STATENS GEOTEKNISKA INSTITUT
SWEDISH GEOTECHNICAL INSTITUTE

Recommendations for planning, surveillance, inspection with LS DTM. Usefulness of LS DTM in landslide hazard mapping and slope management – Deliverable 8

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Deliverable 8 – Recommendations for planning, surveillance, inspection with LS DTM. Usefulness of LS DTM in landslide hazard mapping and slope management

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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 comprises recommendations for the planning of a Laser scanned digital terrain model (LS DTM) and a description of the usefulness of LS DTM in landslide hazard mapping, slope stability calculations and slope management, e.g. the usefulness of LS DTM for surveillance and inspection.

The work, 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.

The project is financed by the European Commission and by the Swedish Geotechnical Institute (SGI).

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Linköping, March 2007

Jan Fallsvik

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LIST OF SYMBOLS AND ABBREVIATIONS

F = Factor of safety

LS DTM = Laser scanned digital terrain model

1. Summary

As a basis for overview landslide hazard mapping, detailed topographical databases can be created by using laser scanning of the topography on land combined with multi-beam echo sounding of the bottom topography of rivers, lakes or flanking seashores. These laser scanned digital terrain models, LS DTM, are useful also when performing stability calculations, but also for other types of municipal and infrastructure planning, as wee as for surveillance and inspection purposes. By using GIS the results of different type of analysis for different planning purposes can be combined by so called overlay analysis resulting in new combined information, for example areas which have prerequisites for both landslides and to be flooded.

The costs for using a LS DTM:s are fairly higher than the existing "manual" techniques, however if a created LS DTM for more purposes than only one, the total costs will be less.

2. Scope

The scope of the task is to demonstrate the usefulness of using LS DTM:s for planning purposes, and especially for performing landslide hazard mapping and slope stability calculations. Landslide hazard zonation method based on Laser scanning and multi-beam echo sounding

3. Introduction

Laser scanning of the topography of the ground surface performed from an aircraft, combined with multi-beam echo sounding from a boat, regarding the bottom topography under water, delivers a very detailed topographical information of the ground surface. The LESSLOSS Sub-project 1.1.1.1, Fallsvik [2006a and b], has shown that the method can be used for delivering necessary basis for:

- Landslide hazard zonation and management,
- Detailed slope stability analyses

However, the method can also be used for delivering necessary basis for other planning purposes, for example:

- Inventory and monitoring of debris flow hazard,
- Municipal planning of exploitation areas,
- Planning of roads, railroads and other infrastructure projects
- Inventory of the risk for flooding
- Inventory and monitoring of the risk for erosion along sea coasts as well as lake and river shores
- Production of topographical maps, etc.

Both Laser scanning and multi-beam sounding are expensive to perform, however, the excellent product, which the measurements can deliver, can justify the employment of the methods. Further, the multipurpose advantage of the methods indicates that in many cases could different municipal authorities, governmental authorities, organisations and enterprises perform the financing in co-operation.

3.1.1 Swedish methodology for landslide hazard mapping

The Commission on Slope Stability – a research commission under The Royal Swedish Academy of Engineering Sciences – was initiated with the task to initiate and co-ordinate research and to provide information on slope stability and methods of stabilisation. The Commission was operational between the years 1988 and 1996, and in 1995 guidelines for stability analyses of natural slopes were published. These guidelines are structured in such a way that the investigation is carried out in three stages with increasing extent. These different stages in the slope stability investigation for slopes with clay and silt layers are described below. The overview landslide mapping is performed in the so called Stage 1. The methodology is closer described in LESSLOSS deliverable No. 7, Fallsvik [2006a].

3.1.2 Stage 1 – Overview landslide hazard mapping

The first stage of the overview landslide hazard mapping in slopes with clay and silt layers, is financed by the Swedish government and administrated by the Swedish Agency for Rescue Services (SRSA), mapping is carried out nation-wide and successively in the totally 21 Swedish provinces. The mapping is carried out individually for each municipality. The work is performed by firms of geotechnical consultants, purchased by the SRSA, which is aided by the Swedish Geotechnical Institute (SGI).

The overview landslide hazard mapping is divided in two Sub-stages, Fallsvik, J and Viberg, L., [1998]:

- Sub-stage 1a, division of the land into areas with and without prerequisites for initial slope failure in clay and silt
- Sub-stage 1b, overview assessment of the stability under prevailing conditions based on survey calculations

3.1.2.1 *Sub-stage 1a*

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.
- 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.
- The Stability Zone III comprises areas with bedrock outcrops or where the soil layers do not contain clay or silt.

The division 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 division into stability zones is presented in colours on maps, scale of 1:5000 to 1:10,000. The legend used for these maps, is shown in Table 3.1. 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

3.1.2.2 *Sub-stage 1b*

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 "Guidelines for Slope Stability Investigations" issued by the Commission on Slope 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.

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, Map 1b, to a scale of 1:5000 to 1:10,000. Areas where a detailed investigation is judged to have high priority are marked on the map, together with a comment. 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.

3.1.3 Stage 2 – Detailed investigations

The hazard mapping in Sub-stage 1b forms the basis for decisions on where detailed stability investigations should be performed in Stage 2. The principal aim of this stage is to clarify if there is a real stability problem or not. The detailed stability investigations are normally financed by the municipality and/or concerned land owners.

According to the Guidelines for Slope Stability Investigations, Commission on Slope Stability, [1995], a number of sections regarded as the most critical are chosen based on topographical conditions and rough calculations. In these sections geotechnical field and laboratory investigations are performed.

Based on the field and laboratory investigations the prerequisites for the calculations are clarified. Detailed slope stability calculations are then carried out. Slope stability calculations are normally carried out for circular slip surfaces by using reliable computer programs.

3.1.4 Stage 3 – Extended and supplementary investigations

If needed, following the detailed investigation an extended and eventually also a supplementary investigation are carried out. In the Guidelines, Swedish Commission on Slope Stability, [1995] these extended and supplementary investigations are described. The 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 analysis
- giving the basis for design of eventual preventive measures

The geotechnical field and laboratory investigations for the extended investigation are more qualified and/or covering a wider area compared to the earlier investigations.

3.2 WORK CARRIED OUT ON TOPOGRAPHICAL DATA IN THE LESSLOSS PROJECT

In the LESSLOSS project the Swedish Geotechnical Institute (SGI-SW) has developed a GIS-application for areas with clay and silt soil layers, where topographical information achieved by Laser scanning (LIDAR) and multi-beam echo sounding was used as a basis for overview landslide hazard mapping, LESSLOSS project, Sub-task 1.1.1.1, Deliverable No. 7, Fallsvik [2006a]. As a further demonstration, the topographical information was also used as a basis for carrying out detailed stability investigations based on slope stability calculations, LESSLOSS deliverable No. 6, Fallsvik [2006b].

The work was carried out in a test area around Lilla Edet town in SW Sweden, situated on the banks of Sweden's largest river, Göta Älv. As comparison, additional work leading to extended information was also performed along the Eskilstuna River passing through the towns of Eskilstuna and Torshälla.

3.2.1 Laser scanning

The Laser scanning included in the LESSLOSS sub-project 1.1.1.1 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, Fallsvik [2006]. The TopEye system is described in Appendix A.

3.2.2 Multi-beam echo sounding

For creating a detailed terrain model of the bottom topography of selected sections of the Göta Älv River, bathymetric measurements was performed by multi-beam echo sounding. Before the LESSLOSS project, these measurements were commissioned the Swedsish Geotechnical Institute (SGI-SW) for other purposes, 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 Multibeam Echo Sounding, Fallsvik [2006a].

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.

3.2.3 Information gathered by GIS-transformation of the topographical data

By using ArcGIS, a Geographical Information System (GIS), the topographical information, achieved by the Laser scanning and echo sounding, was combined with a digital version of the local geological soil map, LESSLOSS deliverable No. 7, Fallsvik [2006a], SGU [2005], and Engdahl [2005]. The digital soil map was completed with information on the soil layer conditions under the bottom of the river.

A GIS-based algorithm, earlier developed in the Swedish Governmental financed R&D project NAKASE [2001], was implemented to perform the classification of the investigated area into landslide hazard zones. The algorithm, including the database it is connected to, was adjusted to fit the LESSLOSS-project. Thus, the algorithm could also be used with the topographical database achieved by Laser scanning and multi-beam echo sounding.

The GIS-algorithm delivers a digital map, where the investigated land area is classified in three different so-called Stability Zones, Figure 3.1 and Table 3.1. The objective of this classification is to accomplish an overview subdivision of where the stability conditions are satisfactory (Zone II and III) and where the stability conditions should be investigated further (Zone I).

Table 3.1 Definition of the Stability Zones in soils with layers of clay and/or silt.

Stability zone	Description	Prerequisites for landslides / Need for further stability investigation	Colour on the maps in Figure 3.2
Zone I	• Areas with soil layers of clay and/or silt. • The slope inclination exceeds 1:10.	Yes	Orange
Zone II	• Areas with soil layers of clay and/or silt. • The slope inclination is less than 1:10.	No	Yellow
Zone III	• Areas lacking soil layers of clay and/or silt. "Firm ground" areas.	No	Green

3.2.4 The Lilla Edet test site

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. Historically, especially 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. The town was selected to become a LESSLOSS sub task test site of three reasons:

1. The site is prone for landslides providing much substance to study, like old landslide scars, active erosion, etc.

2. The site is previously well investigated, providing possibilities to comparison

3. In another earlier project, the bottom topography of the Göta Älv River had previously been investigated by detailed Multi-beam Echo Sounding.

The region around Lilla Edet 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 surface levels often vary widely, and high clay slopes have been formed next to erosive watercourses. The geological processes have accordingly given rise to slope stability problems, which must always be taken into consideration, Ahlberg and Ottosson [1994].

The Göta Älv River is the largest river in Scandinavia draining the "inland sea" Lake Vänern, Figure 3.2. The river estuary is situated in Gothenburg. The river is a vital fairway; 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 stations. 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.

Several major landslides have occurred in the Göta Älv River Valley, including the Bohus/Jordfallet landslide in around 1150, Intagan in 1648, Surte in 1950, Göta in 1957 and Agnesberg in 1993.

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, Figure 3.2, which was the outstanding highest frequency of all the studied municipalities.

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. 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. Three employed were killed and three were injured in the completely destroyed paper mill in Göta.

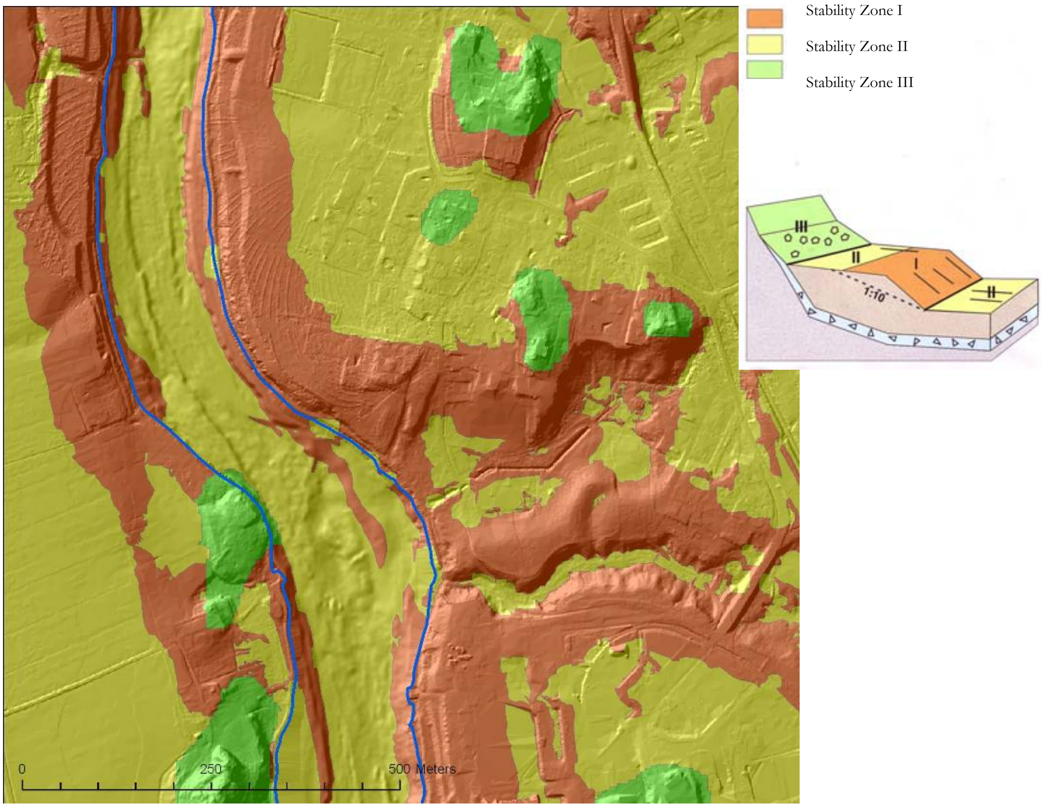

Figure 3.1 Göta Älv River through Lilla Edet town. Map presenting the result of the overview landslide hazard mapping, LESSLOSS deliverable No. 7, Fallsvik [2006a]. The very high level of detail combined wit the GIS "hill shade function" gives the image a three dimensional impression. The photo below: The Göta River through Lilla Edet.

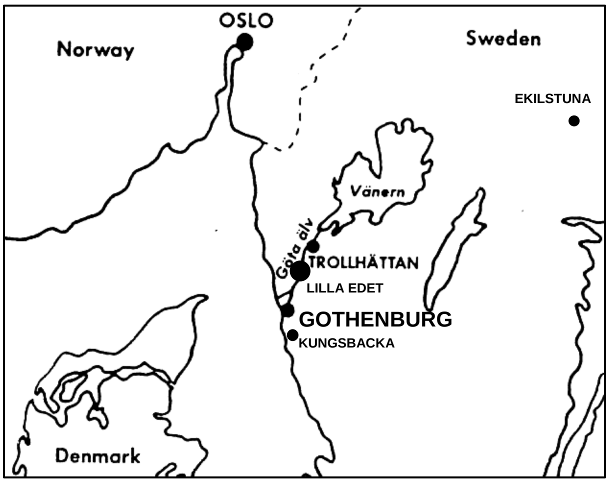

Figure 3.2 **The position of the Lilla Edet test site. The Lilla Edet town is situated on the banks of the Göta Älv River, which is the largest river in Scandinavia, draining the "inland sea" Lake Vänern. Around 30 kilometres downstream Lilla Edet, the river splits into two arms, the southern of these finding its estuary in Gothenburg. Also, see the positions of the towns Eskilstuna and Kungsbacka, referred to in the chapters following below.Comparison with existing methodology**

4.Comparison with existing methodology

4.1 QUALITATIVE COMPARISON

4.1.1 Overview landslide hazard mapping

Compared to the existing manual methodology, the overview landslide hazard mapping according to the method adopted in Sweden based on Laser scanning, multi-beam echo sounding and GIS-processing deliver:

- A much higher exactness in the result due to the topographical exactness of the in data and a lower possibility of man made errors

- The detailed geometry data can be used in more detailed investigation stages saving costs for levelling. However, control levelling should always be performed in detailed slope stability calculations.

- An option to use the results as one of the sets of information forming in-data for GIS-processing in further municipal planning.

In the Figures 4.1a and 4.1b the manual method respectively the Laser-scanned, echo-sounded and GIS-based methods are compared exemplified with a selected area in Eskilstuna.

4.1.2 The Eskilstuna River test site

In the purpose to demonstrate the possibility to perform a very detailed flooding risk map, LIDAR measurements had earlier been carried out along the Eskilstuna River, positioned around 100 km west of Stockholm. These measurements were financed by the Swedish Emergency Management Agency R&D-project "KRISGIS", Yacoub et al [2004]. However, compared to the LESSLOSS project in Lilla Edet, the sounding of the river bottom in the Eskilstuna project was coarser, because only ordinary "single" echo sounding from a small boat was performed, and compared to multi-beam sounding in spare spots on the river.

The river in central parts of Eskilstuna

Figure 4.1a ”The Manuel” Map, Stage 1a, performed according to the in Sweden commonly used method for manually performed overview landslide mapping. Extract from the manual overview mapping carried out in Eskilstuna, SRSA /Bohusgeo [1996]. Legend, see below.

Stability zone	**Description**	**Prerequisites for landslides / Need for further stability investigation**	**Legend for the map in Figure 4.1a**	**Legend[1] for the map in Figure 4.1b**
Zone I	• Areas with soil layers of clay and/or silt. • The slope inclination exceeds 1:10.	Yes	Hatched	Orange
Zone II	• Areas with soil layers of clay and/or silt. • The slope inclination is less than 1:10.	No	Yellow	Yellow
Zone III	• Areas lacking soil layers of clay and/or silt. “Firm ground” areas.	No	Green	Green

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[1] In the GIS-produced maps, a revised legend was chosen in the purpose to simplify and make the presentations clearer in the further maps reporting overlay of different databases.

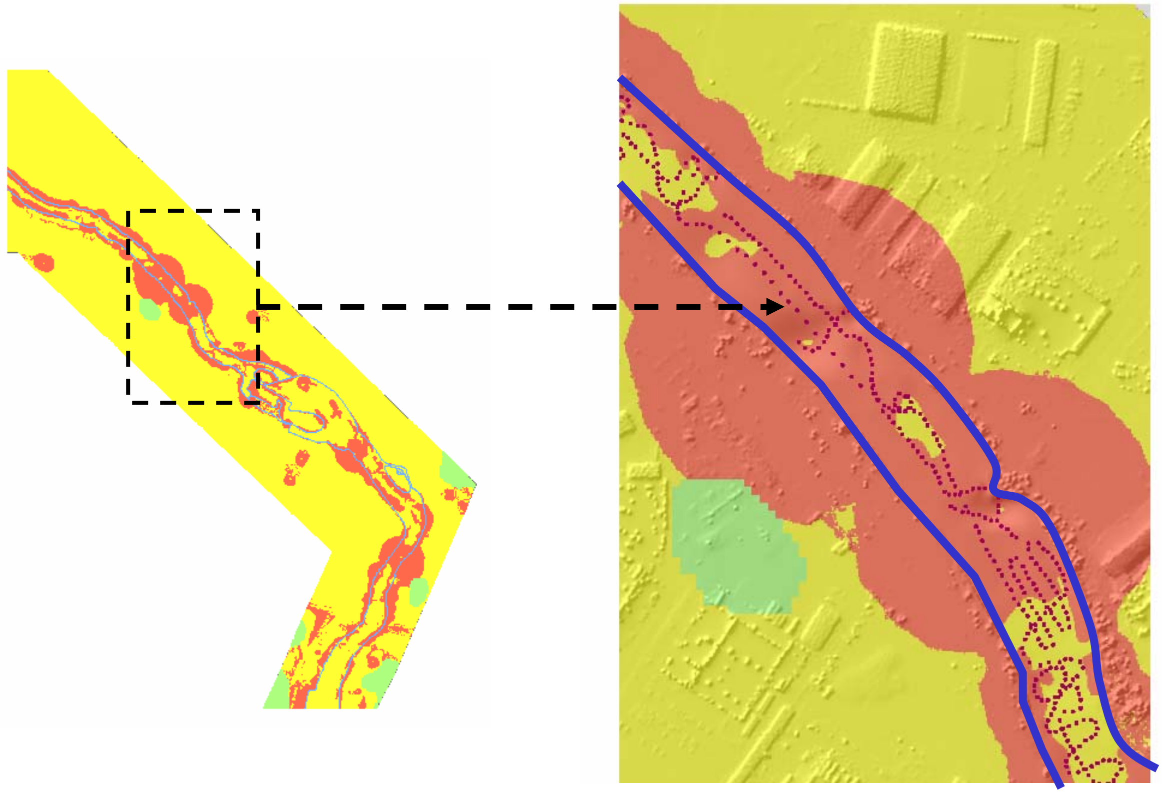


Figure 4.1b **Map Stage 1a based on Laser scanning, echo sonding (ordinary single beam) and GIS-processing using the NAKASE algorithm. (The same extracted area of Ekilstuna river as in Figure 4.1a.) The influence from the river bottom topography on the zoning is obvious. In the magnification, the dots indicate the points in the river where single beam echo sounding was performed. (Legend, se Table 3.1). Map presenting the result of the overview landslide hazard mapping, LESSLOSS deliverable No. 7, Fallsvik [2006a]. Legend, see Figure 4.1a.**

4.1.3 Stability calculations based on LS DTM

In overview stability investigations estimations, rough stability calculations often are based on topographical information based on measurements of the elevation iso-lines on topographical maps. In detailed stability investigations, the stability calculations usually are based on levelling on land and manual plumbing of the bottom of rivers or lakes from a small boat, or in wintertime from the ice.

In this Sub-task 1.1.1.1 of the LESSLOSS-project, detailed stability calculation were demonstrated for a selected section “Section 5” in the Lilla Edet test site, based both on standard sets of topographical information and on the digital database achieved from Laser scanning and multi-beam echo sounding, Fallsvik [2006b]: The stability calculations were based on the following three different sets geometry, which was archived along the Section 5 by respectively:

1. Measuring of elevation lines on a detailed topographical map

2. Levelling

3. LIDAR scanning

As a comparison, the three sets of geometry are drawn in the diagram in Figure 4.2.

Sources of errors which generate the difference between the three profiles could be:

- The exact position of the measured section can have differed

- When levelling and plumbing: Error in the chaining (measuring of the horizontal distance from the 0-point) of the measured points

- Errors in the Laser scanned data, i.e. due to vegetation obstacles

etc.

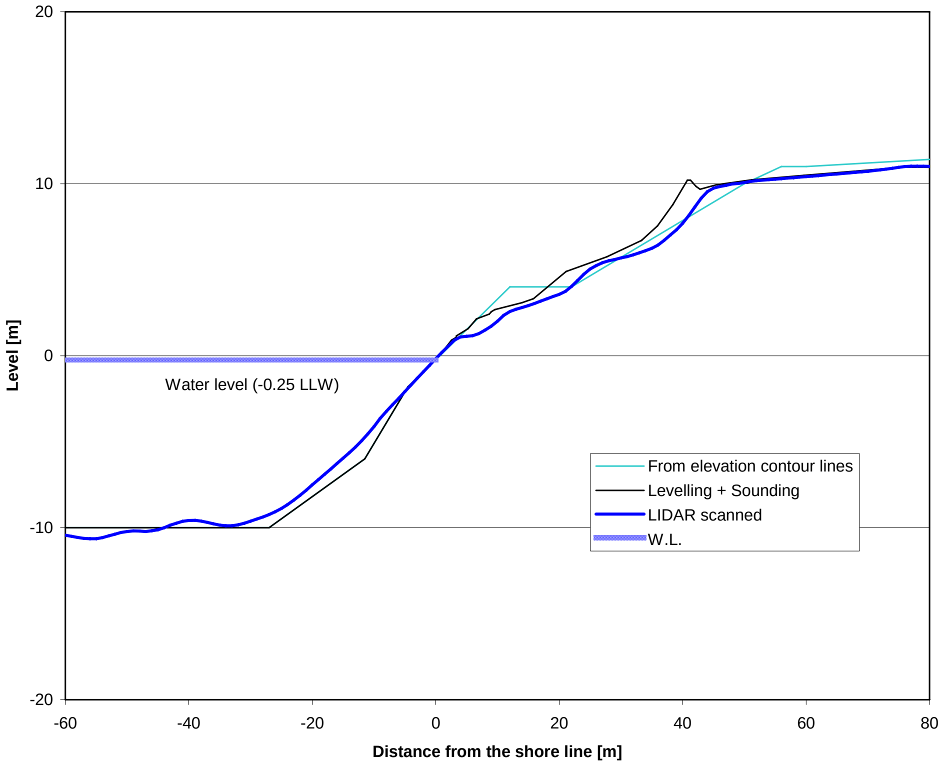


Figure 4.2 **Comparison between the three available information sets on the geometry along the Section 5, achieved by measuring on elevation lines on a detailed topographical map, levelling, and LIDAR scanning respectively, Fallsvik [2006b]. Observe the different scales in horizontal and vertical directions.**

The stability calculations, based on Laser scanning and multi-beam sounding, provide an increased level of information on the stability conditions due to the more detailed geometry. The estimation of the stability conditions will stand on a better ground.

The detailed digital topographical database also facilitates performing of complementary stability calculations in sections in the area where geotechnical investigations have been carried out. Perpendicular to a calculated section, the stability conditions differ for instance along a slope developed by erosion in marine clay layers predominantly depending on the topography. The soil layer conditions however do not differ to the same degree. To demonstrate how the stability conditions differ along the same slope, in this LESSLOSS sub-task, ten sections were drawn parallel to the test section, “Section 5”, Fallsvik [2006b]. The position of Section 5 on the slope to Göta River in Lilla Edet, and the selected ten parallel sections are illustrated by Figure 4.4.

The Laser scanned and multi-beam sounded topographical database facilitated the achievement of the geometry of these parallel sections. In comparison, ordinary levelling and manual plumbing of these ten extra sections had been far too expensive to carry out in a typical ordinary stability investigation. The results of the detailed slope stability calculations based on Laser scanned and multi-beam sounded information are presented in Figure 4.3, which shows how the lowest calculated factor of stability (*F*) varies between Section 5 and the ten parallel sections, for undrained and combined analysis respectively. "Lowest" means the lowest *F*-value calculated for a number of anticipated slide surfaces in each section. The end- and centre-points of the sliding surfaces with the lowest calculated *F*-factor (combined analysis) are indicated for each section in Figure 4.4.

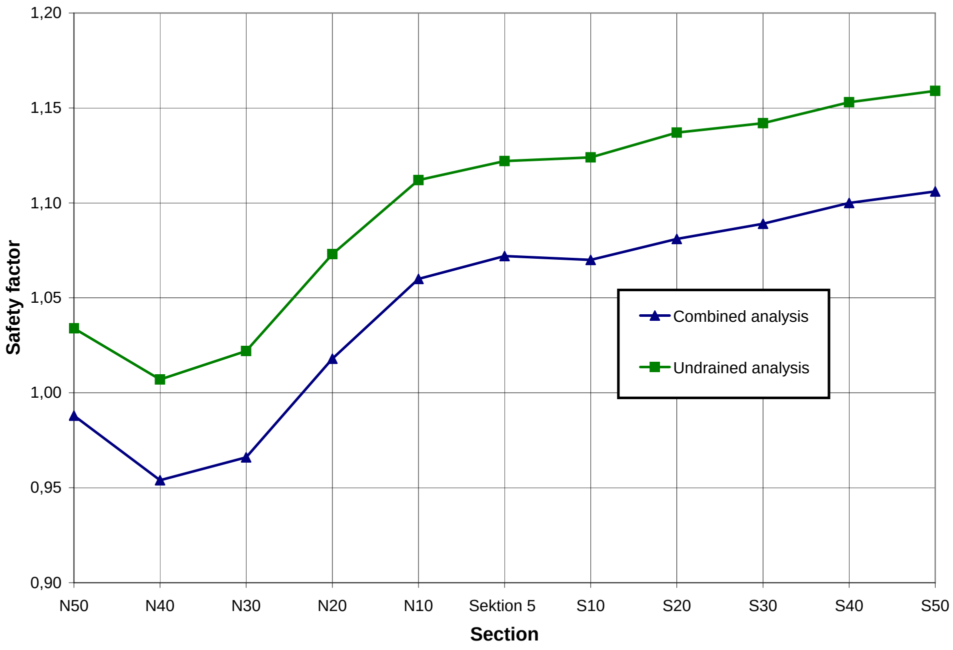
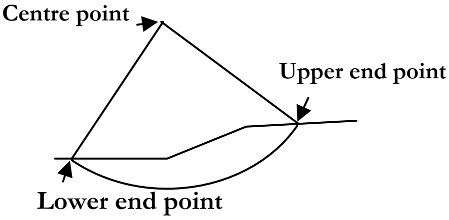


Figure 4.3 Variation of the lowest calculated factor of stability (*F*) between Section 5 and the ten parallel sections north and south of Section 5. The calculations have been performed for both undrained and combined analysis. “Lowest calculated factor of stability ” indicates that the *F*-value is achieved from the sliding surface along each section calculated to have the lowest *F*-value. The theories regarding undrained and combined analysis respectively are described in Fallsvik [2006b].



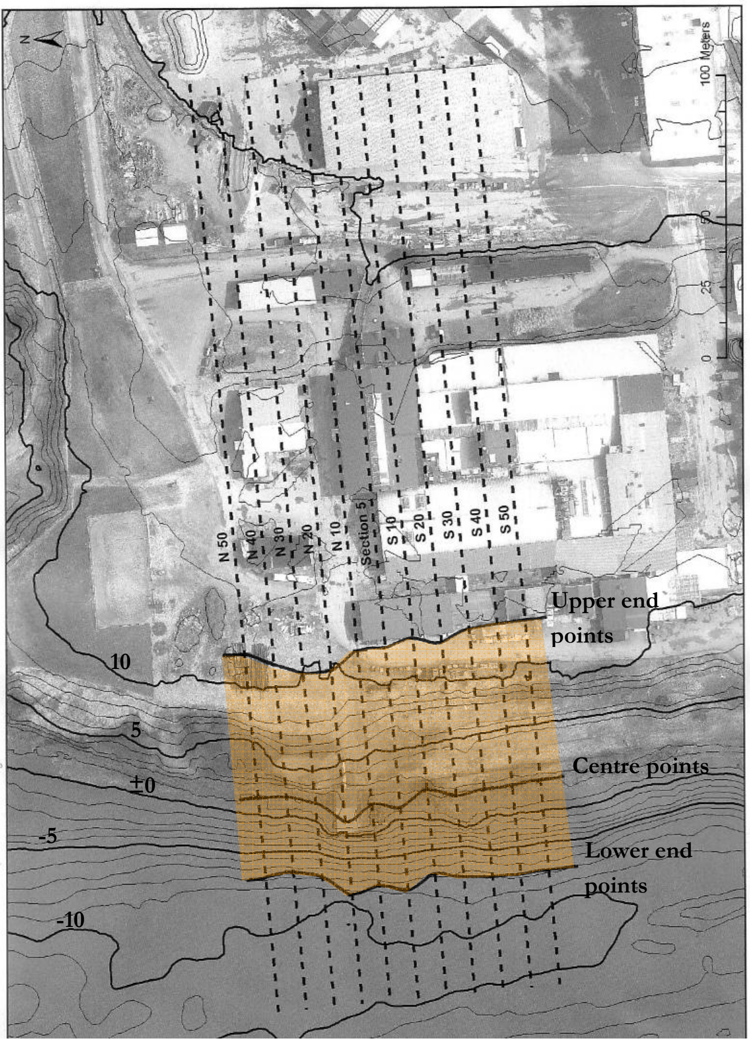


Figure 4.4 The position of the 10 extra sections, parallel to the test section "Section 5" in Lilla Edet, where stability calculations also was performed (5 sections on each side of Section 5). The horizontal distance between two adjacent sections is 10 m, Fallsvik [2006b]. Also the positions in each section of the end- and centre-points of the slide surfaces with the lowest calculated *F*-value according to combined analysis is shown. (Direction: North to the left).

4.2 AMOUNT OF INFORMATION

The amount of information achieved from Laser-scanning and multi-bream echo sounding is huge.

4.2.1 Laser scanning

The density of the Laser scanning is typically 7-10 measured points per m^2. Consequently, in the Lilla Edet test site, where 8 km^2 were Laser-scanned, 56-80 million points were measured, each stored with their x-, y -and z-coordinates.

4.2.2 Multi-beam echo sounding

The density of the multi-beam echo sounding decreases with the water depth:

- Shallow water	25 measured points per m^2
- Moderate depths, around 10 m	10 measured points per m^2
- Depths around 20 m	5 measured points per m^2

4.3 EFFICIENCY

4.3.1 Laser scanning

The carrier of the Laser scanning equipment can be an ordinary airplane or a helicopter. The efficiency of the Laser-scanning procedure is around 1 km^2 per hour. Depending on the distance from the base of the aircraft, the time for mobilisation of the aircraft will differ.

4.3.2 Multi-beam echo sounding

The speed of vessel (used in the Göta River) carrying the equipment is 6-7 knots, which facilitates a quantity of river bottom measurements of 1-4 km^2 per day, depending on the scale of the river and the complexity of the geometry of the river.

4.3.3 GIS-processing

The companies performing Laser scanning and multi-beam echo sounding refine, analyse and extract the raw topographical data from the measurements to provide in-data for further GIS-processing.

With these in-data as a starting point, a skilled GIS-operator can perform the needed GIS-processing for constructing the map during 2-4 days.

The work consists of the following items:

1. Gathering of the topographical in data from the Laser scanning and multi-beam echo sounding.

2. Assembling of the topographical in data in a raster grid

3. Gathering of the available digital geological soil map on land and extrapolation of the soil conditions to the river bottom

4. Executing of the algorithm achieved from the NAKASE-project .

4.4 COSTS

4.4.1 The costs for performing the existing "manual" method

The costs for overview landslide hazard mapping "manual" method (the Stage 1a) is estimated to differ between 500 and 2000 Euros per km^2 including field control and reporting. The given wide cost interval is due to for example changing range of prices, e.g. the competition situation between different contractors, and varying complexity of different investigated municipalities, for instance concentrated or spread built up areas.

The results produced by the "manual" method cannot easily be used for subsequent computer works. When choosing to use the manual method, in cases the results of the mapping are necessary as in-data in further GIS-based municipal planning, there will be extra costs for eventual digitalization of the manually made maps. Furthermore, costs will also show if an intended further GIS-processing will be impossible because of the lack of digital data. The two latter costs are difficult to estimate.

Calculated example No 1:

Given: An area planned to be investigated, which comprises 30 km^2, including a river, which comprises 3 km^2. Mapping Stage 1a.

Calculation:

30 × 1250 = 37500 Euro

4.4.2 The costs for performing the new “digital” method

The costs for performing the new method for overview landslide hazard mapping can be divided into the three procedures scanning, multi-beam echo sounding and GIS-processing, see Table 4:1. Also in this case the given wide cost intervals are due to for example changing range of prices, e.g. the competition situation between different contractors, and varying complexity of different investigated municipalities, for instance concentrated or spread built up areas.

Table 4:1 **Typical costs for performing the new overview landslide hazard mapping method, rough estimates, Sterner [2007] and Nilsson [2007]**

Procedure	Mobilisation and set up of equipment (costs for establishing)	Operational costs	Refining, analysis and reporting of measured data
Laser scanning	Flat rate (average costs) including the three procedures: 600-900 Euro/km^2		
Multi-beam echo sounding	2500-7500 Euro (In extreme cases up to 15,000 Euro)	5000-6000 Euro/day Water depth 2-7m: 5500 Euro/km^2 Water depth 10-20 m: 1600 Euro/km^2	2000 Euro per measured km^2
GIS-processing and reporting		Quantity 10 km^2: 300 Euro/km^2 Quantity >20 km^2: 150 Euro/km^2	7000 Euro (including field control, geotechnical analysis and reporting)

Calculated example No 2

Given: Same area as above – an area planned to be investigated, which comprises 30 km^2, including a river, which comprises 3 km^2. The average depth of the river is 10 m. The area is situated 500 km from the base of the airplane carrying the Laser equipment and 200 km from the base of the vessel carrying the multi-beam echo sounding equipment. Mapping Stage 1a.

Calculation:

Establishing of the aircraft, performing of the Laser scanning, and refining, analysis and reporting results of the Laser scanning ((30-3)×7500 Euro):	20250 Euro
Establishing of the vessel for the multi-beam echo sounding:	3500 Euro
Performing the multi-beam echo sounding (3×1600 Euro):	4800 Euro
Refining, analysis and reporting results of the multi-beam echo sounding:	6000 Euro
GIS-processing	4500 Euro
Field control, geotechnical analysis and reporting	7000 Euro
Total costs:	46050 Euro

The calculated costs achieved in the fictive examples above indicates that if a LS DTM only is needed for carrying out overview landslide hazard planning, one should choose to instead follow the existing old "manual" method, which will be cheaper. However, the rather small cost difference also indicates that establishing of a LS DTM should be considered, as soon as the LS DTM also could be estimated to be used for other purposes, for example topographical basis for stability calculations, municipal and infrastructure planning, etc.

Calculated example No 3

Given: Stability calculations are selected to be performed in ten sections on the slopes flanking a river within an area where also overview landslide hazard mapping is planned. The costs for achieving the geometry of the sections by performing levelling on land and plumbing from a boat is around 1200 Euros per section. The total costs for the ten sections will be:

$$10 \times 1200 = 12000 \text{ Euros}$$

If we instead had chosen to establish a LS DTM to perform the overview landslide hazard mapping, the database could be used to extract the geometry of the ten sections with a much higher degree of detail compared levelled and plumbed geometry. A skilled GIS-operator can perform such an extract in half a day , which will cost around 3200 Euro.

Further, savings could also be achieved because the set of geometrical data for the sections extracted from the LS DTM can be given a suitable format for directly installation in the data routine of the computer programme used for the stability calculations. Hence, the time consuming tapping on computer keyboard is avoided for inserting the topographical in-data.

5. Pros and cons with new and existing methods

5.1 THE EXISTING METHOD

5.1.1 Pros

An important pro of the existing method is the simplicity. No GIS-specialist is needed and the costs for computer equipment and programmes are low. There are normally low costs connected to achieving base material as paper maps, drawings etc.

5.1.2 Cons

The cons of the existing method mainly involves the time consuming manual measurements and the required continuous comparisons between different maps during construction, which generates both high costs and increases risk of man made errors.

The topographical information basis is coarse, normally consisting of the elevation isolines which must be measured on topographical paper maps. The result cannot easily be used for subsequent computer works.

Normally, the results from the existing manual method are reported as documents on paper or as pdf-prints, which not easily can be used as a basis for GIS-processing when executing further municipal planning.

5.2 THE NEW METHOD BASED ON LASER-SCANNING, ECHO SOUNDING AND GIS-PROCESSING

5.2.1 Pros

The new method, based on Laser-scanning, multi-beam echo sounding and GIS-processing, avoids time consuming manual labour with analogue paper maps, and its low degree of human intervention ensure a low number of errors.

The results from the new method for overview landslide hazard mapping can be reported both in paper documents and digitally as a new database. The latter can easily be used as a basis for GIS-processing when executing further municipal planning.

The topographical database can be used for other purposes as for example planning of new buildings and infrastructure and for performing hazard maps for flooding of rivers, planning of dredging of fairways, etc. This possibility to sharing costs, e.g. the opportunity to joint financing of the Laser scanning and the multi-beam echo sounding, will drastically decrease the costs for each party.

5.2.2 Cons

An important con of the new method is its complexity for users with low knowledge and skills in GIS-processing. A GIS-specialist is needed and there are costs for investments in computer equipment and programmes.

There is also a risk, which must be avoided, that the work can be “taken over” by a GIS-specialist lacking essential geological and geotechnical knowledge. If so, there is a plausible risk that the resulting data base and maps will contain factual and logical errors.

One important basis for the new method is digital geological soil maps, which are not available for all provinces. Where these maps are not available, the method can not be used, or the geological map must be digitized, generating considerable costs.

Even where a digital map is available, there will be a cost connected to a fee linked to the permission for its use.

5.3 SUBSEQUENT PROJECTS

The new method delivers its results as digital databases. When generating digital data bases, one important pro is that they easily can be used as basis when performing further subsequent GIS-based municipal planning.

In the first example, performed in Kungsbacka, the skills obtained in the LESSLOSS project were used. As the production of the overview landslide hazard map was preceded by GIS-based construction of a hazard map for flooding, the results of the latter could be used in a GIS-based overlay analysis between the two databases, and subsequently areas could be found, which have prerequisites for both landslides and flooding, Fallsvik & Hågeryd [2007]. The project is a good example to illustrate this pro of the new method. The production of the hazard map for flooding was also based on Laser scanning of the topography; hence its basis had the same level of detail as the overview landslide hazard map.

As a second example, the methodology was performed for the Eskilstuna test site, which also turned out as good example to illustrate this pro of the new method.

However, in a third example, attempted for the LESSLOSS-test site in Lilla Edet, the information from an overview hazard map for flooding was attempted to be used as a GIS-performed overlay on the overview landslide hazard map earlier performed in the LESSLOSS-project, Fallsvik [2006a]. In this case, however, the resulting would have been based on GIS-assembling of two data bases representing different levels of detail, e.g. they were originally attempted to provide basis for different map scales.

5.3.1 Overview landslide mapping in Kungsbacka town

The town Kungsbacka is situated some 30 km south of Gothenburg on the Swedish west coast, see overview map Figure 3.1.

The Kungsbacka municipal council had initialized Laser scanning of the town and its vicinity in the purpose to constitute the basis for detailed planning of flooding hazards along the Kungsbacka River and its tributary streams. When the engineers of the municipal council was informed about the results of the GIS-based overview landslide mapping based on Laser scanning in the neighbouring Lilla Edet, carried out in the LESSLOSS project, they initialized the same type of project for Kungsbacka. This commission was performed on consultant basis by the SGI-SW in cooperation with the Swedish Geological Survey (SGU).

5.3.1.1 *Site description*

The site comprises the core of the Kungsbacka town and its closes vicinity, a landscape with shallow valleys between low hills. The investigated area comprises 20 km^2. The valleys are filled with soil layers of very soft to soft clay of thickness reaching 100 m depth. When approaching the low hills, the depth of the clay layers decreases. The undrained shear strength of the clay varies between 8 and 40 kPa; generally, the shear strength increases by the depth. The hills consist of bedrock outcrops, predominantly surrounded by coarse soil layers as till and gravel. In the hills there are narrow gorges, which predominantly are filled by thin layers of coarse sediments; however, infrequently these gravel layers can be under-bedded by thin layers of clay.

The rivers Kungsbackaån, Rolfsån, and tributary smaller streams follow the shallow valleys. The height of the river flank slopes typically varies between 1 and 5 m. Irregularly along the tributary streams, however, the height of their gently inclined flank slopes can reach 15 m.

5.3.1.2 *GIS overlay together with the flooding hazard map*

As indicated above, the hazards of flooding also had been mapped in the area. This mapping, also based on the Laser-scanned data on the topography, was performed by the Swedish Meteorological and Hydrological Institute (SMHI, 2006). The mapping was reported as digital maps, including a map indicating areas with prerequisites to be flooded within 100 years of recurrence.

By using GIS-based overlay analysis, the results of the flooding hazard and landslide hazard mapping were used to indicate areas, which both have prerequisites for flooding and landslides. This coincidence is important, because while flooding prevails the pore pressures in the clay layers in a slope will increase, which in its turn will decrease the shear strength of the clay. During flooding, the heavy load of the water masses will act as a counter weight on the slope, hence preventing triggering of a landslide. However, when the flooding is diminishing, the counter weight from the water masses will decrease. Due to the very low hydrological conductivity (the permeability) of the clay, the elevated pore pressures in the clay will not decrease in the same pace, hence the lowered shear strength can trigger a landslide. During flooding, also strong currents in the streaming water can erode the bottom of the slop, hence increasing the inclination of the slope.

The result of the performed GIS-based overview landslide mapping is presented in Figure 5.1 (magnification of a selected area, Figure 5.2, and legend, Figure 5.3).

In the Kungsbacka River, Figure 5.4, the bottom topography was measured by echo sounding (single beam). However, neither in the Rolfsån River, nor in the other streams, echo sounding has not been performed. Where the water-depths are unknown, 50 m wide buffer zones are drawn on each side of the watercourse, which is the common routine in Swedish overview landslide mapping, commonly carried out manually.

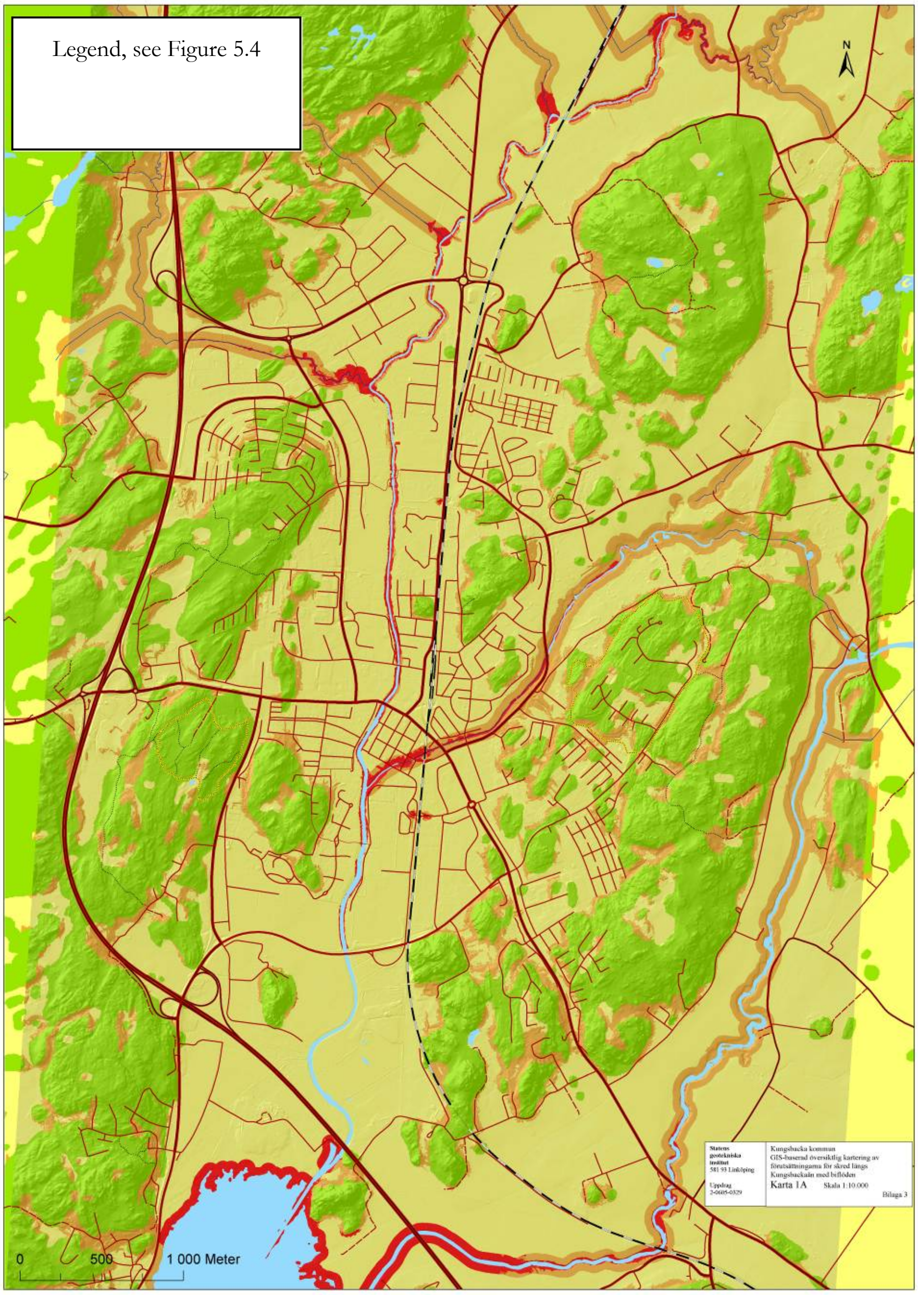


Figure 5.1 Result of GIS overlay between the overview landslide hazard map and the flooding hazard map – both based on the laser scanned topography. (legend, see Figure 5.3)

Figure 5.2 Result of GIS overlay between the overview landslide hazard map and the flooding hazard map – both based on the laser scanned topography. Magnification of the area around the centre of the town (legend, see Figure 5.3).

Stability zones	Description	Prerequisites for landslides	Prerequisites for flooding	Need for further stability investigation	Colour on the maps, Figures 5.1, 5.2 and 5.5
Zone I-F	• Areas with soil layers of clay and/or silt. • The slope inclination exceeds 1:10. • Area which will be flooded	Yes	Yes	Yes	Orange
Zone I	• Areas with soil layers of clay and/or silt. • The slope inclination exceeds 1:10. • Area which not will be flooded	Yes	No	Yes	Brick-red
Zone II	• Areas with soil layers of clay and/or silt. • The slope inclination is less than 1:10.	No	(Not considered)	No	Yellow
Zone III	• Areas lacking soil layers of clay and/or silt. “Firm ground” areas.	No	(Not considered)	No	Green

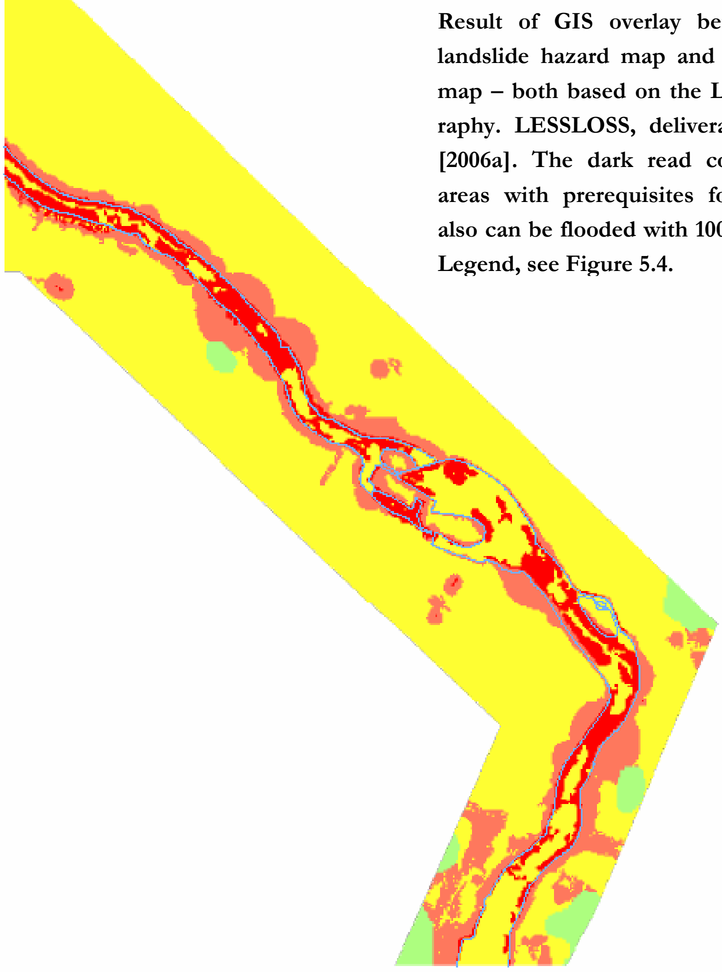
Figure 5.3 Legend for the maps in Figure 5.1, 5.2 and 5.5.

Figure 5.4 Kungsbacka River in the centre parts of Kungsbacka. The clay layers can reach 100 m depth.

5.3.2 Overview landslide mapping in Eskilstuna town

By using the potential of the ArcGIS, a overlay analysis was also performed in the Eskilstuna test site, see Capter 4. Also there, sub-areas could be indicated, which have prerequisites for both landslides and flooding. A database was created as a basis for a digital map, Figure 5.5.

Figure 5.5 **The Eskilstuna River through Eskilstuna town. Result of GIS overlay between the overview landslide hazard map and the flooding hazard map – both based on the Laser scanned topography. LESSLOSS, deliverable No. 7, Fallsvik [2006a]. The dark read colour indicates sub-areas with prerequisites for landslides, which also can be flooded with 100 years return period. Legend, see Figure 5.4.**



Furthermore, these new databases, based on the combined hazard information on both landslide and flooding, can be used as a new GIS-overlay in further municipal planning and so on – the procedure can be continued.

5.3.3 GIS-overlay performed between two databases intended for two different scales, Lilla Edet

Application: The results of the overview Landslide hazard mapping in the LESSLOSS-project in Lilla Edet town was attempted to be overlaid with an earlier performed so called General Flood Hazard Map covering the entire Göta River.

The hazards of flooding have been mapped along the Göta River. However, this mapping was considerably coarse, because it was based on an ordinary elevation database on the topography, the Swedish General Elevation Grid ("GSD-Höjddata", c/c 50 m grid) and not Laser-scanned data. The used topographical model of the river basin was coarse. To calculate the flooding hazard, a topographical model of the river was created based on measured sections across the watercourse as well as blueprints for structures as bridges and dams.

The Swedish Meteorological and Hydrological Institute performed the mapping on commission by the Swedish Rescue Services Agency (SRSA, 2000). The mapping was reported as digital maps, including a map indicating areas with prerequisites to be flooded within 100 years of recurrence. The general flood hazard mapping was performed to be presented in a relatively small scale, around 1:50,000, and consequently its generalization is correspondingly high. When combining its results by overlay-technique together with data with a larger scale, errors due to its higher degree of generalization were magnified to an unacceptable degree.

GIS-overlay was carried out between the landslide hazard mapping performed in the LESSLOSS-project and the overview hazard map for flooding. Due to the too small scale of the latter mapping, the result of the overlay was unacceptable. The inexactness became magnified in an unacceptable degree, which generates an altogether too coarse zigzagging and straight lined pattern of the boarder lines of the areas prone to be flooded. In the magnified scale, the magnified errors frequently cause that the border lines even cross over outside of the river shoreline.

6. Using LS DTM – Recommendations

6.1 PLANNING OF WORK

A digital terrain model is an excellent information basis for municipal and infrastructure planning purposes. Good tools to achieving the digital terrain model are Laser scanning of the topography on land, and multi-beam echo sounding of the bottom topography of rivers, lakes and bordering sea shores in the investigated area. The hitherto existing methods are to base planning and projecting on studies of paper for example by carrying out time consuming manual measurements and comparisons between different paper maps. Now, the possibility to use digital terrain model combined with GIS-technique can facilitate the planning of the work, and also decreasing and the volume of the work as well as raising its quality.

It is relatively more expensive to construct a digital terrain model by using Laser scanning and multi-beam echo sounding, compared to the traditional way of gathering topographical information. However, the gained higher quality and multi-functional value of a digital terrain model can decrease the total costs for municipalities and other responsible parties, which perform many different categories of mapping and physical planning. Besides landslide hazard mapping, dealt with in the LESSLOSS-project, municipalities have to carry out for instance construction of detailed topographical maps, planning of areas for exploitation, new roads, dams, ports, and sewers, planning of measures against natural accidents as flooding, landslides and debris flows, environmental planning, etc. Therefore, it is recommended to perform a digital terrain model by Laser scanning and complemented by multi-beam echo sounding for planning purposes.

6.2 STABILITY CALCULATIONS

A LS DTM is an excellent topographical basis both for overview and detailed stability calculations. The high level of detail and covering of a continuous area facilitates a free choice and number of selected sections where stability calculations can be performed.

6.3 SURVEILLANCE AND INSPECTION

Repeated Laser scanning and multi-beam echo sounding can identify movements, i.e. erosion and minor landslides, giving indication and hence warning for landslides presumptive areas. Geotechnical analysis and stability calculations followed by preventive measures can then quickly be directed to be performed in the affected area, and by imminent danger also evacuation of people.

For instance during a period with high precipitation and flooding of rivers erosion can have sharpened the relief of the flanking river slopes above the shoreline as well as on the river bottom. Indications achieved by studying the results from repeated Laser scanning and echo sounding give information on eventual topographical change. By utilising a GIS-system areas with both soil material loss and gain due to erosion and transport can be detected and analysed.

7. Usefulness of LS DTM in landslide hazard mapping and slope management

7.1 CONCLUSIONS AND RECOMMENDATIONS

Laser scanned digital terrain models is a useful tool for performing overview landslide hazard mapping. The gathered database can also be used as a topographical basis when performing stability calculations. The LS DTM database has a multi-purpose; there is a general usefulness of the database as a basis for different GIS-applications in municipal and infrastructure planning, as well as for surveillance, and also for decision of landslide warning areas.

If the database can be used for different planning purposes, it will save costs. However, if it is only used for one application, for instance overview landslide hazard mapping, the economy yields to be uncertain. Nevertheless, the general usefulness of the database indicates that there must be several planning applications which can finance the investment of Laser scanning and multi-beam echo sounding to create the detailed digital database.

Therefore, despite the costs, it is recommended for planning purposes to invest in an LS DTM – a digital terrain model – by Laser scanning complemented by multi-beam echo sounding.

7.2 FURTHER DEVELOPMENT

Besides overview landslide hazard mapping as tested in the LESSLOSS-project, GIS-methods based on LS DTM:s could most certainly be developed to be used also for the following geotechnical applications:

- Overview hazard maps for:
  - Debris flows
  - Landslides in till
  - Rockslides
  - Gully growth
- Surveillance and possibly pre-warning systems for different types of landslides
- Detailed mapping of coast and river erosion hazard and sediment transport.
- Digital databases for performing detailed stability investigations both for R&D and municipal and infrastructure planning purposes
- Geotechnical municipality and infrastructure planning:
  - “Geo-calculation”, e.g. economical calculation of geotechnical construction costs
  - Optimised choice of best alternative corridors for new roads or railways
  - Optimised choice of best alternative areas for development of new homes, industry, schools, commercial centres, etc.
  - Digital database for projecting of new streets, sewers, ports, hydropower plants, channels, roads, railways, etc.

Besides the geotechnical applications there are other applications already in use or under development for example construction of detailed topographical maps and detailed mapping of flooding hazard.

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APPENDIX A. THE TOPEYE MK II – LIDAR SYSTEM WITH INTEGRATED DIGITAL CAMERA

(The folllowing information on the TopEye system is achieved from Fallsvik [2006a].)

TopEye Mk II introduces an industrial fibre Laser technology to full control of the transmitted Laser pulse's properties, Sterner [2006], and TopEye AB [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 metres.

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 m^2. 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 feed back 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 an other 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 co-ordinates 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.

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.

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 A.1.

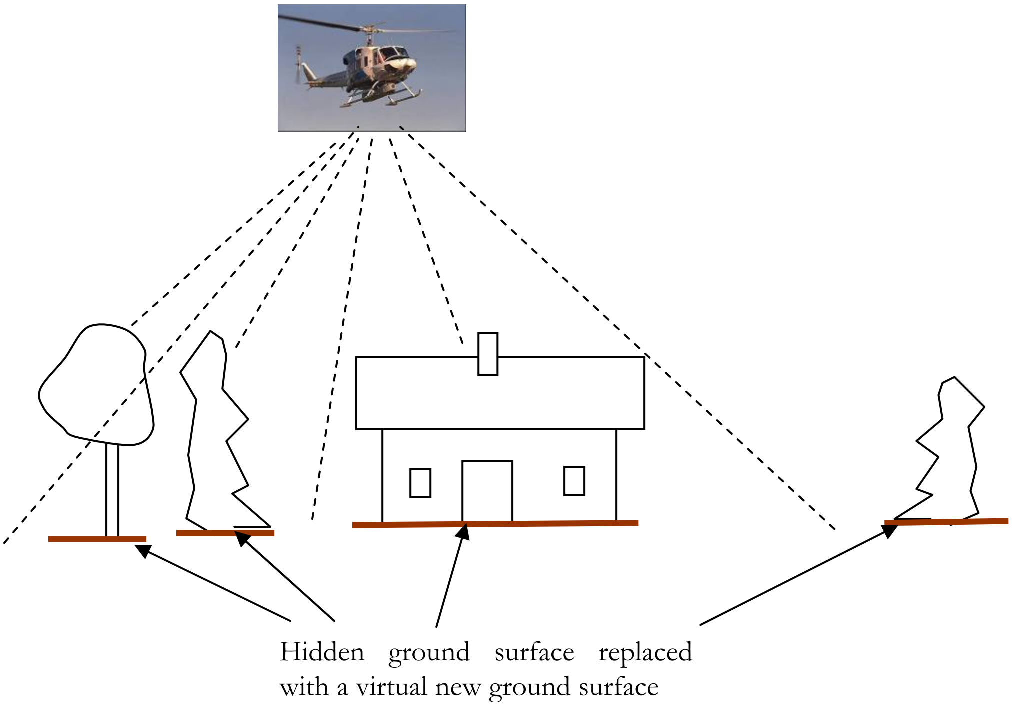

Figure A.1 **Where obstacles are found like trees, bushes, houses, etc., which are hiding the ground surface, an algorithm "neutralises" them, by replacing the obstacles with a virtual ground surface normalised to the neighbouring ground surface.**

Accuracy in x-, y- and z-directions

The accuracy in estimation of heights is ± 0.1 metres. In x- and y-direction the accuracy is achieved by the point density which is between 7-10 points per m^2.

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