIONING**

Network-RTK has been used during the entire survey. The systems used can be summarised as followed:

The Global Positioning System, GPS, is a satellite based radio navigation system managed by the US Ministry of Defence. The system is based on 24 satellites circling in six different orbits around the Earth. The satellites send signals containing information, which the so-called GPS-receiver uses for calculation of the actual position. The receiver must simultaneously gain signals from at least three satellites to succeed in performing the calculation. The accuracy is better than 20 m in 95% of the calculations, which surely is far too low for the actual purpose to continuously measuring an exact position of the vessel during measuring the river bottom topography.

To increase the accuracy a so-called DGPS-receiver is used. By using this complementary equipment the accuracy is drastically increased to ±1 m, however, officially the accuracy is only guaranteed to ±4 m.

The GPS-information can only be used for high accuracy determination of the X- and Y-coordinates. However, for determining the Z-coordinate (the altitude), the GPS is not useful because its accuracy is too low. Instead, locally installed water level gauges are used for adjustments of the actual river water elevation to the accurate local levelling coordinate system.

By using a fixed base point, within or adjacent to the area to be measured, the accuracy can be still further increased. A base station transceiver is established on the fixed point, which sends corrections to the receiver onboard the vessel. This system is called RTK (Real Time Kinematic) and increases the positioning accuracy to ±0.015-0.020 m horizontally and ±0.020-0.30 m vertically.
THE MULTI-BEAM ECHO SOUNDING

The multi-beam echo sounder Simrad EM 3000 gains the possibility to perform marine measurements in an effective way and also collect high quality depth-data within a width on the bottom, which is 7-8 times the water depth, see Figure D.2. The multi-beam echo sounder is mounted on the vessel, and the survey can be performed in a water depth exceeding 2 m. Measurements can be carried out close to the river banks, and the measured data will be gathered in a 3-dimensional model. The results are reported as maps, in digital models or as sets of XYZ co-ordinate data points.

After repeated multi-beam surveys in rivers, for instance annually, changes in the bottom slopes, spots with erosion and bottom structures can be detected and measured. The multi-beam echo sounder works with 254 beams (frequency 300 kHz), which simultaneously collects the water depth data.

Within the area to be measured, collected high-resolution data is covering 100% of the river bottom. As far as possible, the pattern of the vessel routs during measuring is held...
parallel. The water depth and the bottom topography determine the distance between the survey lines, so a guaranteed 25% overlap of measured data will be acquired. This practice ensures that all sectors of the river bottom will be covered, however, it also gains a control of the precision of the data collection. Typical sectors where complementary measurements often are needed are bottom segments adjacent to quaysides and riverbanks, as well as bottom segments with an undulating topography, which causes a varying width of measuring cover.

In the Göta Älv River the measurements have been performed along 3-4 parallel survey lines, depending on the local water depth conditions. The measurements were carried out according to the demands stated by the Swedish Maritime Administration (ref. IHO SH 44).

As a summary, after corrections due to position, vessel movements, the sound velocity through water, and checking the actual water stand, the accuracy of the measurements of the water depths typically was ±0.1 m.

MEASUREMENTS OF THE SPEED OF SOUND IN WATER

The sound velocity in water differs by the water temperature and the salt content. Therefore, a good estimation of the prevailing sound velocity is an essential factor for obtaining a good precision in the multi-beam measurements of the water depth. The measurements of the sound velocity carried out in the river water by an AML SVP Sound velocity profiler indicated very small variation, due to the sweet water conditions combined with a relatively even temperature distribution from the water surface down to the bottom.

CALIBRATION

First the DGPS and the Sound velocity profiler were calibrated. Secondly, the multi-beam echo sounder system was calibrated in three ways, according to:

- Pitch: The movements of the vessel longitudinally
- Roll: The movements of the vessel transversionally
- Time: Delay in data transfer internally in the computer system

Before the measurements were performed also the functionality and the precision of the Swepos RTK network was tested.
Data processing
The measured data was processed in the following steps:

1. The measured water depth data was checked by comparison to anticipated river bottom conditions.

2. The measured water depth data was adjusted according to water level variations by using the computer programme “Neptune”.

3. The water depth database was cleaned from false data points and “back-ground noise” by using so-called base criteria and manually by using the computer programme “Point Edit”.

4. The water depth data was controlled, approved, sustained and stored with their co-ordinates (X, Y, Z) in two data sets, “rejected data” and “accepted data” respectively.

5. The water depth data is transformed by using the computer programme “Cfloor” to forming a grid with 2x2 m cells. The “Cfloor” programme is based on the “Roxar spiral grid method”.

6. Altitude contour lines, 0.5 m equidistant, are acquired also by using the “Cfloor” programme.

7. The water depth data is stored in XYZ grid node format.

8. The water depth data is converted to “ArcView” compatible format i.e. “Shape” files.

Co-ordinate system
The co-ordinate system used is described in Table D.1.
<table>
<thead>
<tr>
<th>Co-ordinate system</th>
<th>Table D.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>RT90 2.5 gon V</td>
<td>RT90</td>
</tr>
<tr>
<td>Ellipsoid Bessel</td>
<td>Bessel</td>
</tr>
<tr>
<td>Semi Major Axis 6377397.155</td>
<td>Central Scale Factor 1.0</td>
</tr>
<tr>
<td>False Easting 1500000 m</td>
<td>False Northing 0 m</td>
</tr>
<tr>
<td>Latitude Origin 0°</td>
<td>Central Meridian 15.80827777</td>
</tr>
<tr>
<td>Height system: RH00</td>
<td></td>
</tr>
</tbody>
</table>

**HEIGHT SYSTEM**

During measuring, the altitude of the measuring vessel is acquired related to the WGS 84 ellipsoid, see Figure D.3. This altitude differs from the Swedish geoid model "RH 70".

![Figure D.3](image)

Figure D.3 Relations between the subsurface, the "RH 70" geoid and the "WGS84" ellipsoid.

After conversion from the “WGS89” ellipsoid to the Swedish RH70 geoid based height system, the river bottom topography was acquired by the precision 0.05-0.01m.

Almost the entire Sweden is influenced by isostatic uplift because of the huge unload due to the melting of the 3 km thick Scandinavian inland ice. In Sweden the isostatic uplift differs between 0-8 mm per year, however, in Lilla Edet the isostatic uplift is 1 mm per year.
APPENDIX E  The further investigation Stages 2 and 3 in the Swedish programme for stability investigations

STAGE 2 – DETAILED INVESTIGATIONS

The hazard mapping in Stage 1 is a basis for decisions on where detailed stability investigations should be performed in Stage 2. According to the directives of the Swedish Commission on Soil Stability, the detailed stability investigations are based on calculations according to both of:

- Undrained analysis, and
- Combined analysis respectively.

Slope stability calculations are normally carried out by using reliable computer programs.

Slip surfaces of planar, circular and arbitrary shapes are considered. Both drained and undrained behaviour of the soil should be considered (so-called combined analysis) for each slice. In the combined analysis, the drained shear strength is compared to the undrained shear strength for each section of the slip surface, and the lowest strength is used in the calculation, Larsson (1984). The drained and combined analyses should be carried out for the most unfavourable groundwater and pore pressure conditions.

The recommendations concerning safety factors differ depending on the type of land use, the consequences involved, the type of investigation (rough estimate or detailed) and the type of stability analysis. Depending on the direct consequences of a landslide for human life, buildings and structures, the slope stability calculations should be carried out with different requirements, Table E.1. Four different types of land use are employed:
New development (new exploitation areas)

When planning areas on, above, beside or below clay and silt slopes with the intention of new exploitation with buildings and structures, i.e. dwellings, hotels, commercial areas, schools, industrial areas, roads, ski-lift installations, dams, major drainage systems, sewers and cables etc., the demands on the required safety factor, $F$, are the highest. Also rebuilding and extension of existing buildings and structures fall into this category.

Built-up areas (existing buildings and constructions)

The requirements are slightly lower for areas that are already built-up, e.g. areas including present buildings and structures. However, these requirements are only applicable as long as there are no factors or actions that reduce stability. Restrictions therefore often have to be imposed in slopes with low factor of safety.

Other urban areas

The requirements are even lower for “other urban areas” e.g. areas containing only buildings and structures of less importance and areas, which are visited by people only during daytime. This category involves local streets, parking lots, garages, secondary sewers and cables, parks, pedestrian and bicycle paths and sports grounds.

Natural and farm land

In natural and farm land there are no demands.

Required calculated safety factor

In the different investigation stages, the required calculated safety factor, $F$, is dependent on the different type of land use as described above, and the slope stability analysis method, see Table E.1 (Swedish Commission on Slope Stability, 1995).

In some cases, the recommended levels of the safety factor, $F$, may be slightly higher or lower, depending on the amount of favourable and unfavourable prerequisites. Prerequisites that should be regarded are:

- Type and amount of field and laboratory tests
- Geometry and condition of the slope
- Ground- and pore-water situations
Sub-Task 1.1.1.1 – Zonation and landslide hazard by means of LS DTM

– Soil properties

– Consequences of a slide, the extension of slope stability analyses.

If a calculated factor $F$ is acceptable according to Table E.1, no further investigation is normally required, if all the preconditions are fulfilled.
Table E.1  Chart of required calculated safety factors, $F$, in various investigation stages with respect to land use. (After Swedish Commission on slope stability, 1995). Where the required safety factors are given within a span, the $F$-value is meant to be chosen with guidance from the local situation in the slope with regard to favourable and unfavourable conditions.

<table>
<thead>
<tr>
<th>Investigation stage</th>
<th>Intended or present type of land use</th>
<th>New development</th>
<th>Existing buildings and constructions</th>
<th>Other urban areas</th>
<th>Undeveloped area, open country</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stage 1: Geotechni-</td>
<td>Detailed investigation must be</td>
<td>$F_c &gt; 2$ +</td>
<td>$F_c &gt; 2$</td>
<td>$F_c$, $F_\phi$, and $F_{comb} &gt; 1$</td>
<td></td>
</tr>
<tr>
<td>cal inspection and</td>
<td>carried out</td>
<td>$F_\phi &gt; 1.5$</td>
<td>$F_\phi &gt; 1.5$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>rough estimate</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stage 2: Detailed</td>
<td>$F_c \geq 1.7$ - 1.5 + $F_{comb} \geq 1.45$ - 1.35</td>
<td>$F_c \geq 1.7$ - 1.5 + $F_{comb} \geq 1.45$ - 1.35</td>
<td>$F_c \geq 1.6$ - 1.4 + $F_{comb} \geq 1.4$ - 1.3</td>
<td>$F_c$, $F_\phi$, and $F_{comb} &gt; 1$ (if surrounding land is unaffected)</td>
<td></td>
</tr>
<tr>
<td>investigation</td>
<td>$F_\phi \geq 1.3$ (sand)</td>
<td>$F_\phi \geq 1.3$ (sand)</td>
<td>$F_\phi \geq 1.3$ (sand)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stage 3: Extended</td>
<td>$F_c \geq 1.5$ - 1.4 + $F_{comb} \geq 1.35$ - 1.30</td>
<td>$F_c \geq 1.4$ - 1.3 + $F_{comb} \geq 1.3$ - 1.2</td>
<td>$F_c \geq 1.3$ - 1.2 + $F_{comb} \geq 1.2$ - 1.15</td>
<td>$F_c$, $F_\phi$, and $F_{comb} &gt; 1$ (if surrounding land is unaffected)</td>
<td></td>
</tr>
<tr>
<td>and supplementary</td>
<td>$F_\phi \geq 1.3$ (sand)</td>
<td>$F_\phi \geq 1.3$ (sand)</td>
<td>$F_\phi \geq 1.2$ - 1.15 (sand)</td>
<td>(lower values refer to existing structure of less importance)</td>
<td></td>
</tr>
<tr>
<td>investigations</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note:
In the chart, the sign ‘+’ indicates that for each section, the stability calculations must be carried out according to two different analysis methods.

**STAGE 3 – EXTENDED AND SUPPLEMENTARY INVESTIGATIONS**

If needed, an extended and/or supplementary investigation following the detailed investigation is carried out. In the guidelines for slope stability investigations of clay, silt and sand sediments (see Swedish Commission on Slope Stability, 1995) these extended and supplementary investigations are described. These investigations aim at:

− giving the basis for a more accurate slope stability calculation

− giving the size of the area at risk

− giving the basis for a consequence analyses
– giving the basis for planning of preventive measures

When the calculated safety factor, $F$, is too low according to Table E.1, in some cases extended information on the geotechnical conditions, e.g. extended information on slope and soil layer geometry, ground water and pore pressure conditions, soil properties and external load conditions, can provide approval because of two reasons – solitary or combined:

1. The extended information may indicate a positive revision of the geotechnical conditions, which after renewed stability calculations provides an acceptable safety factor, $F$.

2. According to Table E.1, the access to the extended information permits a lower demand on the required safety factor, $F$.

For a slope, having poor stability conditions according to the detailed stability investigation, the following alternative decisions must be made dependent on the actual situation:

- New development
  - Finding alternative areas to develop
  - Strengthening of the slope

- Existing buildings and constructions
  - Strengthening of the slope
  - Establishing restrictions
  - Installation of landslide warning systems
  - Abandoning of the area, e.g. evacuation and reconstruction of the buildings and constructions

For the alternatives strengthening of the slope, introduction of restrictions and installation of landslide warning systems, in most cases supplementary stability investigations must be performed, for example to forming the basis for design of preventive measures.
APPENDIX F  Description of the region around Lilla Edet
and the test area

THE SOUTHWEST REGION OF SWEDEN – A GEOTECHNICAL PROBLEM AREA
The Southwest region of Sweden around and north of the Gothenburg area – especially
the Göta Ålv River Valley – has long been well known for a large number of landslides in
clay, for example the Tuve landslide in 1977 attracting particular attention.

The region in question is characterised by its coastline and long valleys with deep deposits
of marine soft clays. Clay layer depths of between 15 and 100 m are common. The long
valleys are enclosed by high formations of bare rock outcrops. Therefore, the ground sur-
face levels often vary widely, and high clay slopes have been formed next to erosive wa-
tercourses. The geological processes have accordingly given rise to slope stability prob-
lems, which must always be taken into consideration, Ahlberg and Ottosson (1994).

THE GÖTA ÅLV VALLEY
The Göta Ålv River is the largest river in Scandinavia draining the “inland sea” Lake
Vänern, Figure F.1. The river estuary is situated in Gothenburg. The river is a vital fair-
way; ocean-going merchant vessels sail the river to the lake Vänern, where a number of
ports are situated. In the towns of Lilla Edet and Trollhättan, huge locks are constructed
to lift the ships for passing the waterfalls. In these sites, there are also water power sta-
tions.

In addition, on shore the valley is an important transport route. The main road and a
double-tracked railroad between Gothenburg and Trollhättan follow the eastern riverside,
partly close to the riverbanks.

The valley is densely populated. Gothenburg suburbs, and further north, a number towns
and villages are situated on both sides of the river.
Several major landslides have occurred in the Göta Älv River Valley, including the Bohus/Jordfallet landslide in around 1150, Intag in 1648, Surte in 1950, Göta in 1957 and Agnesberg in 1993.

**LILLA EDET TOWN**

In a general inventory performed by the SGI in the municipalities along the Göta Älv River Valley, the frequency of previous landslides in different municipalities in the area was studied, Inganäs & Viberg (1979). The number of previous landslides appeared to be 130 in the area of the Lilla Edet municipality, which was the outstanding highest frequency of all the studied municipalities, Figure F.1.

In the urbanised areas of the Lilla Edet town (4000 inhabitants), dwellings, schools, service areas, factories, a major lock, a water power plant and other constructions are situated close to the banks of the Göta Älv River, Figure F.2. The soil layers in the area contain clay and quick clay, and hence many landslides have occurred in the area and its vicinity, both during prehistoric and modern time. Some of these landslides have affected built up areas, hence causing loss of human life and property.

In 1957, a major landslide occurred in the southern rim of Lilla Edet town, however mainly in the neighbouring village Göta. Four employed were killed in the completely destroyed paper mill in Göta.

![Figure F.1](image)

**Figure F.1** The position of the Lilla Edet test site. The Lilla Edet town is situated on the banks of the Göta Älv River, which is the largest river in Scandinavia, draining the "inland sea" Lake Vänern. Around 30 kilometres downstream Lilla Edet, the...
river splits into two arms, the southern of these finding its estuary in Gothenburg (Göteborg).

Figure F.2 Lilla Edet town (4000 inhabitants), SW Sweden. Dwellings, schools, service areas, factories, a major lock, a water power plant and other constructions are situated close to the banks of the Göta Älv River. The lines indicate the pattern of the helicopter routes for performing the TopEye laser scanning, covering 8 km², see text below.
GEOLOGICAL CONDITIONS IN THE TEST SITE AREA AND INDICATION OF OLD LANDSLIDE SCARS

In 1959 the Swedish Geological Survey mapped the soil conditions and scars from landslides along the Göta Älv river banks, SGU (1959). In Figure F.4 the area locally around Lilla Edet is extracted (Figure F.3, corresponding legend).

Figure F.3 Quaternary deposits in the Göta Älv Valley, Legend for the map in Figure F.4.
Admission: SGU Dnr 08/1369/2005
According to the description linked to the geological map, SGU (1959), the fjord sediments in the Göta Älv Valley were deposited in deep and salt seawater, SGU (1959). The clay content is generally high, in the heavy clay about 60% of the material is finer than $2 \times 10^{-6} \text{m}$. The clay is rich in iron sulphides, often visible as dark bands or varves. The silty medium clay (less than 40% clay and about 35% silt) was deposited in a slowly-running water comparatively near the shore. The light clay with fine sand (less than 35% clay and about 50% silt) was deposited when the neighbouring hills, due to the post-glacial isostatical elevation of the land, rose above the water surface, and hence the breakers could attack the ground composed by till or glacial deposits.

The alluvial sediments were deposited in fresh and shallow running water, forming the sandy and silty delta-deposits of the Göta Älv River. To a high degree they are now removed by erosion phenomena, such as gully development, fluvial erosion and landslides.

**The Digital Quaternary Soil Map**

In the LESSLOSS-project sub-task the digital Quaternary Soil Map, SGU (2005) and Engdahl (2006), has been used as one information layer in the GIS-processing.

**The soil layers on land**

The digital soil map is based on stereo interpretation of aerial photos combined with field verification. The field verification was performed using a hand-held probe, auger, and shovel. Complementary information on the soil layer stratigraphy and thickness has been collected from open cuts and by borings performed by the Swedish Geological Survey (SGU) and others.

In general, the SGU soil mapping is of soil conditions at a depth of 0.5 m below the ground surface. In the LESSLOSS-project, clay layers deeper than 0.5 m below the ground surface are also included on the map, even if coarser superficial soils exist above the clay, such as washed deposits, fluvial deposits or peat.
The soil layers on the river bottom

The Göta Älv River bottom has been scanned with side scanning sonar. The river fairway was used as a reference line for mapping. The resulting sonar image looks like a greyscale aerial photo. Generally, darker shades on the sonar image indicate coarse-grained soils, whereas lighter shades indicate fine-grained soils, such as clay. The resulting soil assessment based on the sonar images was verified by studying seismic profiles, and by probing.

Former stability mapping in Lilla Edet

Stability mapping has been carried out earlier in Lilla Edet according to the on-going national general overview landslide hazard mapping programme. On commission by the Swedish Rescue Services Agency, the Lilla Edet area has been investigated by Räddningsverket/GF Konsult AB (2002), following the “manually performed” method for early stage landslide and erosion risk assessment in slopes in clay and silt adopted for the national survey in Sweden, described in Chapter 3 above. Figure F.5 shows the three sub-areas marked L-06, L-07 and L-08 respectively, which were mapped in the Lilla Edet town. However, in that task, the areas close to the river were not mapped, because at that time detailed investigations of the stability conditions were already performed there.
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In the mosaic in Figure F.6 the result maps of the three mapped sub-areas are roughly fitted in their proper positions to each other.
Figure F.6 The three sub-areas, L-06, L-07 and L-08, mapped by Räddningsverket/GF Kon- sult AB (2002) in Lilla Edet, roughly fitted in their proper positions to each other.