Master Thesis, Department of Geosciences

Human activity as a cause for landslides in Norway

Case study of two man-made debris flows in Otta, Central Southern Norway

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FACULTY OF MATHEMATICS AND NATURAL SCIENCES

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Kai Yao

Oslo, October 2012.

Abstract

Debris flows pose serious hazards in the mountainous area of central southern Norway. On 10th June 2011, a great number of debris flows occurred in Gudbrandsdalen valley. The intense precipitation triggered most of the events; meanwhile human aspects played a vital role in the formation of two events. One is located in Solhjem and the other one is located in Sagdalen.

The primary objective is about to document the two events through pictures, map study and field work. Clarifying the terrain, geological setting and slope model is very helpful for us to understand the formation process. And then, through the precipitation data study, we could not only find out the triggering threshold, but also the trend of the precipitation.

Based on the slope parameters, estimation about the total flow volume and peak discharge could be done. The level of these two parameters could help us understand the level of the hazard.

The main purpose of this paper is to discuss the "man-made" debris flow and its role in the formation mechanisms. And under the climate change, how the future's brief risk estimation in the location is. Therefore, we could set up the more targeted risk mitigation measurements.

1 Introduction

1.1 Background

In the summer of 2011 numerous debris flows occurred in the steep valley area of central southern Norway during a period of intense precipitation, especially in the Otta area. Many debris flows extended onto the property of locals, which introduced not only huge economic deficit, but posing a serious threat to the inhabitants' safety. However, two of these events occurred near Otta are worthy to draw more attention, due to the causes of which were the combination of the natural aspects and human activities. Human activities played the vital role in the formation of these two debris flow.

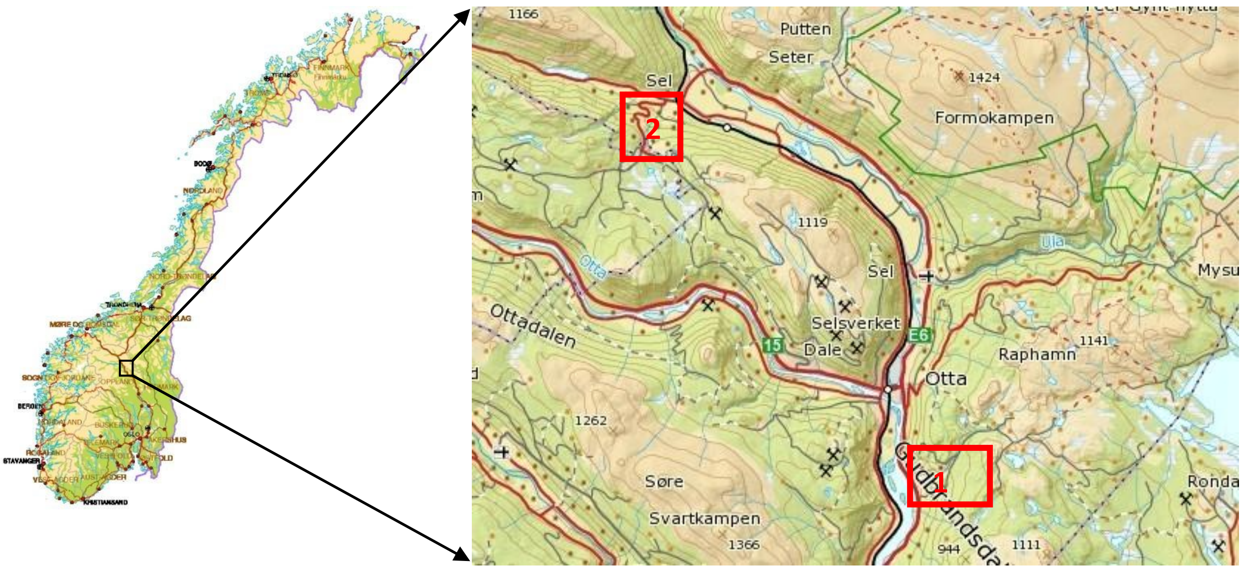


Figure 1.1 Overview maps of the events' locations, red rectangles showing the event 1 and event 2, taken from www.norgeskart.no.

One of the events is located in the Solhjem, south of Otta. Based on GPS data gathering from field observations, the flow initiated at the joining of two roads, reaching E6 road. The flow developed along one old road and turned left to the slope, following an old track of the stream. It entrained numerous pieces of debris, including trees, till and boulders. After impact with the barn house of a local farmer, which destroyed portions of the walls, the flow turned right towards the gentle sloping field between the road and the barn, reaching the main road E6. Most of the erosion occurred in the middle of the flow path. One classic debris flow showed its path compared to next event.

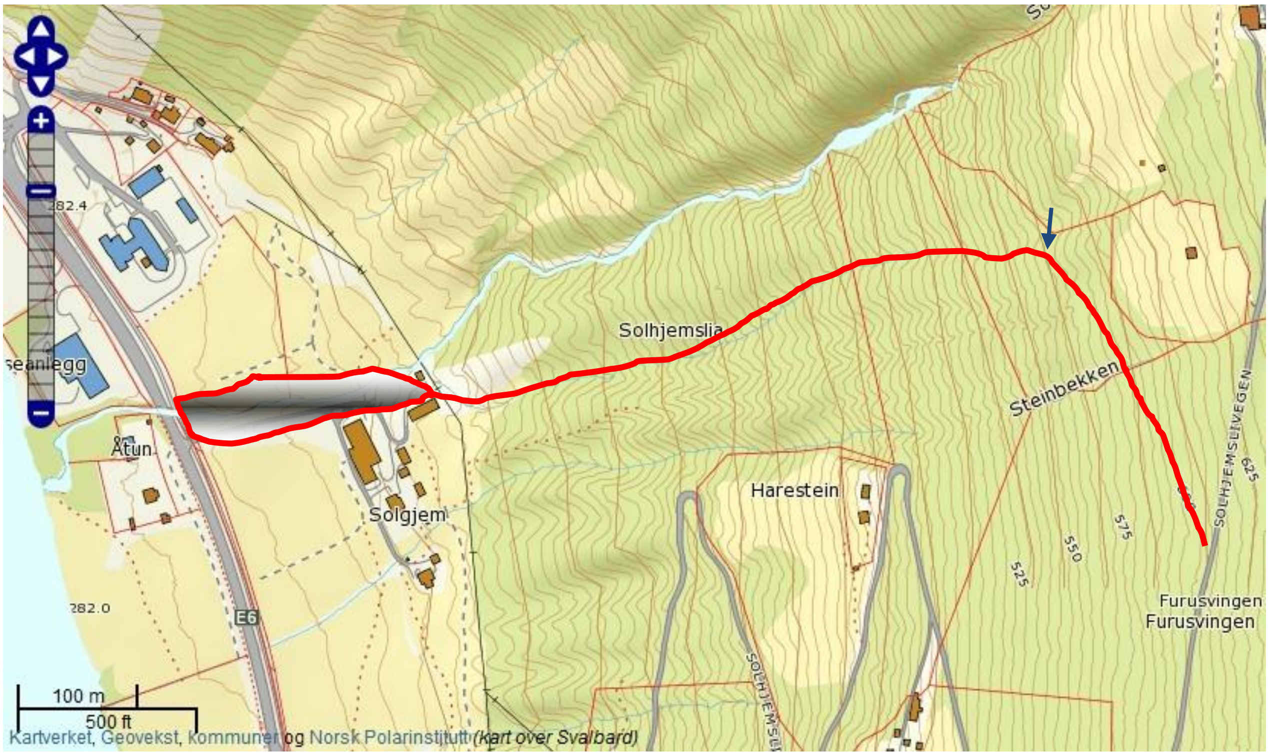


Figure 1.2 The study area map of the Solhjem debris flow occurred in 10th June 2011. Red curve shows the track of the debris flow, and the gray shadow represents the deposition zone, taken from www.norgeskart.no. The pot pointed by the blue arrow was the failure point of the slope.

Event Two is located in Øygarden, north of Otta, which also followed the track of another stream, Sagdalen. It began from the upstream located in the bottom of catchment area, at crossing point of the bridge and the stream. The flow collapsed two bridges under the gentle gradient. The massive boulders and the clogged drainage pipes were carried only down tens meters from the failure positions while the medium-sized rocks and tiny stones were entrained to further. The flushed trees, soil, rest of the rock were carried downstream, thereby causing damage to the houses located closer to the stream bank and bridges. The flow ran over the bridges and the river embankments, reaching the property of the inhabitants.

Figure 1.3 The study area map of the Sagdalen debris flow occurred in 10th June 2011, red curve shows the track of the debris flow, and the two pots pointed by the blue arrows represented the destroyed bridges, taken from www.norgeskart.no.

1.2 Main goals and purposes

First of all, for the new events happened last year, I intend to document these two events, by organizing the detailed information about the gradient of the flow path, the geological setting, the debris flow volume, erosion depth related to the different slope angles and running distances, the runout distances, the maximum instantaneous flow, evaluating the size of the debris flow based on the combination of the meteorological data, witness observation and data from field work.

Secondly, I will attempt to identify the triggering factors and analyze the formation mechanisms of these two events. And then, to analysis the flow process, I will try to reproduce the runoff processes of each event based on the map and pictures details, especially focusing on the role of human activities in the process.

Thirdly, the intense rainfall is the key point to the events. The threshold would be advantageous for us to understand the triggering scenario, so the information about the pre-events from the source location is required for determining the rainfall threshold. Then, combined to the climate changing, I would like to do the risk estimation for the future.

Fourthly, discussion about the relationship between the climate changing, human activities and the debris flow would be described based on the events. And trying to answer the following questions, such as could these be avoided? Could it happen again in the source area? Are the mitigation construction built there going to decrease the hazard or risk? If not, how it could be worked towards to the better way?

1.3 Methods and data

1.3.1 Maps

In the paper, area maps came from www.norgeskart.no. In the maps, information about elevation, stream track, roads and building was offered. From the field observation, as we know the debris flows followed the streams' tracks of Solhjem and Sagdalen, the overview of the events would be presented in the area maps. And the flows's direction could read by the terrain and gradient of the locations. In Solhjem, the old little road, which was the start zone, was not marked in the original map. After adding the missing element of the event, we identified the areas and divided into start zone, transport path, depositional zone. Then combined with the detailed

GPS data, we could get the flow track clearly.

In Sagdalen, we marked two destroyed bridges in the joints of the stream and the roads. Terrain of the catchment area about the surround circumstance could be read and measured in the map. It would be more appropriate that the focus was on the gentle start zone and the end depositional zone, compared to middle valley transport parts of the stream.

Historical events map, soil cover maps and bedrock maps were taken from www.ngu.no. Combined with the information offered by the website, detail explanations were made about the historical events map (see Appendix A). Such information including the place and time that events occurred, and comments with descriptions, got from the website. In the geological maps, soil cover types and thickness were clarified, which could tell us the source materials and limitation of the erosion depth.

1.3.2 GPS data and field observation

Two field trips were arranged during this year, one of which was in April. Not so much information was gathered during the trip due to the snow cover. The other one were completed from 10^{th} June to 13^{th} June 2012. The tools taken with me were camera, GPS locator, notebook and gradiometer. Pictures and GPS data were gathered during this trip, and description based on the observation was recorded according to each point (see Appendix B and C). Principle for choosing the points was based on the fix-distance and special positions. The standard for special position stood for that such one position had abnormal phenomenon such as erosion, widen channel, debris deposits, wooden dam or huge boulders and etc. Serial number from Point 105 to Point 140 was made in Solhjem, while

Point 141 to Point 181 made in Sagdalen. Values of latitude and longitude, also the height about each point were record. For dealing the data to get the distances and slope angles between each two points, I found two equations.

One is calculating the arc length depending on considering the Earth as one sphere. Formula as follow:

$$S = 2 \times 6378137 \times \arcsin\sqrt{\sin^2\frac{a}{2} + \cos(\text{Lat1}) \times \cos(\text{Lat2}) \times \sin^2\frac{b}{2}}\ (\text{m})$$

In the formula, “a” represents the latitude difference between two points and “b” represents the longitude difference between two points. Lat1 and Lat2 stand for the latitude values of two points. “6378137” mean the radius of the earth.

The other formula based on the triangulation transform of mathematics function as follow:

$$C = \sin\left(\text{LatA} \times \frac{\pi}{180}\right) \times \sin\left(\text{LatB} \times \frac{\pi}{180}\right) + \cos\left(\text{LatA} \times \frac{\pi}{180}\right) \times \cos\left(\text{LatB} \times \frac{\pi}{180}\right) \times \cos\left((\text{LonA} - \text{LonB}) \times \frac{\pi}{180}\right)$$

$$S = 6378137 \times \arccos(C) \times \frac{\pi}{180}(\text{m})$$

In the above formula, LatA and LatB represent the latitude of points A and B, also LonA and LonB as the longitude of both points. “6378137” mean the radius of earth. After dealing the number by two equations, the difference is no more than 1%.

Therefore, after calculation we got all the distance values of paths between each two points. Simple slope model including information about slope angles, distances and heights could be set up.

For the uncertainty in the dealing with data, it may come from two sources in GPS part. One is the accuracy of the GPS data gathering by the locator, due to the GPS locator's locating is affected by the woods and the satellite. The other one is the calculation with considering that the Earth as perfect sphere which is actually ellipsoid.

1.3.3 Climate data

For debris flow, when it comes to climate data, we would focus on the precipitation data available from www.senorge.no. Three purposes worthy to mention, the first one is to study the precipitation of triggering scenario at 10th June 2011. Secondly, it is about to set up the threshold combined the precipitation data with the time of the occurrence of the historical events. Unfortunately, only three identified debris flow events were recorded, while only two events could be found related precipitation data.

Other one is about to study the trend of the precipitation since last century, and try to estimate the future changing. After choosing the nearest weather stations to the event, measurements in millimeter since the stations were built, could be presented by table and figure. Average precipitation, maximum precipitation, total volume precipitation and the rainy days could be counted. All these numbers could tell us the basically trend of the climate changing in the source location. And then, we would try to look through the effect to Otta area under such a climate changing.

Data from four stations had been chose to view the precipitation at 10th June 2011, as follow: Høvringen, Sjoa, Preststulen, Skåbu. Such choose was based on the closest principle. And for Skåbu was due only this station in this area had the hourly precipitation data. For the triggering scenarios, data about one weeks around 10th June 2011 from four stations was review. More attention would be paid to data from Skåbu due to more detailed data compared to other stations; even through Skåbu is located in one valley and relatively far away from the two locations, which meaning the data would be some discrepancies with the location's precipitation. Hourly precipitation data have been recorded in this station, which is useful for us to find the triggering threshold by using the mean rainfall intensity to plot in the threshold figure.

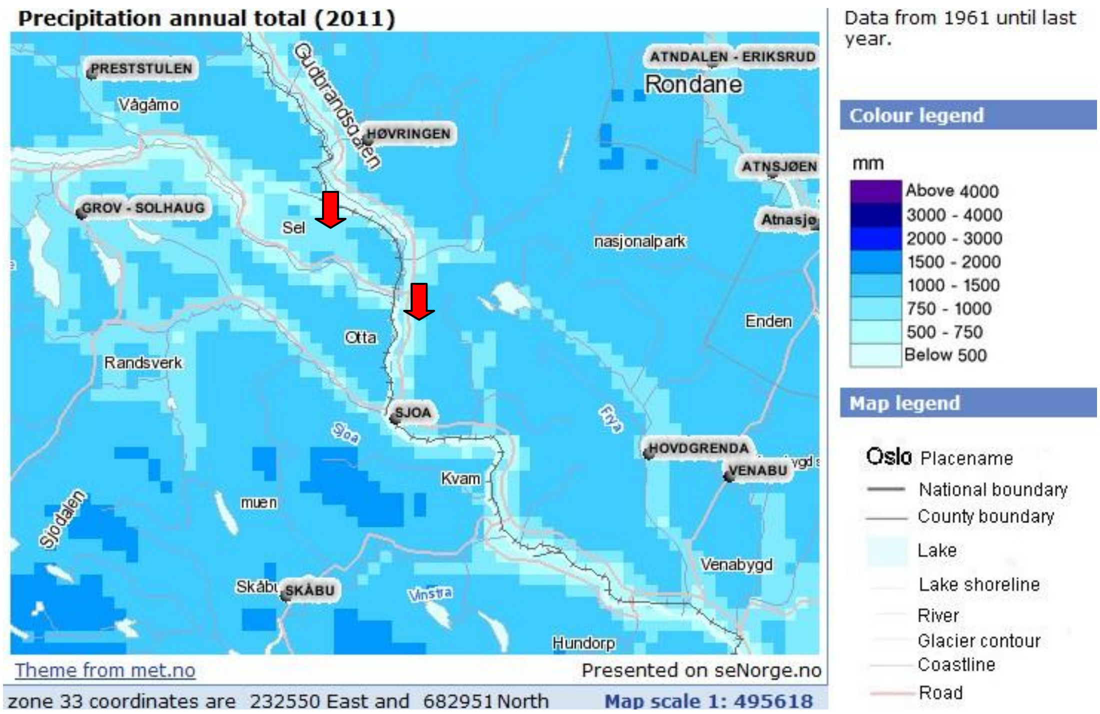


Figure 1.3.3 The annual precipitation map of 2011 with the weather stations, the red arrows point the events.

2 Historical investigation

2.1 Geohazards in Norway

The most common geohazards in Norway are related to avalanches, landslides and floods, including snow avalanches, debris flows, rock falls, rock avalanches and quick-clay slides. Quick-clay slides in exposed marine sediments represent a particularly high hazard in eastern and central Norway, but do also occur in parts of western and northern Norway. Snow avalanches affect large parts of western and northern Norway and are the geohazard which most frequently leads to loss of lives and infrastructure damage in Norway (Jaedicke 2008).

Figure 2.1 The number of deaths caused by landslides and avalanches in the different area in historical archives (1345-1986), taken from www.skrednett.no. Brown rectangles show the area studied in the GeoExtreme Project in 2008 (Jaedicke 2008).

Landslides and avalanches have caused more than 2000 casualties and considerable damage to infrastructure over the last 150 years. Debris flows are responsible for 237 during 1345 and 1986 (Jaedicke 2008).

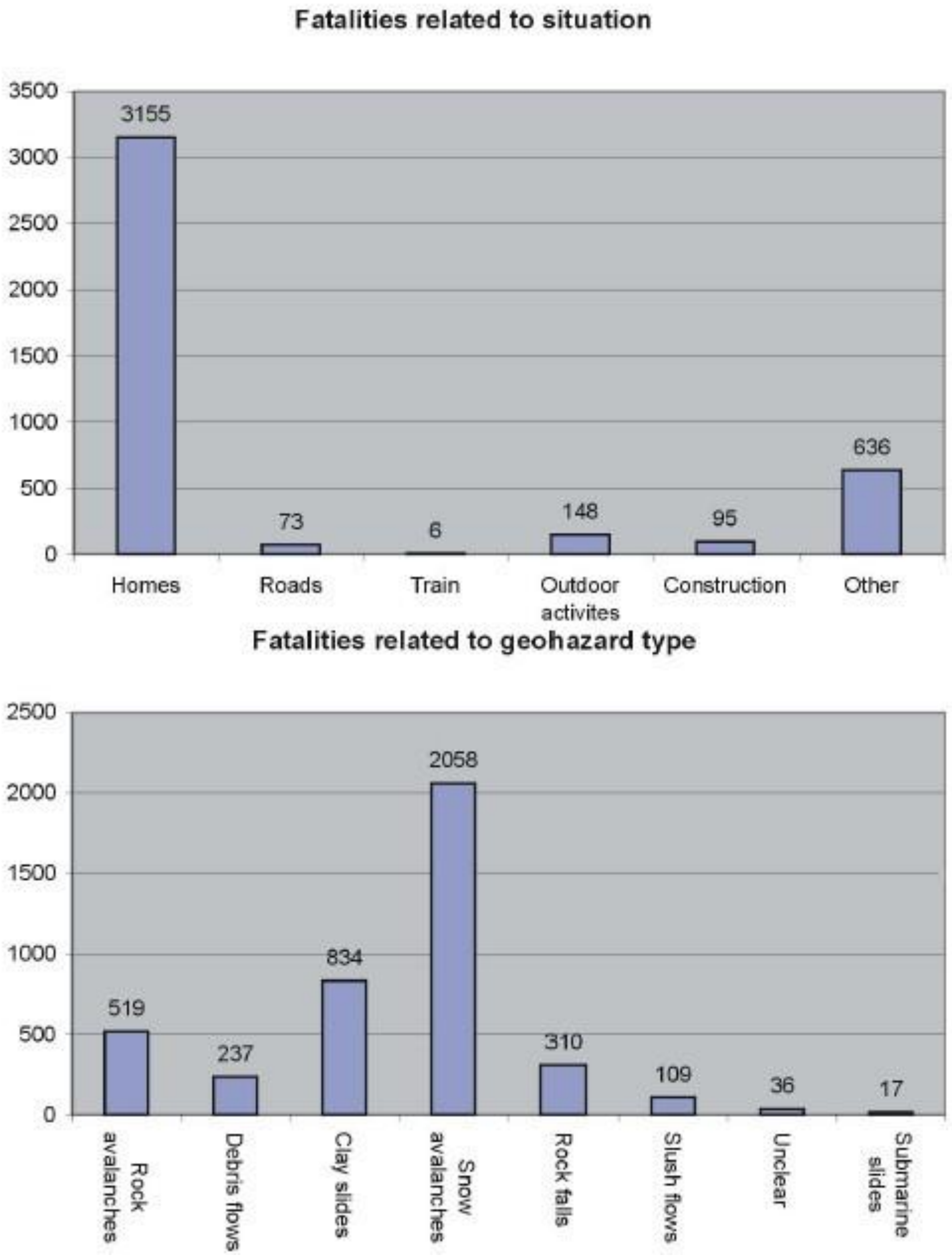


Figure 2.2 The number of fatalities related to situation and type of geohazards during 1345-1986, taken from www.skrednett.no (Jaedicke 2008).

2.2 Known historical events

2.2.1 Fjærland Debris Flow

In Fjærland, the western part of Norway, an enormous debris flow with a total volume over 240000 m^3o ccurred on 8^{th} May 2004.

Triggered by one outburst flood due to a mountainous glacial dam failure, the sudden drainage of the lake scoured a small river gully through a steep terrain on its way from 1000m ASL down to sea level, with entraining large amounts of material along the way and eventually evolving into a debris flow. The valley affected was thus mainly overlain by glacial deposits, with lesser deposits of alluvial material (Breien 2005).

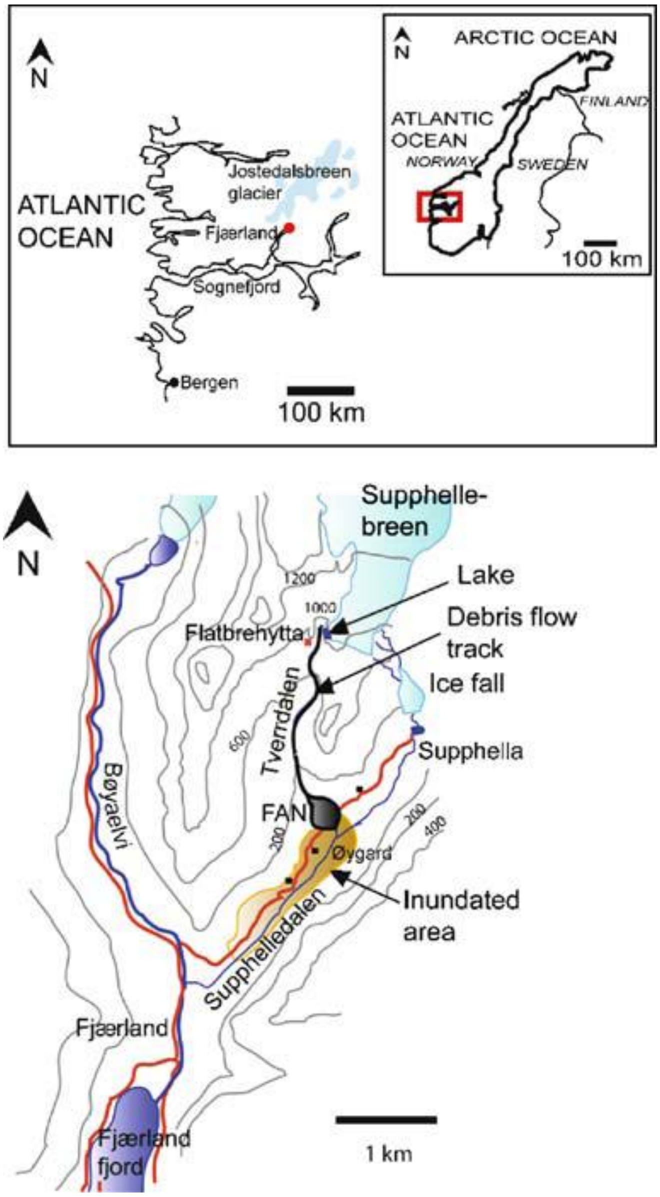


Figure 2.2.1 Map of affected area during 2004 Fjærland Debris Flow, meltwater drained from the glacier via the lake and through Tverrdalen instead of the normal drainage towards Supphella directed south-east through the ice fall (Breien 2008).

The resulting flood travelled across a sandur before it developed into a debris flow that rushed through the steep and narrow tributary valley (Tverrdalen) and ended in a boulder fan deposit where Tverrdalen meets the flat floor of the main valley (Supphelledalen) at around 20 m ASL. The debris flow route has an average gradient of 17 °, but varied from around 4 ° in the uppermost stretch along to the top of a 60 ° steep rock wall, thereafter slanting towards 12 °. The runout distance was about 3,000 m (to the boulder fan), with a total descent of around 1,000 m. Downstream of the fan, floodwater and finer material inundated 250,000 m^2 of the valley's farmland. Tverrdalen and the area around the glacier is a hiking area and the debris flow damaged the most popular path. There were no casualties partly because the event occurred in between the winter and summer seasons (Breien 2008).

The main erosion started downstream of the cliff at 600 m ASL. The developing debris flow followed the stream gully down Tverrdalen, with the steep gradient (25 °). The flow track varies considerably along the route, widening to more than 50 m and scouring to a depth of around 8 m. The deepest erosion was found in the lower parts of the track, where the gradient had eased to 13 ° with totally scoured, in contrast to the higher altitude parts where larger boulders remained. The gully changed from a classical V-shaped river gully to a rectangular trench with almost vertical sides due to debris flow erosion. A revisit to the valley 3 years later showed that this rectangular debris-flow gully is changing back to a V-shape (Breien 2008).

2.2.2 1789 Storofsen Flood

From the historical record, the source location of Gudbrandsdalen, has been subjected to at least six massive flood events since the records began. The dates of these six known events are 22nd July 1789, 7th June 1860, 15th June 1910, 13th June 1923, 1st September 1938 and 2nd July 1958. The largest event took place in July of 1789. The entire event lasted for 3 days from the 21st to 23rd of July, and the worst situation happened in 22nd July with massive precipitation rate. Unfortunately, there is no accurate rainfall data record during the three days; however, the massive rainfall was not the trigger for this tremendous event. Been through rainy autumn and snowy winter of 1788 compared to the other years, the groundwater and snow cover was more than normal years (Furseth 2006).

Figure 2.2.2 Sign stone for the floods occurred in the Gudbrandsdalen, taken by Astor Furseth.

Additionally, the saturated soil was frozen in the winter due to abnormally low temperatures. Following these events, the spring of

1789 was especially unusually warm. Because of the rapid temperature rise, the flood in early 1789 from the melting snow was emerged in June. In the beginning, it was not so bad until combined with the rolling rain started from earlier of July. In this mountainous area, the water gathered from the rainfall and snow melting was flushed from the top of the mountain to the valley, thereby introducing such one event. While the debris flow occurred, it may be more accurately described as “mudslides”. Due to the scouring ability of the heavy rainfall and the surface flow, soil, rock and woods were entrained down to the valley, causing loss of life, structural damage and the destruction of farmland. In the records, it said that just in three days eighty landslides occurred in Gudbrandsdalen (Furseth 2006).

As mentioned previously, there is no precipitation data available. However, from the observations taken during the time of the events, one barrel in Vollan i Sunndalen was fully filled by rainfall in three days, which could be described as approximately corresponds to 320 mm precipitation per day (Furseth 2006). (original words: På bakgrunn av disse tallene forstår vi uten videre at det var få som den gang trodde at disse strøkene noensinne ville bli beboelige igjen. dette gjaldt alle dalfører som har sitt utspring fra Filefjell, Jotunheimen, Dovrefjell og Gudbrandsdalens of Østerdalens fjellområder. Dette var før værvarslingsstasjoner of nedbørmålere, men vi får er visst inntrykk av uværet gjennom det som blir fortalt fra garden Vollan i Sunndalen. Her ble ei tønne full på tre døgn. Dette tilsvarer en nedbørmengde på 320 mm pr. døgn.)

2.3 The landslides in Otta area

The Otta area, Gudbrandsdalen valley, east Norway at 62N °, 25 km^2, is one of the driest areas in Norway with 375 mm annual precipitation (www.met.no) (Jaedicke 2008). The dry climate could also be reflected by the most disturbing geohazard for the inhabitants. As the record of events states, rock falls and avalanches are the most frequent landslide type identified, which also indicates the abundance of loose material available in the area.

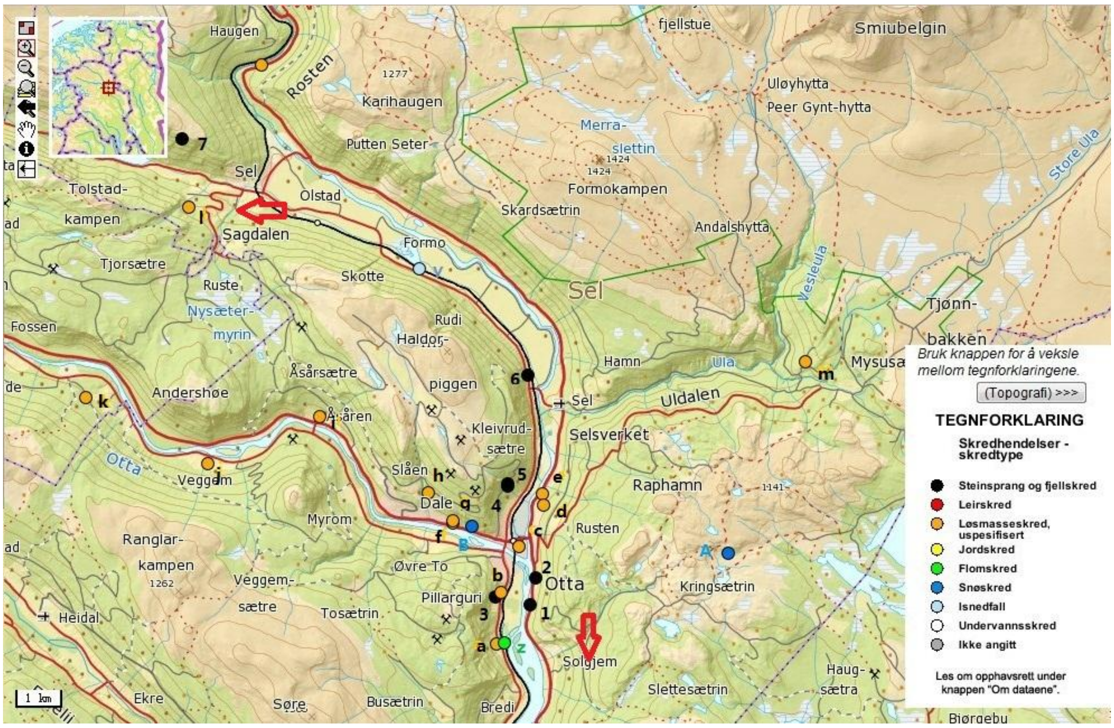


Figure 2.2.3 Map showing the landslides near to source location in Otta, the position pointed by the red arrows represented the 2 events, taken from geo.ngu.no. Detailed information could be found in the Appendix A.

In the map showing above, five different types of colored points (black, yellow, green, blue and light grey), represent more than five types landslides in this area. The black points represent rock falls and avalanches, whereas blue points correspond with the snow avalanches. The marked black points from "1" to "7" show the rock falls and avalanches took place from 1853 to

1972, varying from February to June. From the witness observations, the events occurred suddenly without warning or phenomenon and no pre-movement before the events. There was loss of life reported during three of the events, and houses damaged in all those seven events. The boulders varied from cm- to meter-sized, of which the biggest rock was approximately 40 ton. The points "A" and "B" in blue showed that two snow avalanche events occurred in the same day of 1829 and 1981, 15^{th} July. Such one coincidence revealed the triggering weather factors including precipitation, rapid temperature rising or others occurred in July.

One green point refers to "Flomskred" (debris flow or debris flood) occurred 2^{nd} May 2008. The light grey point shows one event "Isnedfall" (icefall) occurred in 23^{rd} January 1986. One casualty was made by the former event. However, due to the non-detailed recording, more than thirteen events, represented by the yellow points, could not be clarified which type of landslides formed, between April and July varying from 1739 to 2008. The causes which have been detailed refer to were snow melting and massive precipitation in 1789. Most of the thirteen events were recorded with house damage, forest destruction and farmland scouring. Twelve of the events were luckily reported with no fatalities, while the tremendous disaster in Ofsen on 23^{rd} July of 1789 resulted in 68 deaths.

3 Theory of landslides

3.1 Definition

"The term "landslide" describes a wide variety of processes that result in the downward and outward movement of slope-forming materials including rock, soil, artificial fill, or a combination of these. The materials may move by falling, toppling, sliding, spreading, or flowing. And based on the type of material involved and the type of movement, landslides could be classified into different types (Highland 2008)."

3.2 Classifications

TYPE OF MOVEMENT		TYPE OF MATERIAL		
		BEDROCK	ENGINEERING SOILS	
			Predominantly coarse	Predominantly fine
FALLS		Rock fall	Debris fall	Earth fall
TOPPLES		Rock topple	Debris topple	Earth topple
SLIDES	ROTATIONAL	Rock slide	Debris slide	Earth slide
	TRANSLATIONAL			
LATERAL SPREADS		Rock spread	Debris spread	Earth spread
FLOWS		Rock flow (deep creep)	Debris flow	Earth flow
			(soil creep)	
COMPLEX		Combination of two or more principal types of movement		

Figure 3.2 Types of landslides based on the material and movement (Varnes 1978; Highland 2008).

3.2.1 Falls

"The material of soil or rock, or both, due to the gravity attraction, falls from steep slopes or cliffs, descends mainly by falling, bouncing or rolling at very rapid to extremely repaid velocities, which are triggered by natural processes, human activities such as excavation during the road building and maintenance, or mining (Highland 2008)."

Figure 3.2.1 A rockfall occurred in Colorado Usa in 2005, photograph by Colorado Geological Survey (Highland 2008).

3.2.2 Topples

"A topple is recognized as the forward rotation out of a slope of a mass of soil or rock around a point or axis, at extremely slow to extremely rapid, below the center of gravity of the displaced mass, triggered by natural process like water or ice occurring in cracks in the mass, and also vibration or stream erosion (Highland 2008)." To put it another way, due to the unreliable weight distribution of the slope, the top part is too heavy to maintain the slope stability.

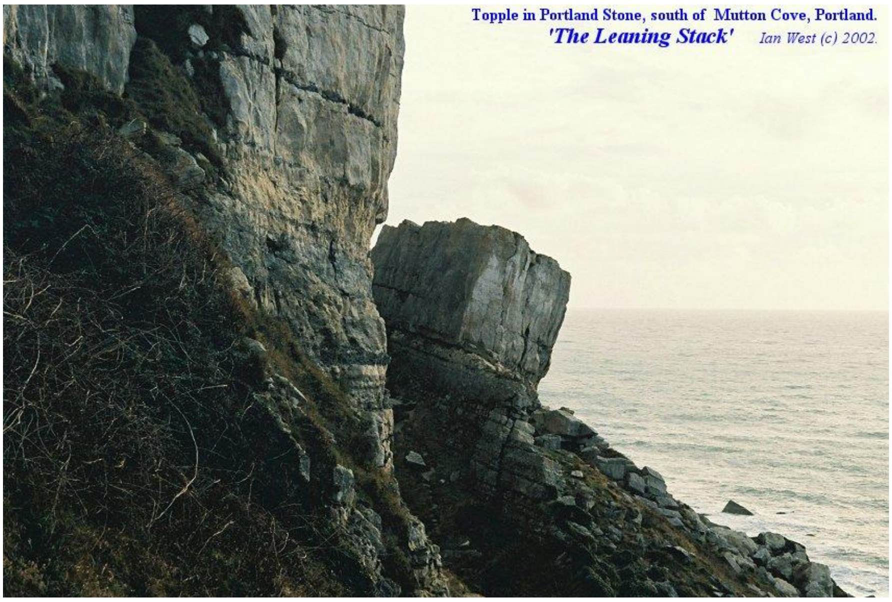


Figure 3.2.2 The Leaning Stack, toppling in Portland Stone, south of Mutton Cove,Portland, photograph by Ian West.

3.2.3 Slides

"The downslope movement of a soil or rock mass on surfaces of rupture or on relatively thin zones of intense shear strain at velocity of extremely slow (less than 0.3 m every 5 years) to moderately fast (1.5m per month) to rapid, is long the slopes ranging from 20 to 40 degrees due to the saturation of the slope leaded by the rainfall or snowmelt, which could be also triggered by earthquake (Highland 2008)."

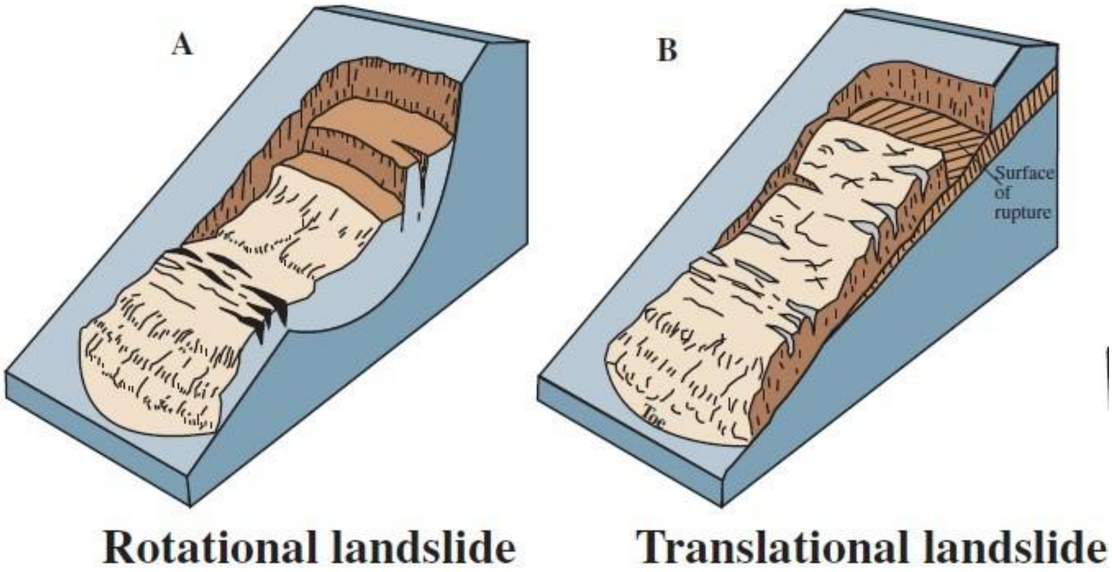


Figure 3.2.3 Two schematics showing the two main types of slides(Highland 2008).

3.2.4 Spreads

“An extension of a cohesive soil or rock mass combined with the general subsidence of the fractured mass of cohesive material into softer underlying material at velocity of slow to moderate and sometimes rapid, resulting from liquefaction or flow of the softer underlying material. The triggering mechanism could be liquefaction of lower weak layer by earthquake shaking, saturation of underlying weaker layer, or plastic deformation of unstable material at depth, or etc. (Highland 2008).”

Figure 3.2.4 Lateral spreads at Hebgen Lake near West Yellowstone. Shaking from the August 18, 1959 magnitude 7.3 Hebgen Lake earthquakes caused liquefaction of sediments beneath the road. Photo: R.B. Colton, USGS.

3.2.5 Flows

"A flow is spatially continuous movement in which the surfaces of shear are short-lived, closely spaced, and usually not preserved. And there is gradation of change from slides to flows, depending on the water content, mobility and evolution of the movement (Highland 2008)." Basically the flow-like slides include debris flow, lahars, debris avalanche, earthflow, slow earthflow (creep) and flows in permafrost.

3.2.6 Complex

In the real cases under study; one case may have a combination of two or more types of principle motion. For example, the Grohovo landslide which occurred in Rječina valley, indicated a complex landslide and evidence of many individual movements could be distinguished. "These are identified as initial (primary) landslides (I), landslides in talus material (II), lateral landslides in soil material (III), reactivated landslides (IV), sliding of separated limestone blocks (V) and rock falls from the limestone cliffs (VI). On the basis of the geological mapping and geophysical surveys, the thickness of the displaced slide mass could be estimated and the position of failure surfaces could be determined (Čedomir Benac 2005)."

3.3 Debris flow

3.3.1 Definition

“In 1910, the definition of debris flow by Stiny in his book Die Muren was one of the first descriptions by “begins with the description of a flood in a mountain torrent, carrying suspended load and transporting quantities of bedload. At a certain limit it has changed into a viscous mass consisting of water, soil, sand, gravel, rocks and wood mixed together, which flows like a lava into the valley” (Jakob and Hungr 2005).”

Figure 3.3.1.1 Debris flow descending Comet Falls on 15 August 2001 (Photo by J.W. Vallance).

For debris flows, in USGS’s definition, it is a form of rapid mass movement in which loose soil, rock and sometimes organic matter combine with water to form a slurry that flows downslope at or over extremely rapid(56 km per hour), which could be deadly and may occur without any warning (Highland 2008).

Velocity is one very important parameter for evaluating the risk level of landslide, especially for debris flow due to the worldwide-spread, long run-off, high hazard. Table of the velocity level following is defined by Cruden and Varnes in 1996.

<table>
<tr><th>Velocity class</th><th>Description</th><th>Velocity (mm/sec)</th><th>Typical velocity</th><th>Typical human response</th></tr>
<tr><td>7</td><td>Extremely rapid</td><td rowspan="7">7→6
$\mathbf{5\times10^{3}}$
6→5
$\mathbf{5\times10^{1}}$
5→4
$\mathbf{5\times10^{-1}}$
4→3
$\mathbf{5\times10^{-3}}$
3→2
$\mathbf{5\times10^{-5}}$
2→1
$\mathbf{5\times10^{-7}}$</td><td rowspan="7">5 m/sec
3 m/min
1.8 m/hr
13 m/month
1.6 m/year
16mm/year</td><td>Nil</td></tr>
<tr><td>6</td><td>Very rapid</td><td>Nil</td></tr>
<tr><td>5</td><td>Rapid</td><td>Evacuation</td></tr>
<tr><td>4</td><td>Moderate</td><td>Evacuation</td></tr>
<tr><td>3</td><td>Slow</td><td>Maintenance</td></tr>
<tr><td>2</td><td>Very slow</td><td>Maintenance</td></tr>
<tr><td>1</td><td>Extremely slow</td><td>Nil</td></tr>
</table>

Table 3.3.1.2 Landslide velocity scale (Jakob and Hungr 2005).

3.3.2 Source materials

“The source materials were divided into two types: debris, a soil containing more than 20% gravel and coarse sizes and earth with less than 20% coarse size (Cruden 1996).”

““Earth” refers to unsorted clayey (plastic) colluviums derived from clays or weathered clay-rich rocks, with a consistency closer to the plastic limit than the liquid limit (Jakob and Hungr 2005). The term “mud” refers to liquid or semi-liquid clayey material (Bates 1984). In 2001, Hungr proposed that the term “mud” be used for soft, remoulded clayey soils whose matrix (sand and finer) is significantly plastic (plasticity index > 5%) and whose liquidity index during motion is greater than 0.5 (Oldrich Hungr 2001).”

““Debris” was defined by Hungr as loose unsorted material of low plasticity such as that produced by mass wasting processes (colluvium), weathering (residual soil), glacier transport (till or ice contact deposits), explosive volcanism (granular pyroclastic deposits), or human activity (e.g., mine spoil) (Jakob and Hungr 2005).”

3.3.3 Types of flow-like landslides

Based on the material components, Hungr proposed the definitions of the different types.

Material	Water content	Special condition	Velocity	Name
Silt, sand, gravel, and debris (talus)	Dry, moist, or saturated	No excess pore-pressure Limited volume	Various	Non-liquefied sand (silt,gravel, debris) flow
Silt, sand, debris, and weak rock	Saturated at rupture surface	Liquefiable material Constant water content	Extremely rapid	Sand (silt, debris, rock) flow slide
Sensitive clay	At or above liquid limit	Liquefaction in situ Constant water content	Extremely rapid	Clay flow slide
Peat	Saturated	Excess pore-pressure	Slow to very rapid	Peat flow
Clay or earth	Near plastic limit	Slow movements Plug flow (sliding)	Less than rapid	Earth flow
Debris	**Saturated**	**Estabilished channel Increased water content**	**Extremely rapid**	**Debris flow**
Mud	At or above	Fine-grained	Greater	Mud flow

	liquid limit	debris flow	than, very rapid	
Debris	Free water present	Flood	Extremely rapid	Debris flood
Debris	Partly or fully saturated	No estabilished channel Relatively shallow, steep source	Extremely rapid	Debri avalanche
Fragmented rock	Various, mainly dry	Intact rock at source Large volume	Extremely rapid	Rock avalanche

Table 3.3.3 Classification of flow type landslides(Jakob and Hungr 2005).

3.3.4 Debris flow path

Typical debris flow path includes three parts: start zone, transport zone, depositional zone. The inclination of start zone ranges from 20 º to 45 º. These may not be sufficient potential energy on flatter slopes to start a failure of granular soil, however the slope steeper than 45 ºusually have too thin soil cover or too discontinuous to be vulnerable to sliding (Jakob and Hungr 2005).

In the middle of the track, the inclination normally decreased as increasing of the runoff till the depositional zone. Erosion and entrainment effect could be observed in this zone with increased depth or widen of the channels. The phenomenon acted by the flows varies differently in cylindrical channels and triangle channels, respectively. For cylindrical, the flowing thickness r_0 is depended on the yield strength of the flow. The three dead regions observed from experiments and field of Bingham fluid shows that the flow in the both sides and bottom is too thin to shear.

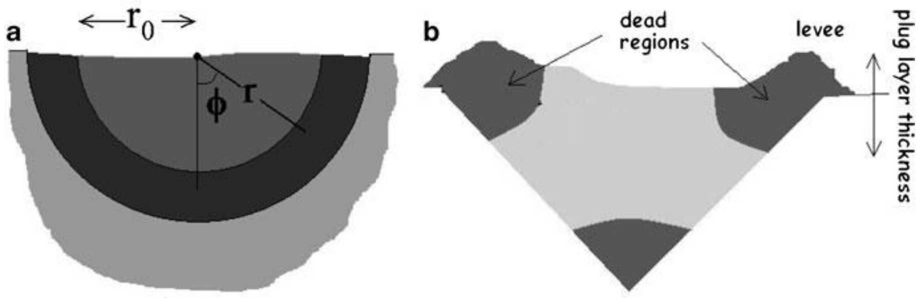


Figure 3.3.4 Bingham fluid flowing in the cylindrical channel and triangle channel, shearing layer in black of cylindrical channel and three dead regions in gray of triangle channel respectively (De Blasio 2011).

Normally, the inclination of deposition zone is gentle, especially compared to the start zone and transport zone. Referred to as a debris fan or colluvial fan, it occurs as a result of a combination of slope reduction and a loss of confinement (Jakob and Hungr 2005). Without the confinement of the channel, the flow would be driven to forward by the movement inertia. In the meanwhile, when the shear strength between flow and open field keep playing the role of friction force slowing down the flow body, the gravity drives the flow into lateral spreading due to the missing of the confinement, instead driving the flow downstream along the slope. The thickness of the flow is becoming thinner and thinner while the internal shear strength increasing. After it exceeds the critical value, the flow would not be able to flow anymore. For the critical angle of the depositional zone, it would be hard to ascertain due to the varied particle size of the flow.

3.3.5 Triggering mechanism

In the worldwide, several mechanisms responsible for triggering debris flows have been verified, such as rainfall, snowmelt, earthquake, landslide, human activity and etc. Rainfall-induced debris flow, however, is the mostly common in Norway. One explanation could be described as follows: due to the intensive precipitation, the pore pressure in the ground keep increasing, thereby introducing the decreasing of the effective strength of the surface cover. Under the driving force under the gravity, the weaken internal effective strength under the critical stress is too weak to keep the material still (De Blasio 2011). Then the failure of the slope occurs. It also could be described as the liquefaction effect.

Though the liquefaction effect lively draw the failure of slopes, it would be hard to explain event two occurred in Sagdalen as mentioned before that no slope failure being observed. The mechanism known as "channel-bed failure" could best fit in this case. The triggering of the debris flow caused by channel-bed failure is due more to the hydrodynamic forces acting on the surface elements of the debris layer than to the landslide failure of a debris layer proposed by Takahashi (Gregoretti and Fontana 2008).

Due to the difference in locations, the grain size, slope angle, terrain, vegetation, availability of source materials and weather characteristics vary, thereby introducing the varied triggering thresholds, which of the rainfall intensity and duration are key factors used to set up the early warning system and evaluate risk levels.

The triggering mechanisms for debris flows due to landslides, snow melt and earthquakes will not being discussed in this paper, while the human activity will be presented in the next chapter.

4 Role of human activities in landslide

4.1 Questionable awareness

It is easier for us to more readily understand that “human” is getting involved in the cases of geohazard when it comes to the “risk”. For “nature hazards” such as floods, earthquakes, landslides and tsunamis, it is always to be more acceptable for us that human society is the “injured party”. However, such a viewpoint needs to be revised when we try to look through the cases occurring in nowadays, which the shadow of the human unwise actions could be reviewed as the triggering causes.

With population expansion tightening the living space of the urban area, people would like to choose to live far in the nature. The demands for electricity, fresh water supply, housing and transportation, have resulted in more and more engineering constructions and in turn have lead to inappropriate behaviors such as slope cutting, deforestation and waste dump. The human needs push the vulnerable circumstance and life safety to the opposite’s sides through those constructions. The symptom has been shown to be persuasive especially in the mega-city. For example, the occurrence of 574 landslides in the region north of Lisbon, about 20% of the total number of landslides were triggered by human activity (slope cutting, artificial fills and river channel diversion) as a consequence of urban development around Lisbon (José Luís Zêzere 1999). To better understand those landslides occurrences, we need to reevaluate our ideas about the role of human activities.

4.2 "Indirectly" of human activity

Compared to intensive precipitation triggering landslides as direct cause, human activities are more inclined to be an "indirect cause". In some case, it appears the source materials are in fact loose waste dumped by people. On 11th July 1994, one exceedingly large debris flow occurred in Xiaoqingling Gold ore area, between Henan Province and Shanxi Province, leading to more than 51 deaths and millions in economics loss, which was triggered by storm (Xu Youning 2009). The debris entrained by the rainfall, mainly coarse and permeable slag particles, was almost exclusively made up of the waste dumped by the local mining company.

Figure 4.2. a) deforestation, taken from www.greeningforward.org b) soapstone dumped in upstream of Sagdalen, some of which being flushed and blocking the drainage channel.

The same situation also took place in another location in China. In Shenfu-Dongsheng Coal field, the largest coal mine in northern of China, more than 14 million m^3 waste from the road construction, mine and building construction were dumped onto the river bank, slope of the mine and the valley (Wang En-long 2003). Based on 64 debris flows recorded during 1989 and 1990, the threshold for triggering one debris flow for this location was estimated at 10mm precipitation in 10 minutes (one year return period rainfalls for the source location), 60 mm precipitation in 24 hours or 20 mm in hour (2 years return period rainfalls). Before the construction of the mine, there was not so frequently debris flow occurring in the location. It clearly suggests that the human activities have aggravated the hazard potential for this area.

Besides the mine waste dump, human causes for landslide include the slope cutting, loading of slope or its crest, drawdown and filling, deforestation, irrigation and lawn watering, artificial vibration such as pile driving, explosions, or other strong ground vibrations, water leakage from utilities and water channel diversion (Highland 2008). Like the Liangshan region, which is located in southwest of China, most landslides are due to unstable slope environment following slope cutting during road construction (Weng Qi-neng 2000). The common factor in all three cases is that human intervention (road construction at Cuyocuyo, deforestation at Calciano, and agrarian change in the Valle dell'Orco) is capable of destroying fragile and temporary equilibrium on slopes and in valleys (Alexander 1992).

4.3 Human contribution to the events

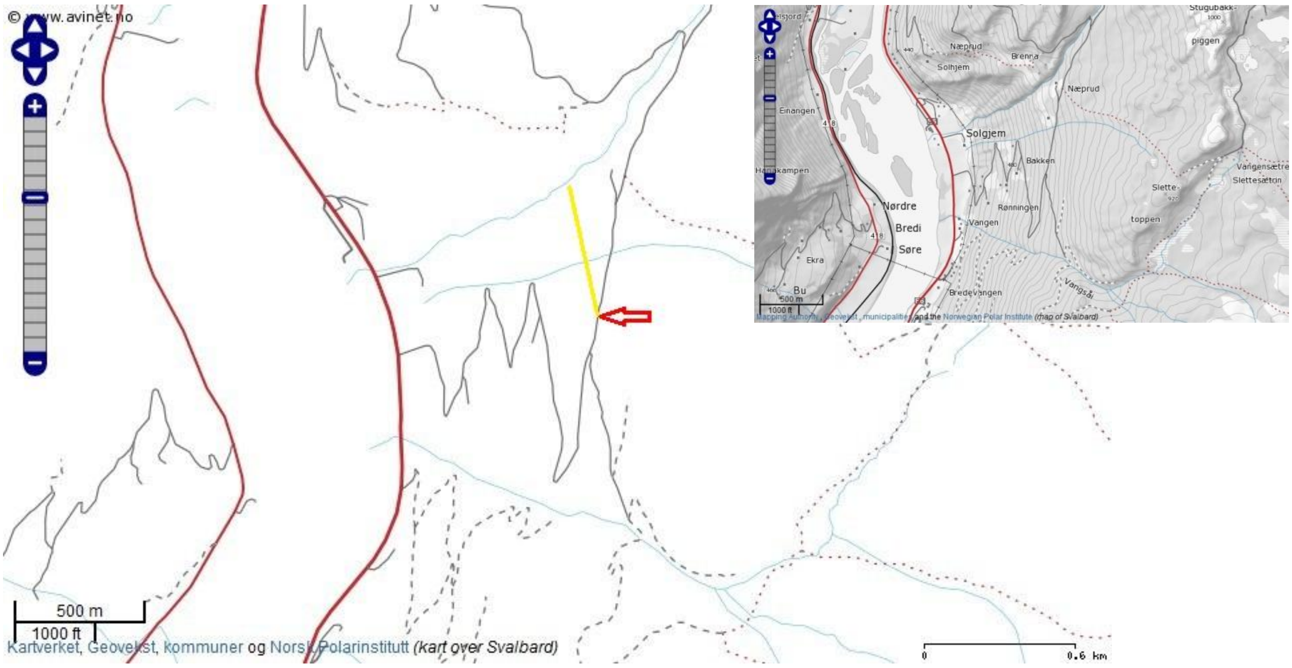


Figure 4.3.1 The road, the black line showing in the map, built in the source location of Solhjem. The yellow line marked in the picture is one old small road unrecorded in www.norgeskart.no, and the joint pointed by the red arrow is the start point of the debris flow in Solhjem. The read lines represent the main high way, taken from www.norgeskart.no.

In Solhjem, the starting point for the debris flow was at exactly the joint of the roads. Due to slope cutting of the main road marked by the black line and the old small road marked by the yellow line, the drainage of the slope had been cut. The surface flow followed the roads direction in the channel instead of following the direction of the elevation difference. And then, the gathering surface flew turn down in the joint through one plastic drainage pipe buried under the road to the old road marked by the yellow line. Walking down the old road, flushed channels could clearly be observed due to the strong erosion, which also indicated us the flow direction. Till the end of the old track where the further failure occurred, the channels became deeper and deeper.

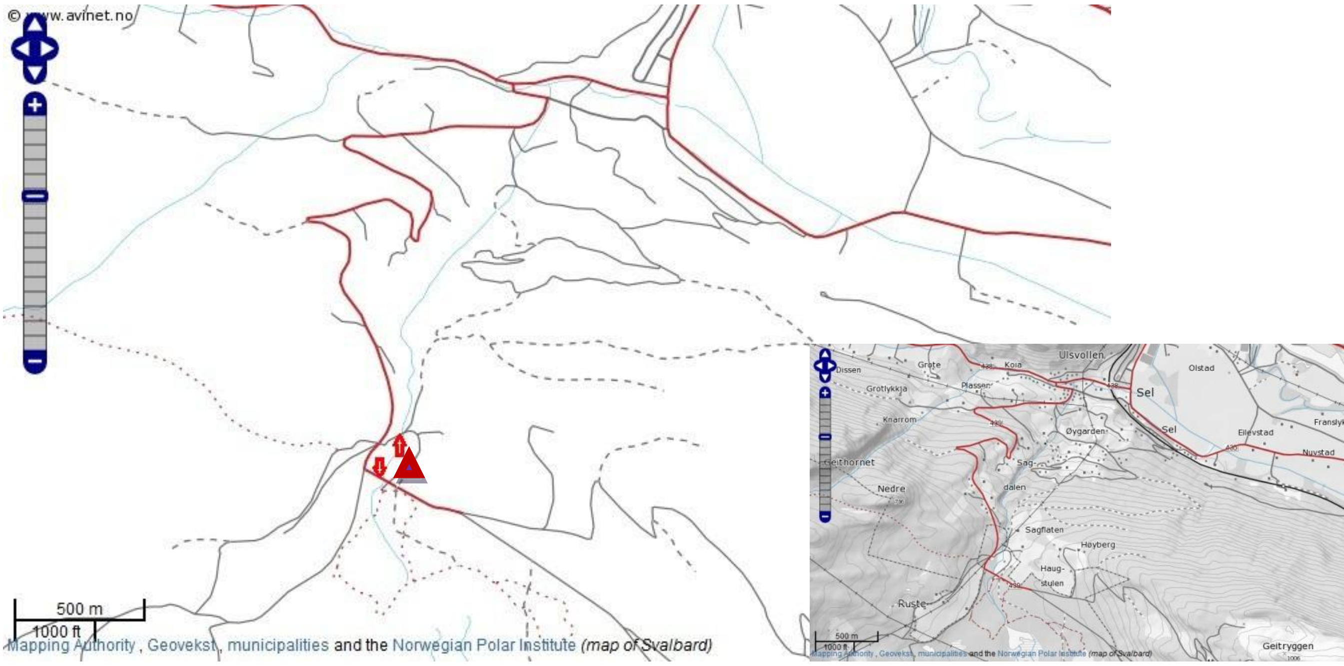


Figure 4.3.2 The two joints of road and river pointed by the red arrow, showed where those two bridge was destroyed. The red triangle showed the position of the dumped soapstone, taken from www.norgeskart.no.

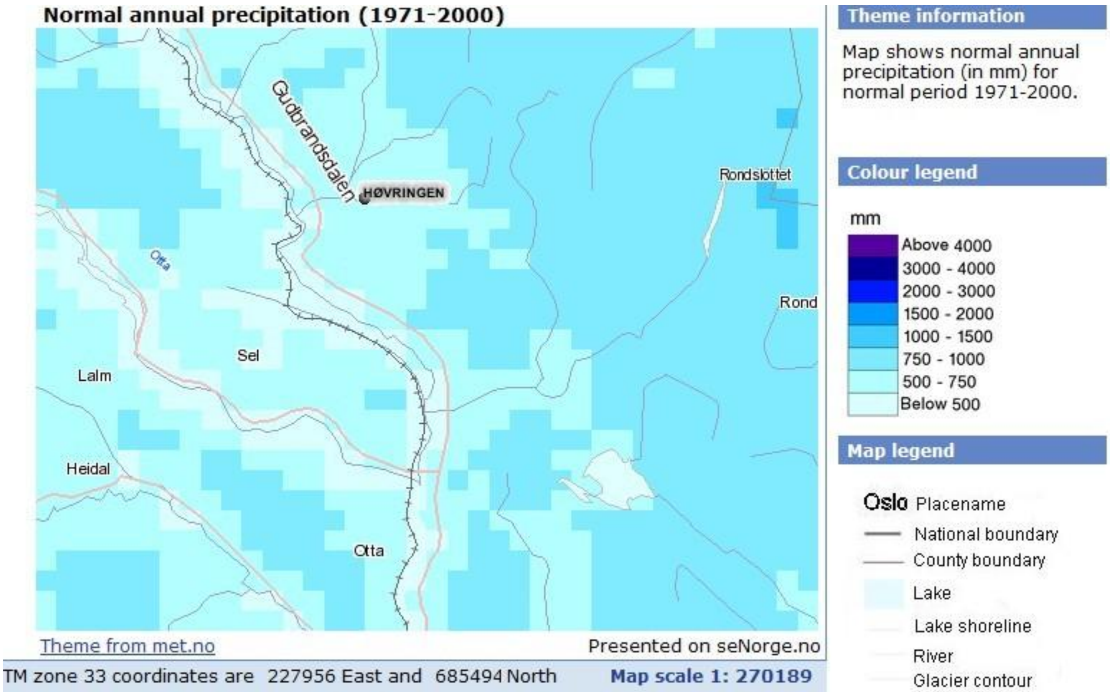
In upstream of Sagdalen, several bridges were built to meet the needs of the transportation. Socket reinforced concrete drainage pipes were buried for the stream going through. The designed pipe could meet the volume of a normal flow situation due to little rainfall. For the first joint, the diameter of the drainage pipe was around 400 mm compared to around 1000 mm diameter of the drainage pipe in the second joint. Though the flow cannot meet half of the pipe mostly of the year, the instantaneous volume could be enlarged several times during the strong precipitation. The flow was capable of carrying rock and depositing in the pipes. Facts worthy to notice were that between the joints, the soapstone waste dumped in the bank offering more source materials and probability to lead to such a situation. Even the diameter of drainage pipe for the second joint reaching 1000mm, completely blocking still managed to be accomplished under such a situation.

Figure 4.3.3 The totally blocked drainage pipe for the second bridge.

4.4 Climate change induced by human impaction

From the worldwide, the climate changing for the half century has been drawn much attention. The interaction between climate change and human impact is one of the most popular subjects found today. The reasons behind this change are still too complicated to comprehend. However, human activities such as deforestation and burning of fossil fuels have been deemed as culprits.

For million years human society has always affected the natural surroundings through all kinds of activities. The low capacity of human production has limited the destruction of the natural ability, maximally leading to changes of the local microclimate. The situation has been changing since the industrial revolution began, influencing much of the world's entire ecosystem. For example, the precipitation and temperature have been affected. As shown below in the forecasting of 2071-2100, the precipitation of Otta would be changed above 20%, based on the modeling study.



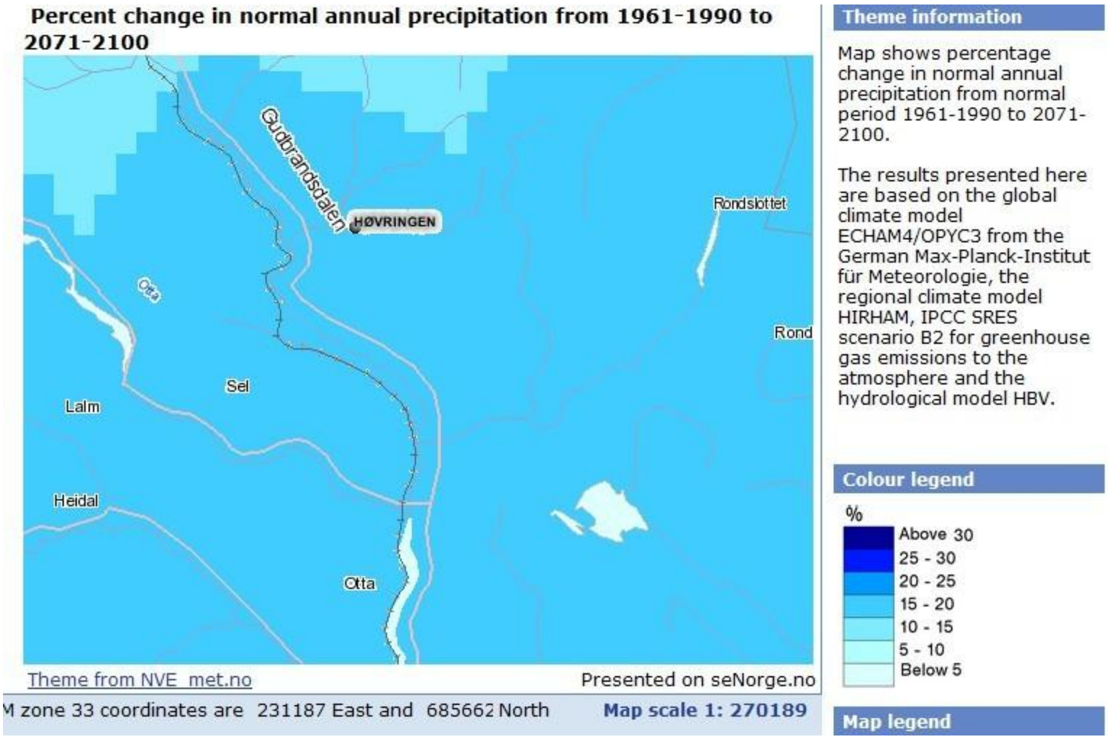
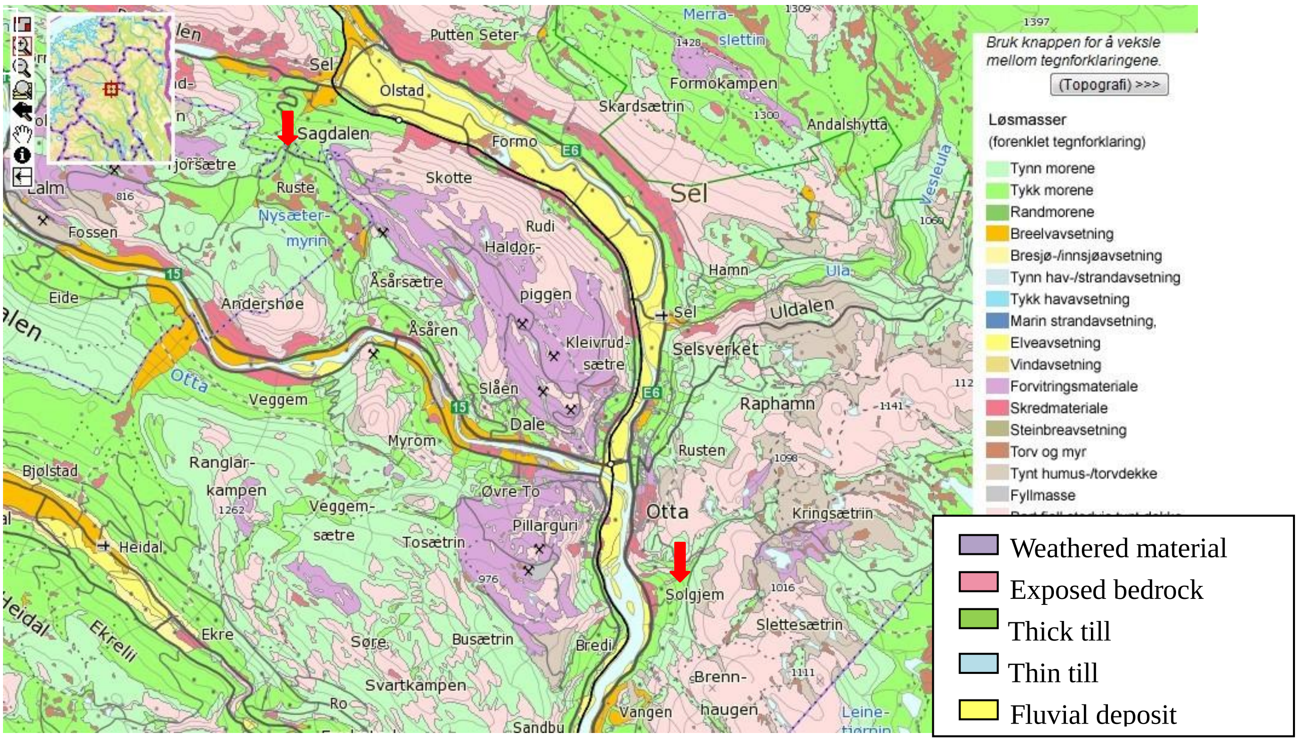


Figure 4.4 The comparison about the precipitation of Otta between 1961-1990 and forecasting of 2071-2100, taken from www.senorge.no.

5 Geological setting and observation

5.1 Geological setting of study area

a)



b)

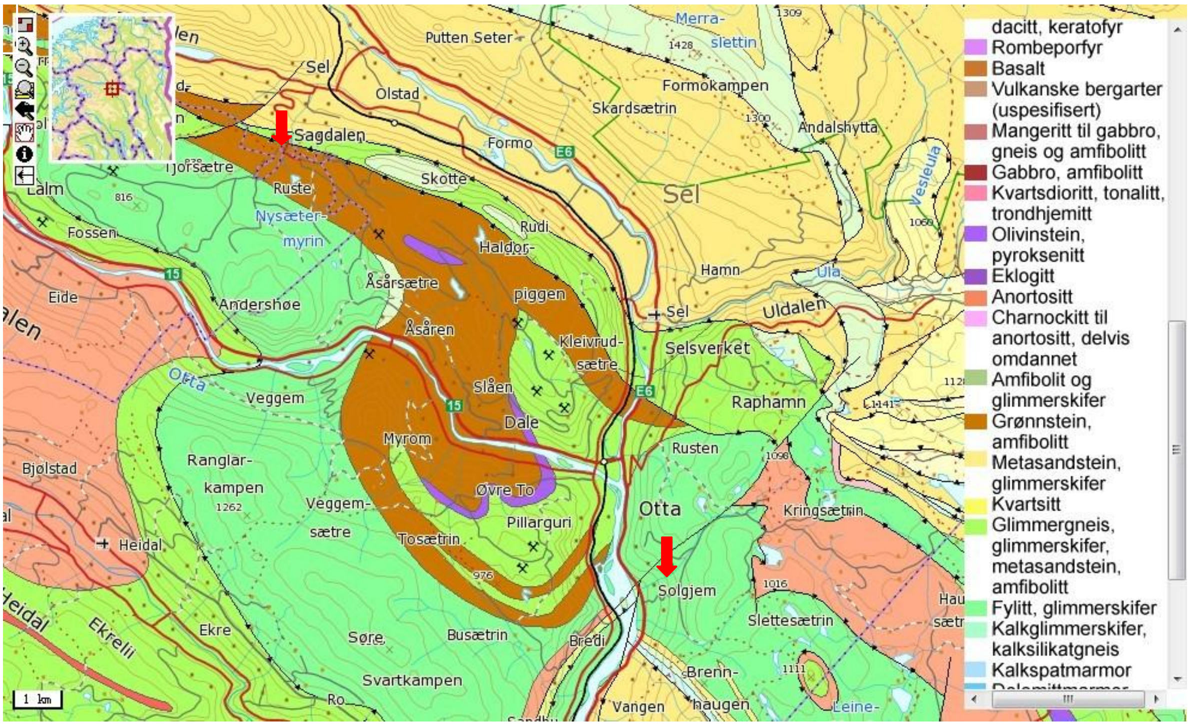


Figure 5.1.1 a). The soil covers of the area, b) the bedrock of the area, taken from www.ngu.no. Two red arrows point to the location. Detailed information of these two locations would be presented under.

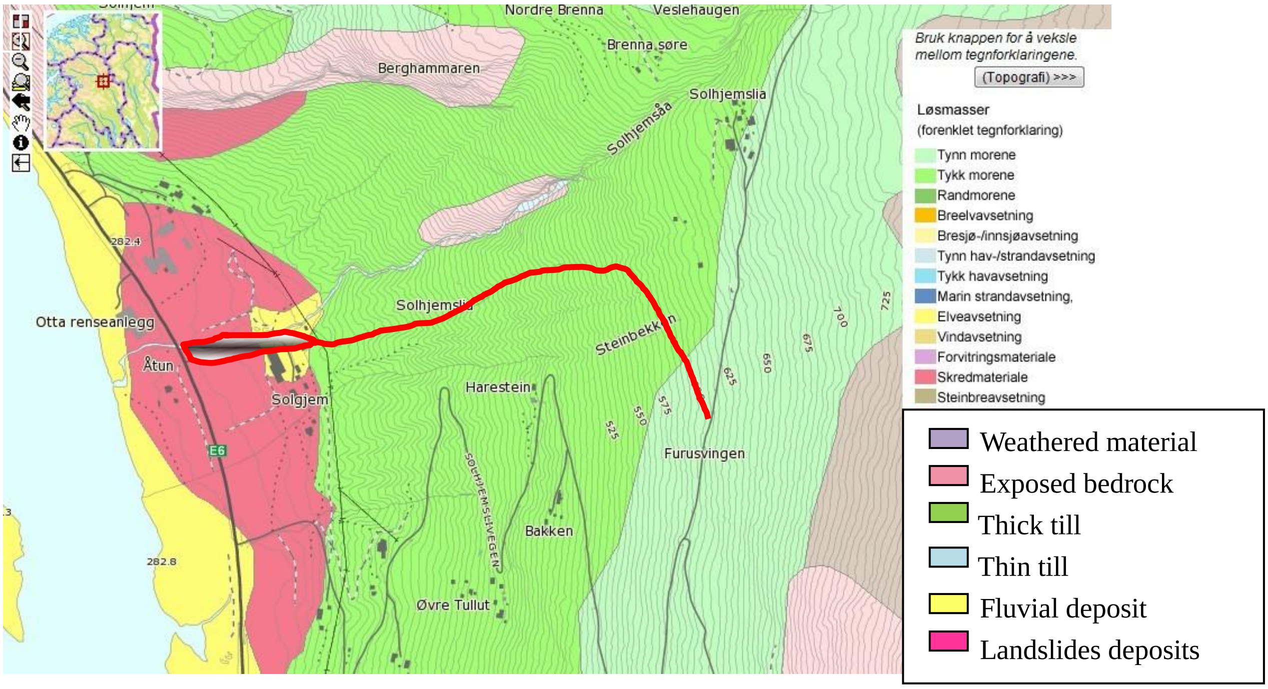
“For the bedrock: the basement rocks, gneiss, in the upper part of Gudbrandsdalen valley formed 1.6 billion years ago. From 600-440 million years Caledonian orogeny produced thrust planes (from the west, three nappies are described) with numerous different metamorphic rocks. In Tertiary uplift, the general erosion contributed to the main terrain and produced the valleys (Bargel 2001).”

“In the last glaciations max (22000-25000 yrs) the ice divide was situated ca east-west across the southern part of Norway resulting in very little, and varying ice movement in the northern Gudbrandsdalen area. Therefore it was very little glacial erosion in this area during the end of the glaciations, and that’s why there is so much over consolidated till in the valley-sides – material that are accessible for debris flows. Because of the E-W ice divide, melt-water was trapped north of this divide during the final deglaciation. This glacial lake had a water level up to c. 655-650 in the Otta area at the most, and the lake was more than 150 km long, occupying many tributary valleys. The drainage happened without much drama (as far as we know), and the ice was gone c. 8500 yrs ago (Bargel 2001)."

In the first figure showing upward, the soil cover in the area presents a complex fragmented strip-sharp distribution with stellated parts located in. Most of the area is taken by the purple or light purple, which means the weathered materials from rock or exposed bedrock respectively. The thick till represented by the green scattered distributes in the whole area. Fluvial deposit represented by yellow could be found in the banks of the river.

For the event in Solhjem, most of the track is located in the area of the thick continuous till (green area), which is allocated and deposited by glacial ice during or at the end of last glaciations, hard-packed, poorly sorted and small often contain anything from clay to stone or boulders. The thickness of the till in the area could vary from 0.5 m to several tens of meters with barely exposed bedrock. Upper part of the track is located to the thin discontinuous till (light blue are). The difference between two areas is about the thickness of the till, while shallow up to 0.5 m and some exposed bedrocks of the upper part.

a)



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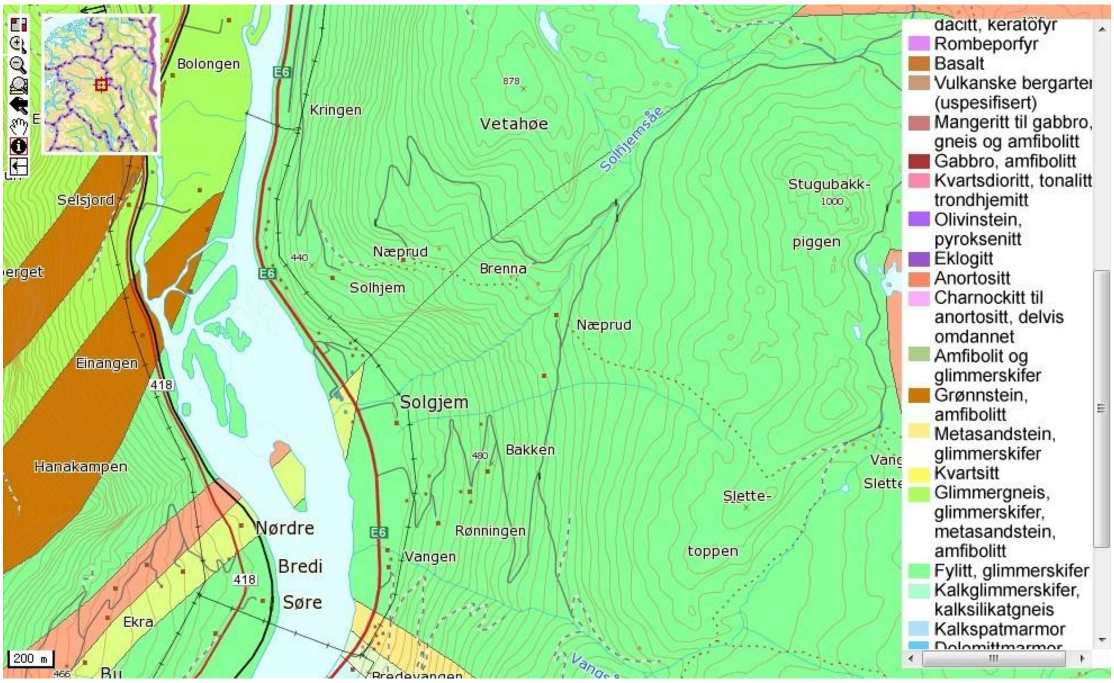


Figure 5.1.2 a) the soil covers of the study area, b) the bedrock of the study area, taken from www.ngu.no.

For the event in Sagdalen, area with the thick till is surrounded the stream valley. Yellow area in the downstream represents that glacial fluvial deposits with tens meters thickness of oblique layers of different grain size varying from fine sand to rocks or boulders. Such information read from the map showing below, the thickness of the soil cover increases with the elevation decreasing and stream flowing from south to north, as pointed by the black arrows. The figure below shows that two bridges being destroyed located in the thick till area.

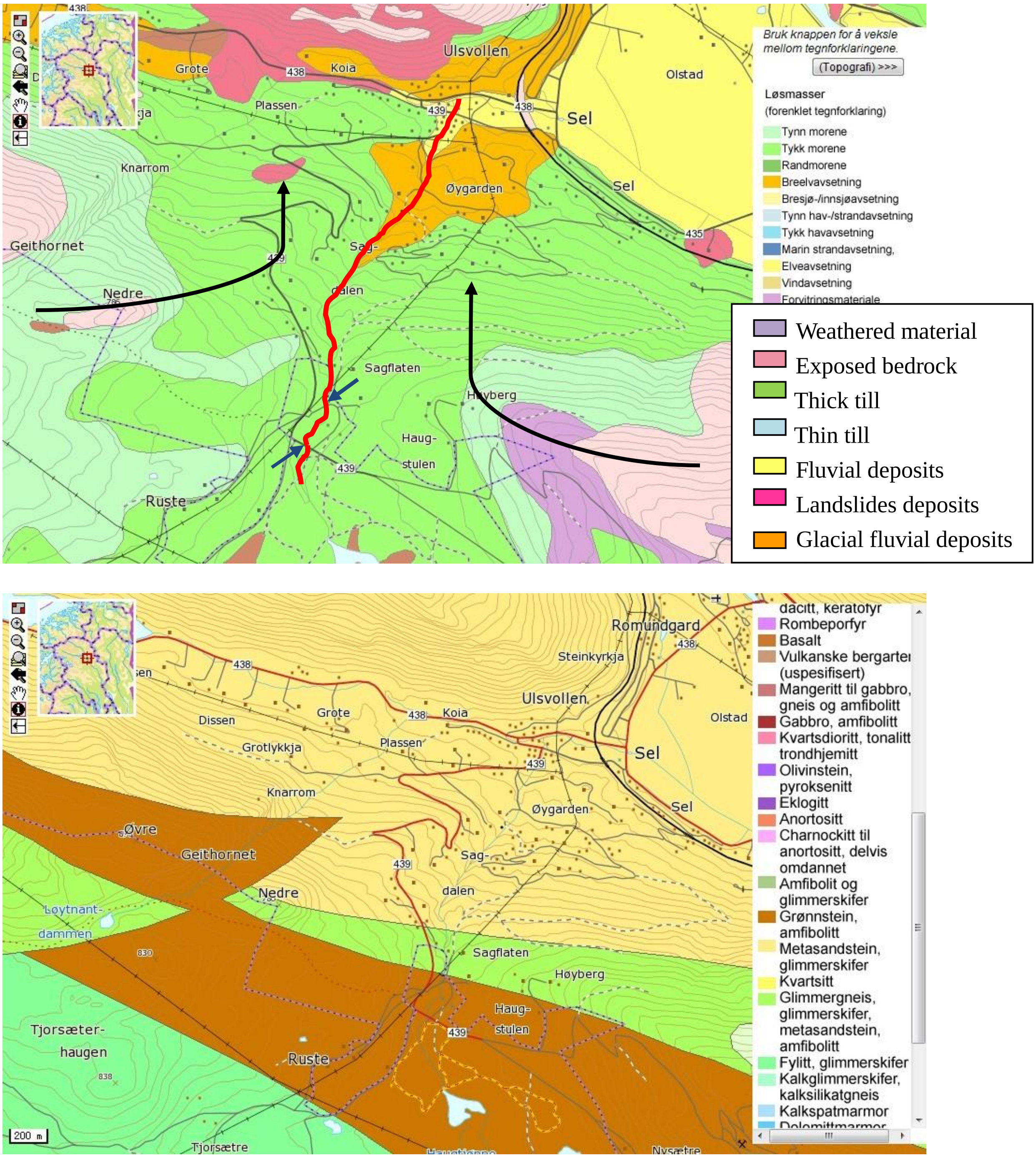
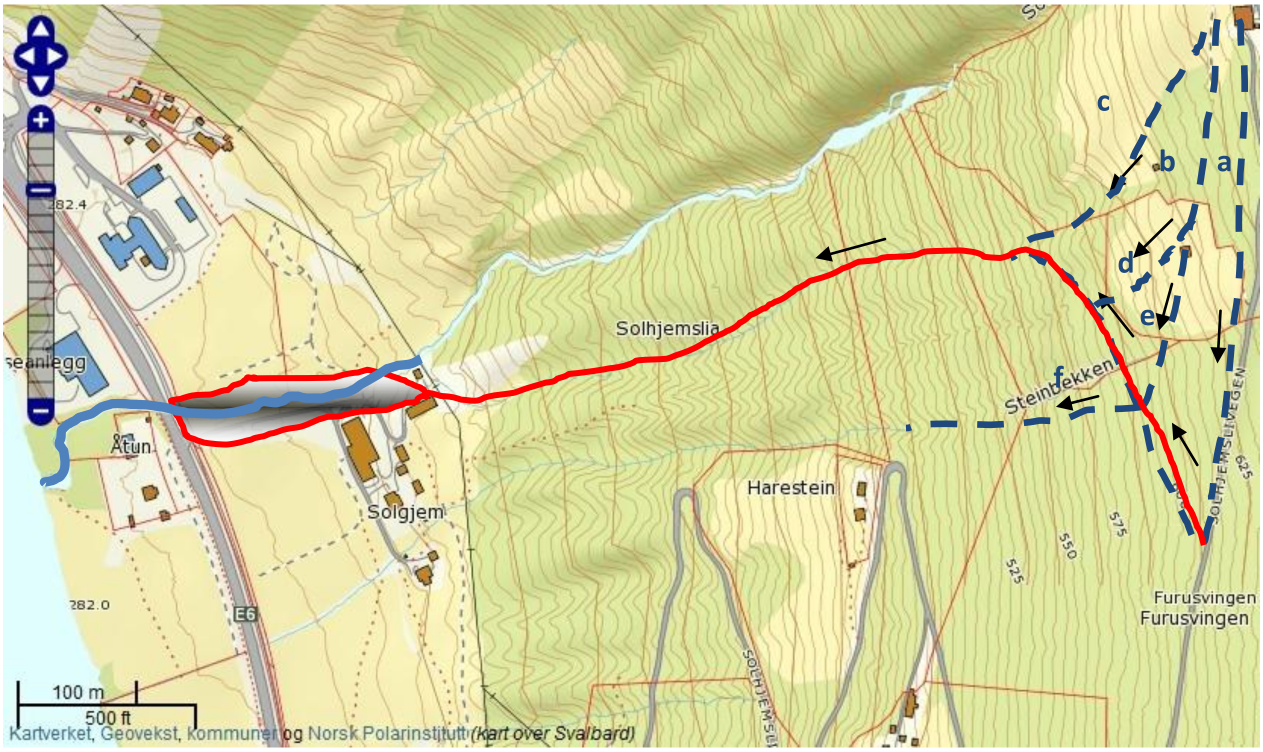


Figure 5.1.3 a) the soil covers of Sagdalen, the arrow showing the increasing trendency of thickness. b) the bedrock of Sagdalen, taken from www.ngu.no.

5.2 Observation in Solhjem

5.2.1 Witness observation

"All these happened just in five to ten minutes; the flow flushed down in the track and broke the walls of barnhouse. Tons of rock was carrying down to the open field. ", described by Hans Roger Solhjem, the owner of the Solhjem Farm. Based on Hans's description, the water gathered from the upper part of the main road, which was divided into three parts. The part a) flew down following the drainage channel of road, and turned left to the old track of the little road through the drainage pipe buried under the main road, while the part b) flew down slope and divided into part d) and part e). Part e) flew over the little road following the down slope, and with part of the flow a) merged into the little stream, part f). In the failure point of the slope, part c) joined other parts by making the shortest cut, leading to the debris flow.



5.2.2 Field Observation

Two trips related to the field work were arranged in April and Jun 2012. Sadly, not too much information got from the April trip due to the track covered by snow. Mostly the field observation of event in Solhjem was basically recorded in 11th June 2012, one year afterwards. The debris deposits have been cleaned up in the lower area. One fence made up of condensed rock and soil was build between the track and the damaged barnhouse. Also the bottom of stream channel in the lower part has been repaired and fixed by tons of huge boulders. During the investigation, the GPS data and comments were made when the author was climbing up. Serial number of the GPS data along the flow developing direction named as follow: Point 105 to Point 112, connecting with Point 140 to Point 114. Detailed map and descriptions could be found in appendix. And pictures were taken while climbing down. The analyses of the field work the key factor for reproducing the scenario and constructing the detailed slope terrain.

Detailed observation recorded in Appendix B combined with the calculation of the GPS data. For the event, start zone, transport path and depositional zone could be clearly observed. The path from Point 105 to Point 112 could be defined as start zone based on the trace. No clearly slope failure occurred in the path, while the track of the flow showed on the road. The erosion depth increased as the declination, from less than 10 cm to more than 20cm in the end of the road. Slightly debris deposit including boulders, till and woods along the road were found. Till the end, the track showed that the flow merged with another stream and turned left, where the failure of the slope observed.

From Point 112, Point 140 to Point 116, it was the transport path.

Along the track, deposits and woods dam-like structures could be observed. The width of the track varied from 1 m to 10 m, while the erosion depth reached to 4-5 meters. The size of the boulders reached to meters. Sediments were totally flushed away in some part of path, such as Point 134 and Point 125. The phenomenon of slope creep showed in some part of slope, indicating the mechanism of liquefaction during the event.

In the depositional zone, the large area took from Point 116 to the main road E6. Brazil nuts effect could be observed on the sediments. The flow broke the barnhouse belonged to the local farmers, but not totally flushed away while the trailer on the yard was. The flow reached to the E6, while the most of debris was depositing to the barn side. The thickness and size of the boulders decreased as the runoff. However, the breadth increased.

5.2.2.1 Start point (Series No. 105) at ASL 648 m

This was the joint point of the main road and old little road. One drainage channel besides the main road located in the left of declination led to the joint point. One plastic pipe was buried under the road for the flow going through. The zone is located in the thin till covers area. Mineral shale was exposed in the bottom of the channels after the plastic pipe. After the joint point, along the little road, shallow channel formed by erosion could be found, showing the flow direction.

Figure 5.2.2.1 Main road of the location and the drainage pipe in the start point. Blue arrows show the declination of the slope and the flow direction in the channels, and mineral shale showing in the second figure in the black circle.

5.2.2.2 Merging point (Series No. 110) at ASL 598m

One track of little stream (part e as mentioned) crossed from the right side of the road and no flow was observed during the investigation. The fine material was flushed away and left the debris including boulders, particles and woods. Some trees were lodging on and blocking the road. Clearly another small track could be found in the left side of the road. Also deepen erosion on the road after the point indicated that the stream flowing in both directions of down-slope and down-road. The phenomenon of deepen erosion track showed that the flow had stronger entrainment capacity after the merging point while the slope angle showed no dramatic changing. It would be reasonable to predict that more flow merged into the direction along the road.

Figure 5.2.2.2.1 The merging stream on the right of the road is in the first picture and the flowing track on the left of the road in the second picture.

Figure 5.2.2.2.2 The channel formed by erosion before (left) and after (right) the merging point.

5.2.2.3 Failure point (Series No. 140) at ASL 572 m

Along the road, track of the channels showed slight left-turning and led to the end. Another small track (part c), found in the right slope, and merged in the position. Huge part of the road was gone with the debris flow. Thorough the walking to here, exposed bedrock and deposits were found.

Figure 5.2.2.3.1 The small track (part c, left) and the slight left turning in the way coming to failure point (right).

5.2.2.4 Exposed bedrock (Series No. 135) at ASL 498 m

Strong erosion phenomenon was showing clearly here. The cover above the bedrock was flushed away. The exposed roots of the standing trees showed the width of the track had been enlarged during the event. Debris could be found in the upper part. As the declination increased, the erosion depth reached over two meters.

Figure 5.2.2.4 Exposed bedrock in the flowing track.

5.2.2.5 Woods "dam" (Series No. 132) at ASL 449 m

Three woods dam-like structures formed by the woods deposits left from debris were found in the track. Point 132 was one of them with narrow width of the track. The lodged trees were crossing the track, due to being stacked by the narrow terrain or bedrock. Huge boulders and plenty of debris deposits were observed in the woods dam. Some of the woods started to decay and weaken the structure, thereby posing one throat about rock falls or debris avalanches. The size of rocks blocked by the dams varied from mm to m.

Figure 5.2.2.5 Woods dams in point 132 (left) and point 128 (right).

5.2.2.6 Creep phenomenon observed

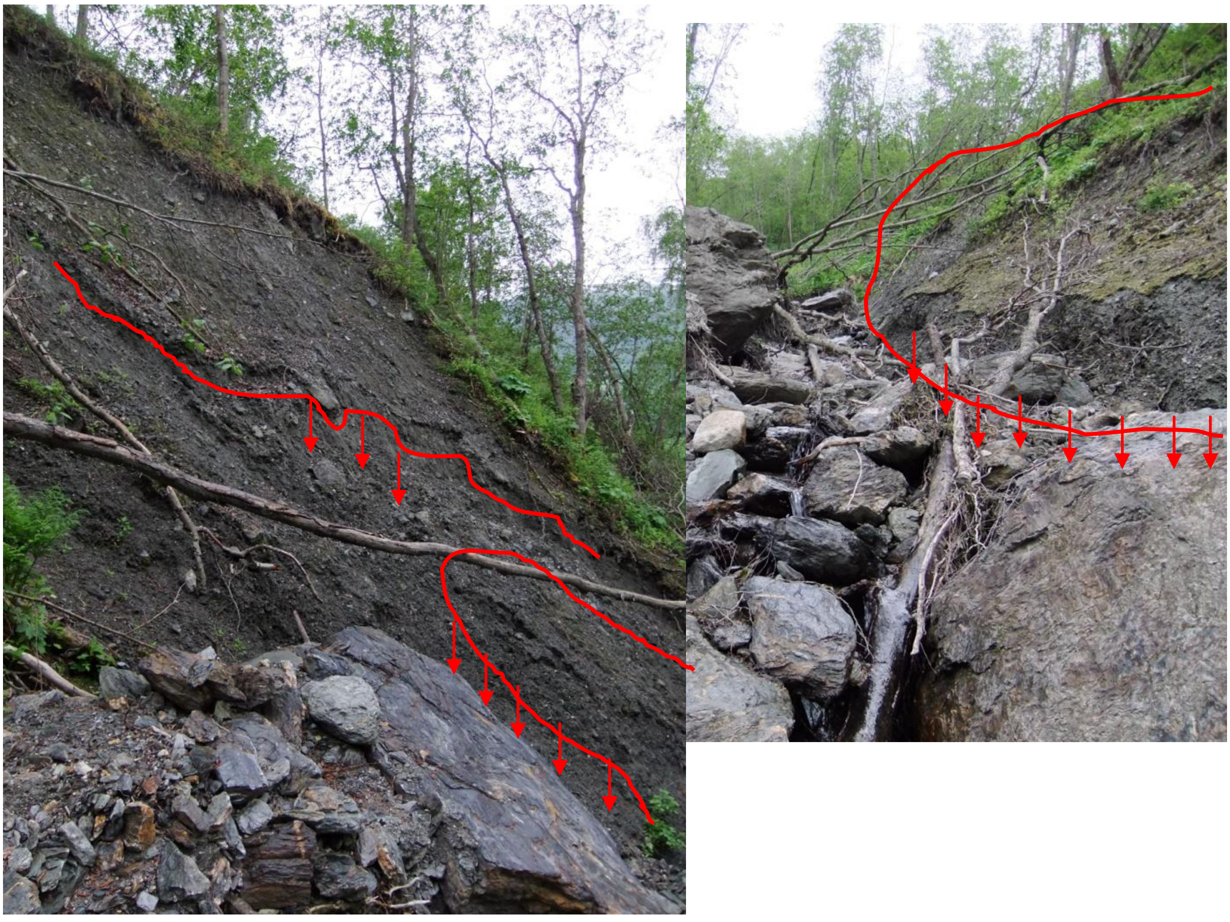


Figure 5.2.2.6 Creep phenomenon observed on the slope along the track.

Along the track, the slopes besides the channel were observed many times of the creep. The maintenance of the surface showed that no clearly flow flushed the slope. The trends of motion showed on the pictures were driven by the gravity while the resistance force was the shear strength. Once the effective shear strength decreased under the critic strength due to the pore pressure of the soil increasing, the balance would be broke.

5.2.2.7 Depositional zone

Figure 5.2.2.8 Depositional zone, a), b), c) taken by Hans Roger, and d) taken by Terje H. B..

Large amount of debris deposited on the open field from the track, spreading and running out till the E6. Most of debris including the woods, particles and boulders did not cross the stream track and lay on the left side of the stream. Part of fine mud and woods were left over on the Point 115, showing in d) and also next to the barnhouse, according to a). We get part of fine materials were left of the flow direction while the particles and boulders were entrainment by the flow to the further right. Huge boulders located on the open field between Point 116 and barnhouse mostly. However, the fine materials and woods entrained by the flow were carrying further than particles till E6. Sadly, the deposits were cleaned up days later, and not left us very good pictures about the further place.

5.2.2.8 Brazil nuts effect

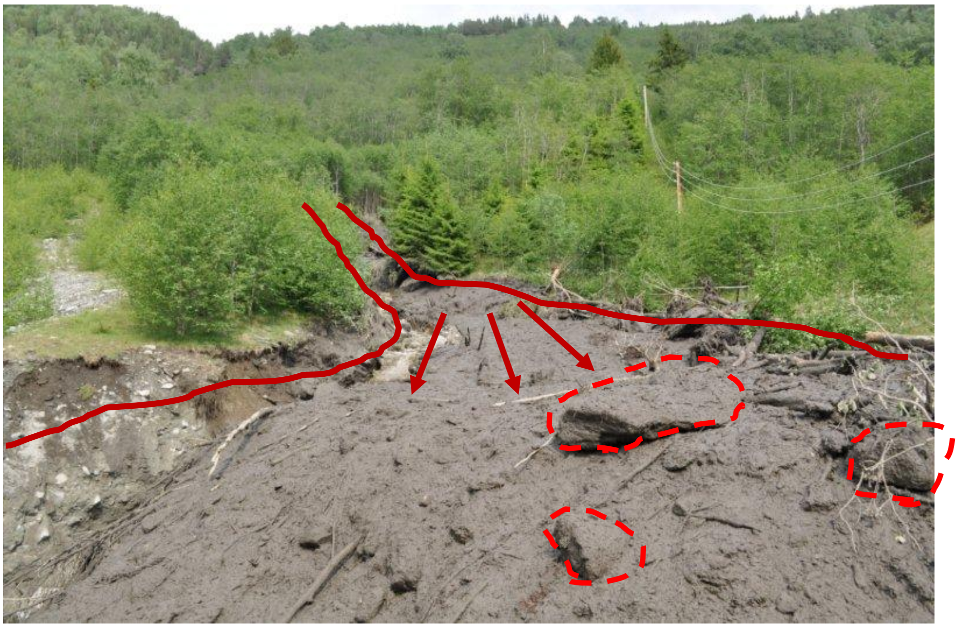


Figure 5.2.2.8 Enlarged depositional fan and huge boulders lay on the fine deposits, taken from Hans Roger.

From the deposits pictures, huge boulders were laying on the fine material and smaller particles. Such the phenomenon has been observed in many events, which named Brazil Nuts Effects. Several explanation including dispersive pressure, kinetic sieving, buoyancy and void filling were presented for such the segregation. When the granular mixture is shaken, voids under the larger boulders, are promptly filled by the small particles, leading to the large grains to rise (De Blasio 2011).

5.3 Observation in Sagdalen

5.3.1 Witness observation

"It happened in the morning, around 8 am-10 am. The rainfall was very heavy. The stream was getting more and more turbulence, level of which kept growing.", described by one inhabitant living next to Point 181, the end of the debris flow of Sagdalen. "The flow did not destroy the whole bridge, just broke the handrail on it. And the flow over the fence and run into the yards."

Figure5.3.1 The pictures in the end of the track, a) showed the damaged bridge; b) showed the flow run over the yards of the locals; c) showed the stream level at 10.30am in 10th June 2011. b) and c) taken from NVE.

5.3.2 Field Observation

The detailed notes made in 13th June 2012 combined with GPS data calculation attach in Appendix C. Serial number along the flow direction named as order: Point 141, Point 142, to Point 181. Detailed map and descriptions could be found in appendix. Pictures and GPS data were gathered during the field investigation. The channel of the stream has already been cleaned up and readjusted with boulders and flat rocks. And one round pool with diameter above 10 m has been built in the position of Point 178, the function of which is for lowering the flow velocity, thereby settling down the debris entrained by the flow. As we know, when the flow volume is fixed, the velocity is inversely proportional to the fluid cross-section area. Enlarging the fluid cross-section would lead to the decreasing of velocity.

Figure 5.3.2 a) the readjusted channel, b) the built pool for risk mitigation.

The whole track of the debris flow run off about 1270 m with average slope 12º, compared to part of the track's angles over 40º. The total height drop was 275 m. Cliffs and water falls were observed. However, the terrains of two damage bridges (Point 143 and Point 153) were not located in the huge declination. The slope angle of the first damaged bridge even showed negative to the flow direction. In other words, gravity was the friction force instead of driving force during the path. The unnatural conflict between the gentle angles and the flow powerful enough to destroy two bridges poses question about the mechanism.

The path from Point 141 to Point 153 located in the catchment area over 12 km^2, where the surrounding area was like a lake. The flat field was exactly in the bottom of the "lake". The surface cover of the area located in the bottom of the "lake" was saturated, part of which was observed accumulation of water. The distance of the path was about 236 m long with 24 m height drop. The average slope angle of the path was no more than 6 °. During the path, four bridges were distributed over the stream. Two of them, which were with drainage pipes, were destroyed. The flushed concrete pipes and debris were not flushed too far away.

Along the track, the declination after the second destroyed bridge increased both in the channel and surround terrain. The channel was located in more like tortuous valley. Several small waterfalls were located in the track with huge elevation drop. Parts of the path was so steep that impossible to climb the slope next to the track. That is the reason there is one gathering gap in the GPS data. Debris deposits, including cm size boulders and woods, could be observed in the gentle paths and turning points. Huge boulders of m size were not carried too far away from the failure points as the small particles and woods did. Sign of slopes failure along the path had been observed more than once, indicating that more loose material joined in the debris flow during the event.

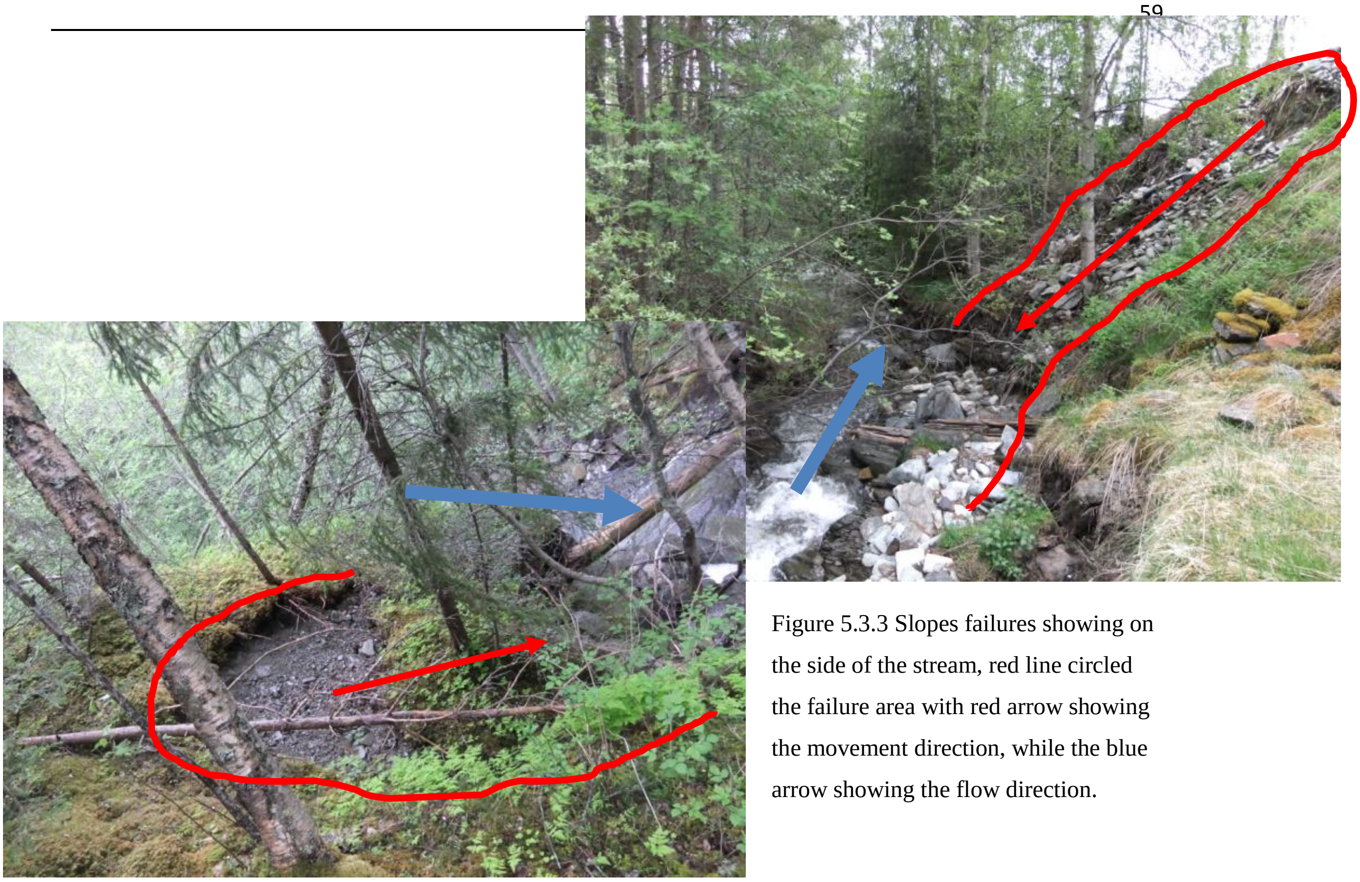


Figure 5.3.3 Slopes failures showing on the side of the stream, red line circled the failure area with red arrow showing the movement direction, while the blue arrow showing the flow direction.

More debris showing in the lower part, mostly of debris was woods, but not so clearly erosion and entrainment phenomenon showed in the track. Several bridges were damaged and repaired, not like the two in the upper part being totally destroyed. The terrain of the track got reducing in gradient, and the width got narrowing down. The readjusted channel started from Point 174.

5.3.2.1 The first destroyed bridge (repaired) in Point 141

Figure5.3.2.1 a) the repaired bridge; b) the open field after the failure point, circled by the red dash line showed the flushed concrete pipes. Area circled by the red solid line in a) and b) showed the debris deposits behind the bridge. c)

The bridge was destroyed during the event. The concrete drainage pipes were flushed away and deposited inside of the 15 m away the failure point. Part of the debris deposited in the right side of the channel, while some of deposits lay on the left. Size of the boulders varied, while the biggest reached 1 m. The new fixed drainage pipes were made of the iron pipe over 1 m diameter instead of concrete pipes. Even though the road just got fixed, boulders already existed in the pipes.

Figure 5.3.2.2 The flushed drainage concrete pipes.

Four of them were flushed and deposited in the left side of the stream, while one taken away by the flow to the slope. One deposited in Point 145 was the farthest, and debris could be seen in one side of the pipe.

The largest boulder found in Point 147, size over 1.2 m length. With another boulder over 1 m size made up one dam-like structure and narrowed down the channel to 1-2 m wide. Another was 4-5 m away from these two boulders.

Figure 5.3.2.3 The three boulders found in the channel, the largest located in the middle.

5.3.2.2 Dumped loose waste

Figure 5.3.2.4 A large amount of waste dumped in Point 150, soap stone on the right bank. The blue arrow showed the flow direction, and the red arrows showed the loose boulders movement direction.

Bunch of loose material were dumped this position, fine loose materials on the left while soap stone on the right side. The large amount of soap stone were carried from some deserted factory, which was hard to find the exactly source. In the end of the slope we could find the sign of the boulders falling from the slope into the channel. The size and the type of the boulders were similar between the channel and the slopes.

Slope failure could be found in the end of the waste dump location. Due to the surface cover being flushed, we could clearly see the slope was made of by boulders and gypsum-like material, which was not natural soil at all. And no deposits showed in the channel, indicating that being entrained away by the flow.

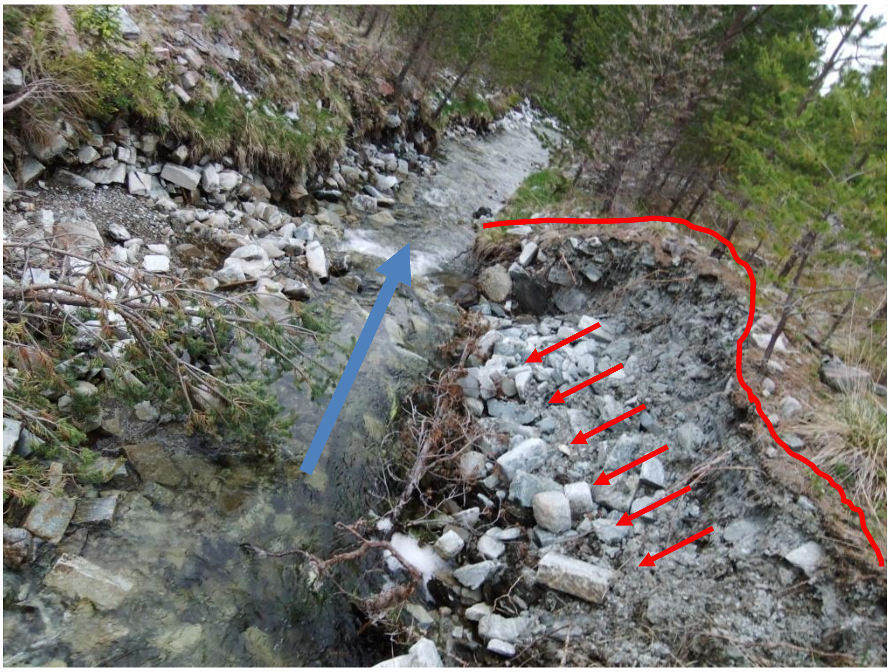


Figure 5.3.2.5 The failure slope in the end of the dumped waste, the blue arrow showed the flow direction.

5.3.2.3 The second destroyed bridges in Point 153

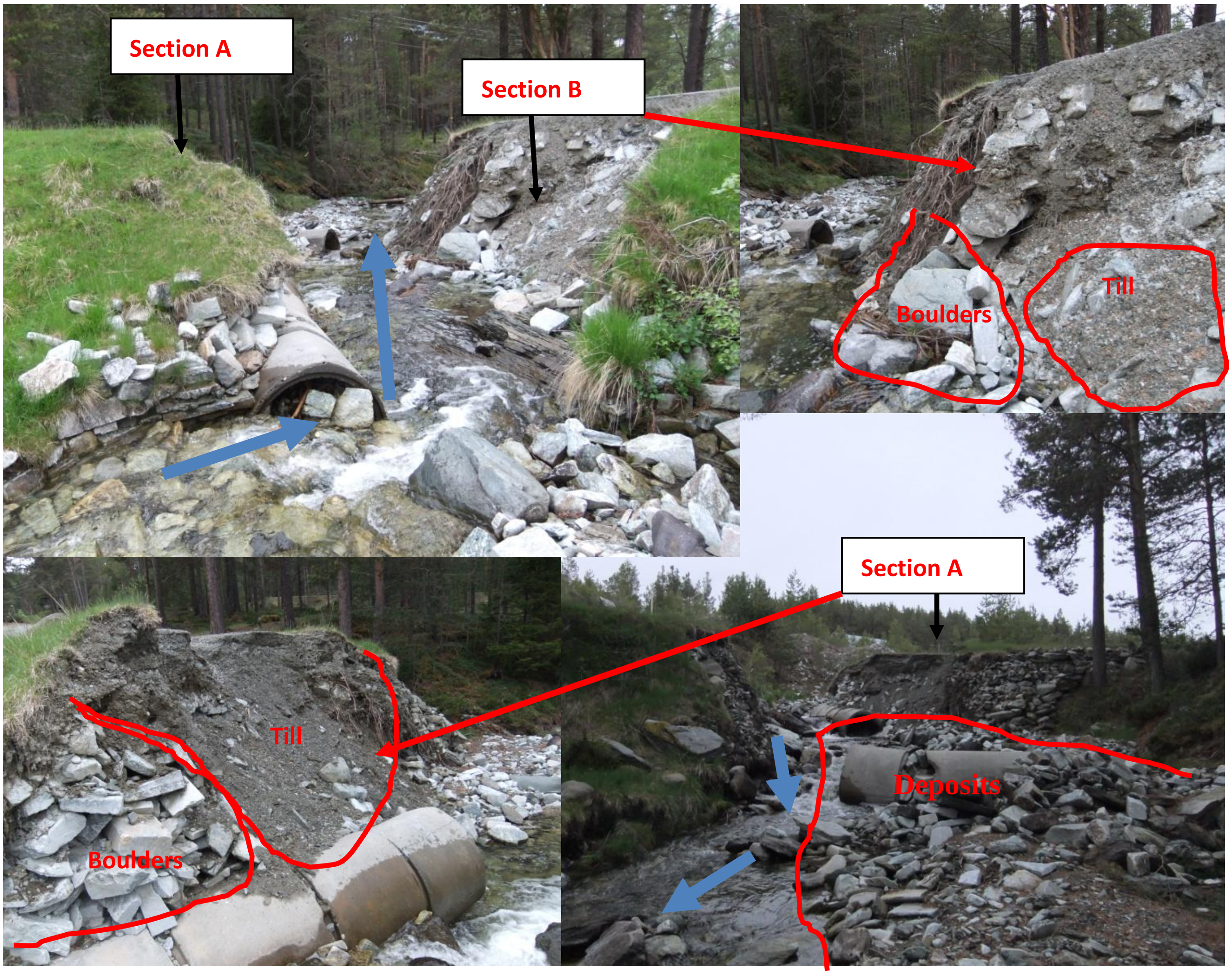


Figure 5.3.2.6 The destroyed bridge in Point 153.

The width of the failure zone was about 5 m between Section A and Section B, while the distance of the diagonal was over 10 m. And the height of the break section was over 2 m. Taking the width of the road into account, which was about 3 m; we could basically estimate the volume of destroyed zone was at least 30 m^3. From the trapezoidal broke section, we could get the materials made of the bridge was extremely loose till and boulders.

Eight concrete socket drainage pipes were found in the location.

Five of them were basically left in the same place as before, while two pipes were flushed four or five meters away from the original location, and deposited in the circled zone in up figure with a large amount of boulders. Where worthy to mention is that all seven tubes have already filled with boulders. The rest one was flushed over 10 m away, closing to the turning of the stream.

Figure 5.3.2.7 a) the front side of the five tubes; b) the back side of the five tubes; c) the middle of the two tubes being flushed away 4-5m away; d) the furthest tube being flushed away.

As we saw in the above figure, the tubes were full with boulders inside, indicating that barely flow could get through from the drainage pipes. Two major depositional zones were found in the channel before the turning point of the stream, Point 159. Lots of the debris were depositing in the left side channel of the flowing direction, gentle zone from Point 154 to Point 158 with 1.7 °declination. The area was about 3 m×63m. Another smaller deposit zone found lower part between Point 157 to Point 18. The size of the boulders varied, however, no more than 1 m except the concrete tubes, which was similar to the size of the boulders in dumped waste. Erosion reaching 40 cm depth could be found in the both sides of the zones' boundary.

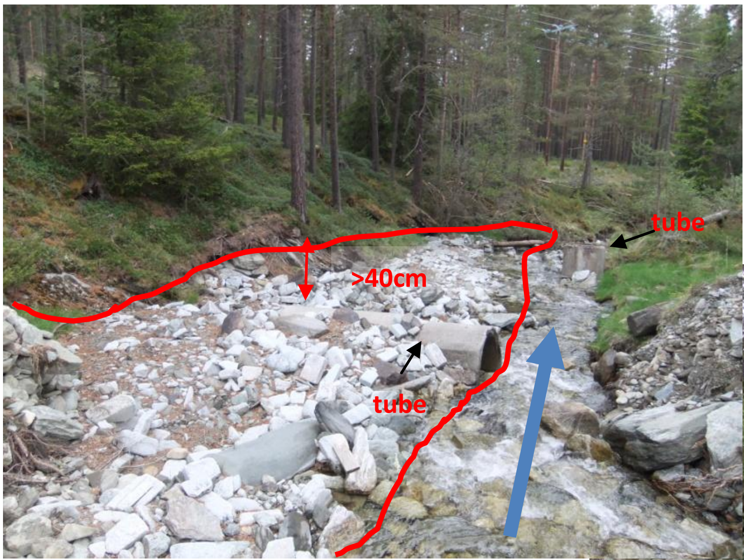


Figure 5.3.2.8 a) depositional zone on left; b) depositional zone on right.

5.3.2.4 Debris deposits along the track

Figure 5.3.2 Debris deposit along the track.

As we mentioned, the terrain of the channel was very changeable, the gradient of which varied from 0 °to 31 °. Part of the valley could even be vertical cliff. Therefore, flow potential diversified. Debris could be found in many gentle areas, or blocked by the woods dam. Due to the trees lodging in the channel, unstable structures formed dam-like around the woods. Undoubtedly such a structure would failure and gain more source materials for the next event.

6 Results and discussion

6.1 Slope characteristics

For the event in Solhjem, the whole runout distance was about 750m, with 366m drop in the elevation. The dip of whole movement was heading from southeast to northwest along the road in the beginning, and then it turned to left, from east to west flowing in the track of the stream. Typical development phases of the debris were identified in such a typical debris flow event. Detailed parameters are showed below table.

Debris flow in Solhjem	Start zone From Point 105 to Point 112	Slope angle	24.3^{o}
		Distance	157.66 m
		Height drop	71 m
		Maximum width	2 m
		Maximum erosion depth	0.2 m
	Transport zone From Point 112 to Point 116	Slope angle	36.8^{o}
		Distance	349.84 m
		Height drop	262 m
		Maximum width	10 m
		Maximum erosion depth	4-5 m
	Depositional zone From Point 116 till main road E6	Slope angle	7.7^{o}
		Distance	242.5 m
		Height drop	32.6 m
		Deposition area	10000 m^2
		Maximum deposit depth	2 m

Table 6.1.1 The morphometric parameters of Solhjem event, detailed information seen from Appendix B.

It is clear that the topography showed by the table is the typical potential terrain for debris flow. The angle of start zone is about 24.3 º, while 36.8º's transport path. The deepest erosion occurred in the area below of the middle in transport path, around Point 129, reflecting the combination of entrainment capacity of the flow and cover's thickness. In upper part, exposed bedrocks were found due to the strong entrainment and thin cover.

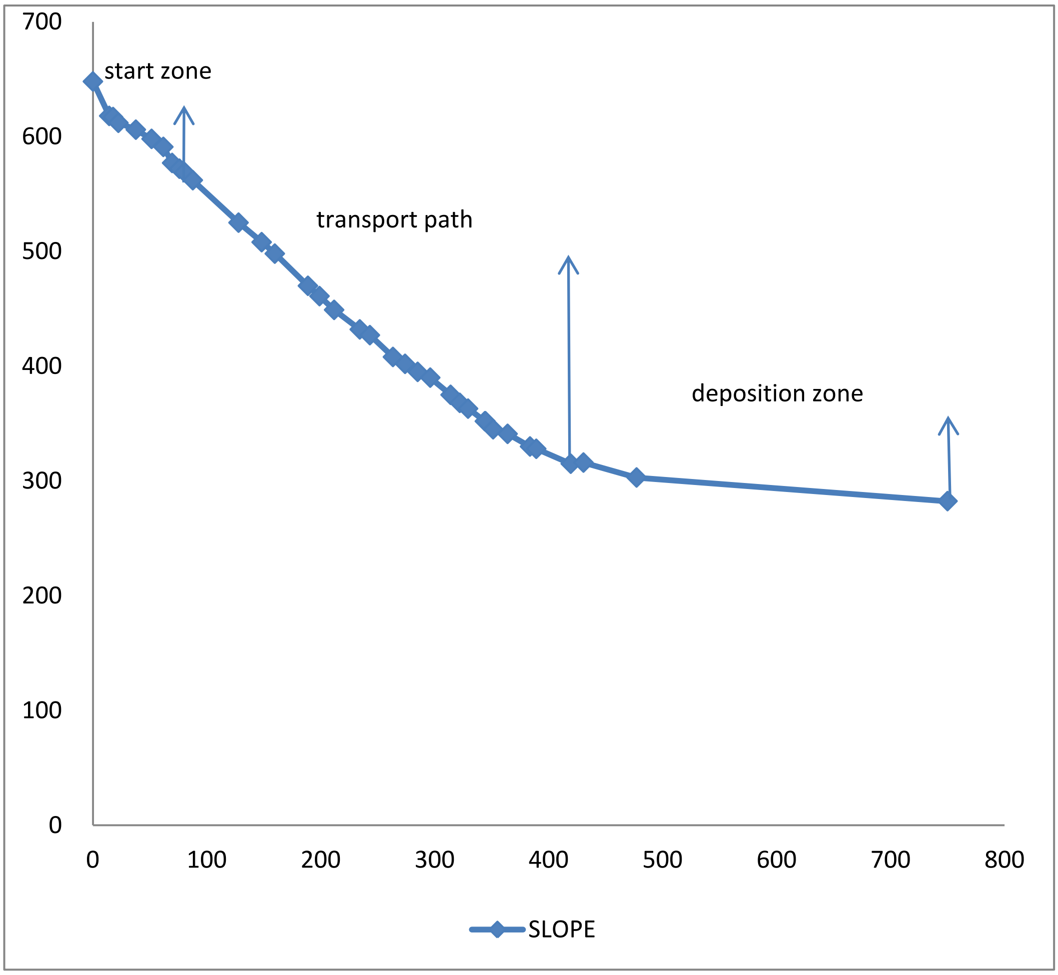


Figure 6.1.2 Simple model of the slope cross section in Solhjem, horizontal axis meaning the distance, and the vertical meaning the ASL.

For the event of Sagdalen, it followed the original channel of the stream, runout of which was about 1263 m, with 275 m height drop. The detailed information about the characteristic of the channel was presented in the table below. The abnormal about this event was topography of the start zone. As mentioned, the gravity in some part was the friction force instead of driving force due to the negative slope angle along the flowing direction.

Debris flow In Sagdalen	Start zone From Point 141 to Point 158	Slope angle	5 º
		Distance	299.38 m
		Height drop	26 m
	Transport path From Point 158 to Point 174	Slope angle	15.3 º
		Distance	712.83 m
		Height drop	195 m
	Deposit path From Point 174 to Point 181	Slope angle	12 º
		Distance	250.79 m
		Height drop	54 m

Table 6.1.3 The morphometric parameters of Sagdalen event, detailed information seen from Appendix C.

For the terrain of Sagdalen, it is hard to say this area has the potential to trigger one debris flow due to the gentle declination as 12 º. And two destroyed bridges were located in the area of the start zone, where was basically flat area showing through the figure below. However, through the map study of surrounding circumstance, we found out the area was located in the bottom of the catchment area. The gathered surface flow from about 12 km^2 area would merge into the stream. Clarifying the topography of the source location would be especially helpful for us to reveal the mechanism of the event’s formation.

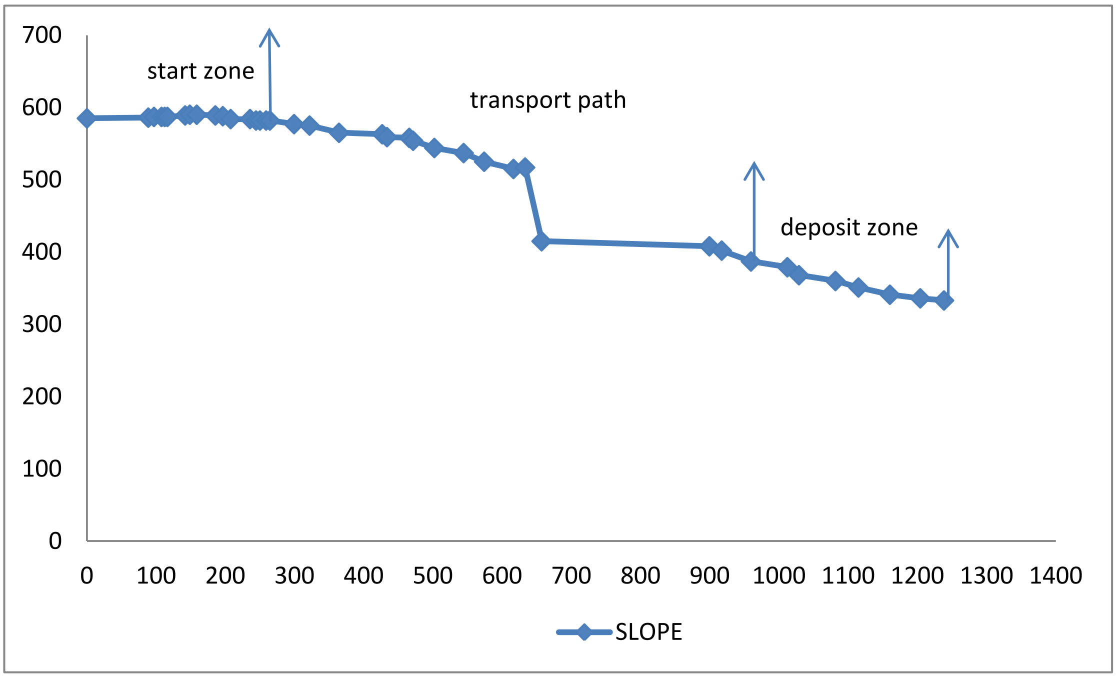


Figure 6.1.4 Simple model of the slope cross section in Sagdalen, the horizontal axis meaning the distance and the vertical meaning the ASL.

6.2 Triggering scenarios

6.2.1 Precipitation

As showing below, it was one rainy week for such one relatively dry location with annual precipitation varied from a minimum of 303 mm/y to a maximum of 478 mm/y during the period 1971-1994 (Melchiorre and Frattini 2011). The total precipitation of the whole week recorded by the station Høvringen was about 106 mm, compared average monthly rainfall above 50mm during June, July and August (Melchiorre and Frattini 2011). From the figures showed below, weekly rainfall amount map a) and daily rainfall amount map b) indicated that correlation between the abnormal rainfall distribution and the debris flow's location was not the coincidence. Precipitation of mostly of the region during 6th June to 13th June was over 100 mm, while part of area exceeding 150 mm.

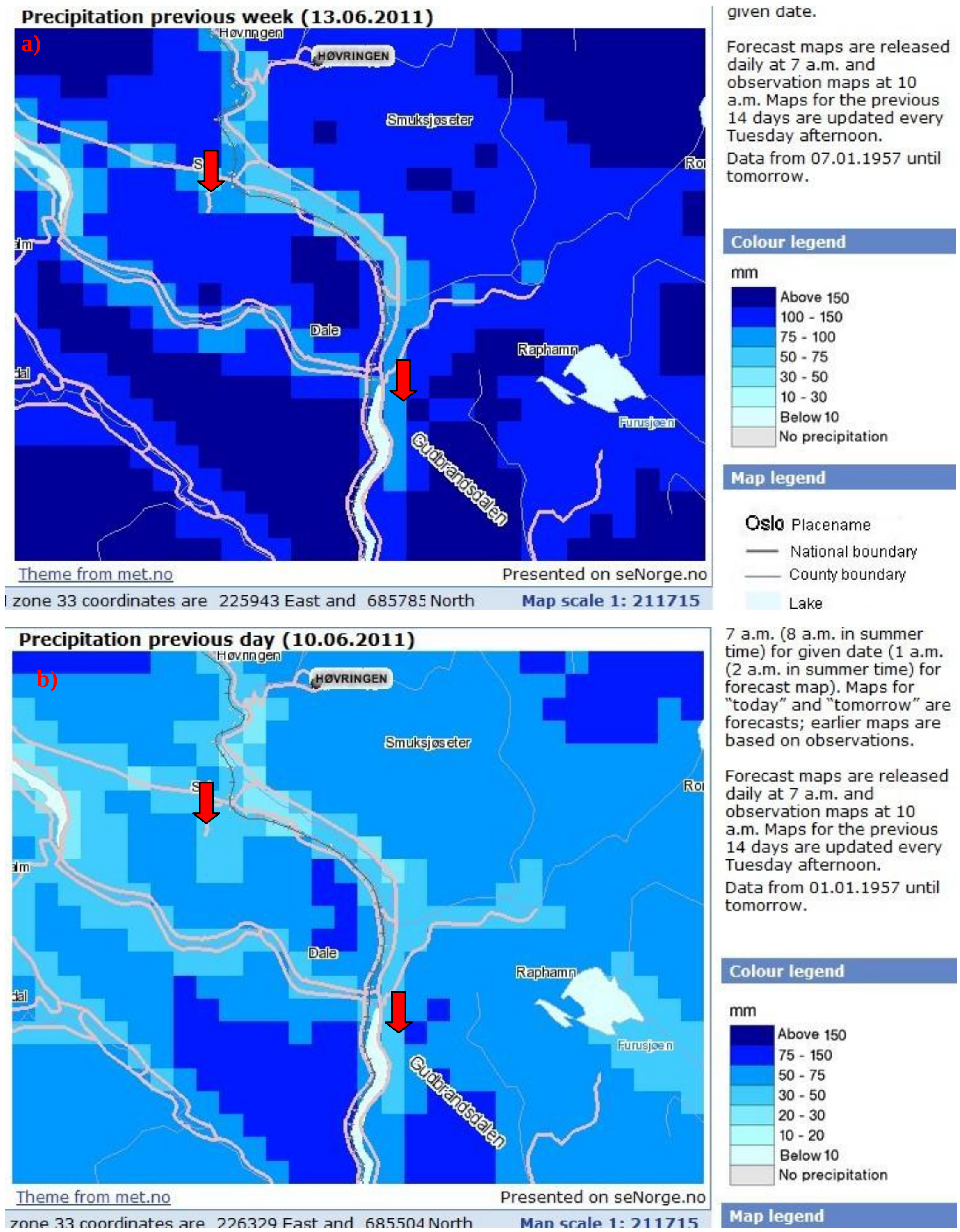


Figure 6.2.1.1 a) amount weekly precipitation till 13th June 2011; b) amount daily precipitation at 10th June 2011.

The station Høvringen between the two events recorded the whole day's precipitation was about 50.4 mm at 10th June, while Sjoa , the one closer to event in Solhjem, was about 59.5 mm. The intensive rainfall came after three days lasting rainfall.

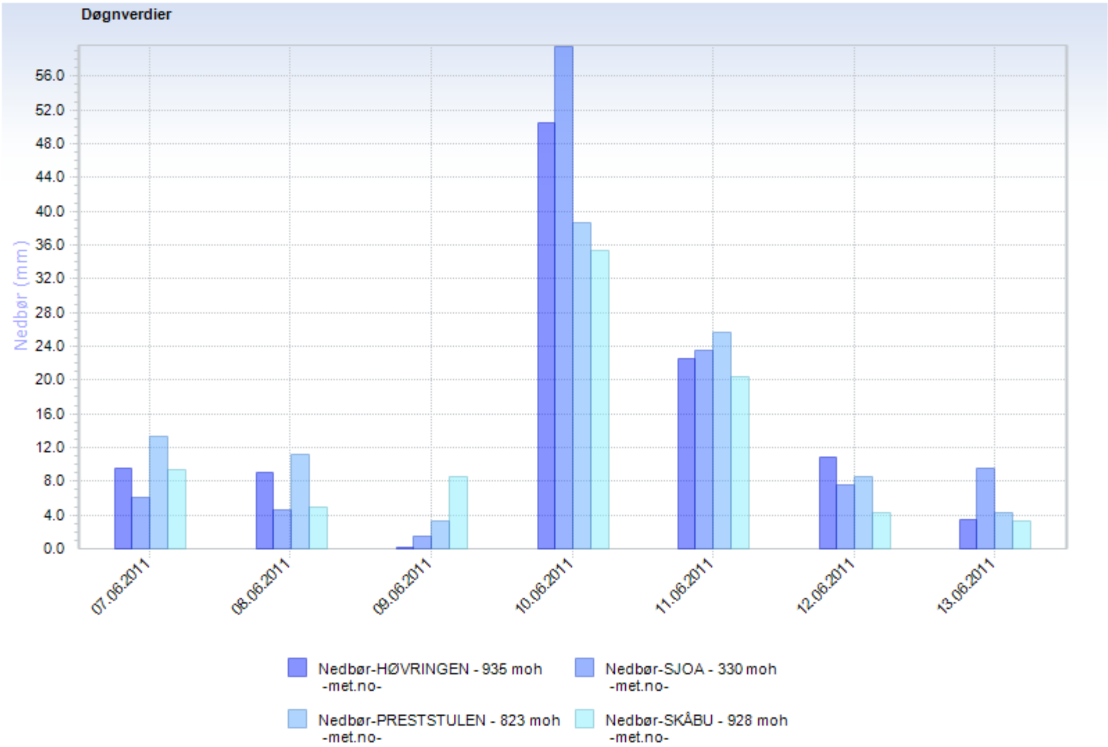


Figure 6.2.1.2 Precipitation data of the source location from four stations, taken from senorge.no.

Table showing below is the values of precipitation for different return periods in Otta area (Melchiorre and Frattini 2011). Antecedent precipitations in three days read from four stations were 18.6 mm for Høvringen, 12.2 mm for Sjoa, 27.7 mm for Preststulen and 22.7 mm for Skåbu. The rainfall occurred in 10th June 2011 could be defined as 100 years precipitation.

Antecedent Precipitation	No			15 mm/4 days			30mm/4 days		
		Future			Future			Future	
precipitation (mm/day)	present	min	max	present	min	max	present	min	max
5 years	38	39	48	25	25	33	12	11	18
50 years	59	61	73	41	42	53	22	20	31
100 years	68	70	83	48	48	61	26	24	36
500 years	93	96	111	67	68	84	39	36	52
1000years	106	108	125	78	79	96	46	43	60

Table 6.2.1.3 Values of precipitation in different antecedent precipitation conditions and for different return periods in Otta area (Melchiorre and Frattini 2011).

6.2.2 Threshold

Hourly precipitation data got from "Skåbu", detailed rainfall intensity showed in the table below. Use the mean intensity precipitation value to plot in the threshold data. We got it fit to the threshold of equation $I = 30\ D^{-0.78}$. And then, the threshold could be set up. Threshold of rainfall intensity for 24 hours' precipitation would be about 2.5 mm/h, and for 12 hours' precipitation would be about 4.3 mm/h.

Time	Instant precipitation (mm)	Duration (h)	Cumulative rainfall (mm)	Mean intensity (mm/h)
01:00	4.2	1	4.2	4.20
02:00	5.1	2	9.3	4.65
03:00	5.2	3	14.5	4.83
04:00	0.8	4	15.3	3.83
05:00	6.2	5	21.5	4.30
06:00	3.6	6	25.1	4.18
07:00	3.0	7	28.1	4.01
08:00	0.2	8	28.3	3.54
09:00	0.8	9	31.1	3.46
10:00	11.3	10	42.4	4.24
11:00	1.2	11	43.6	3.96
12:00	0	12	43.6	3.63

Table 6.2.2.1 Hourly precipitation data from Skåbu station at 10th June 2011, taken from eklima.met.no.

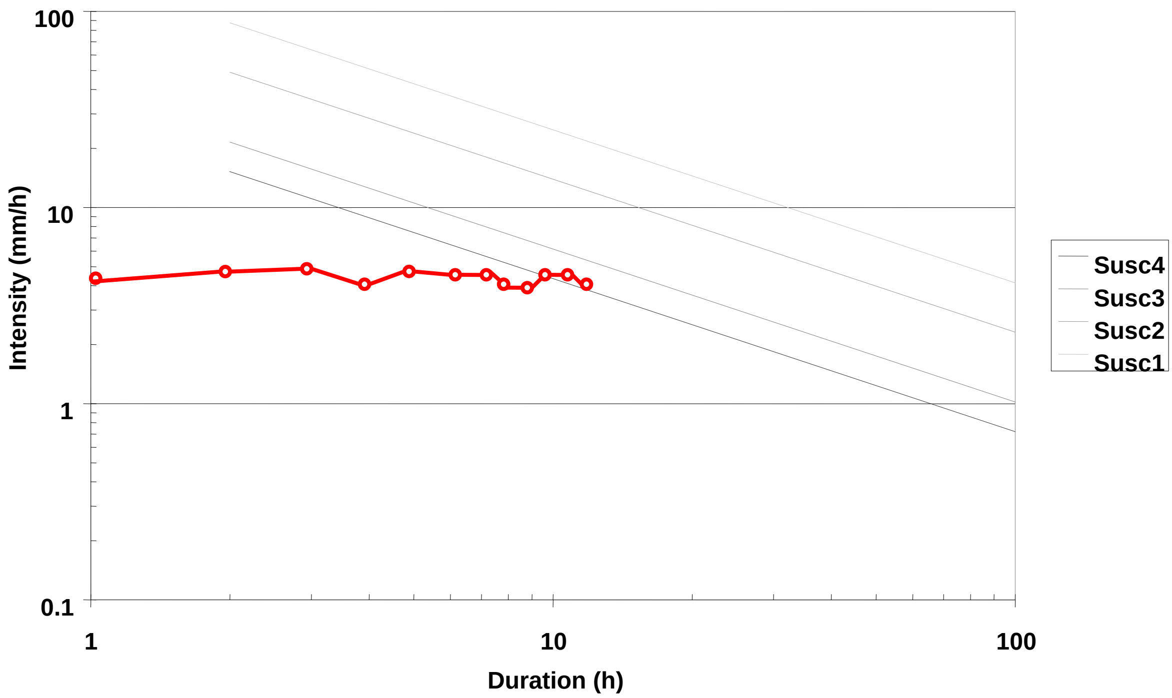


Figure 6.2.2.2 The threshold equations (from Susc4 to Susc1) are: $I = 30\ D^{-0.78}$; $I = 37\ D^{-0.78}$; $I = 84\ D^{-0.78}$; $I = 150\ D^{-0.78}$. Where *I* is rainfall intensity (mm/h) and *D* is duration (hours) (J. Cepeda 2010).

6.3 Estimation

In order to perform a hazard assessment on a fan and eventually to design protective measures against debris flows, it is necessary to estimate the important parameters such as potential debris volume, mean flow velocity, peak discharge, and runout distance (Rickenmann 1999). From the point of view of the evaluation of a potential hazard, the debris-flow volume is one of the most important parameters (Rickenmann 1999). Empirical equation as follows found through hundreds of events: $L = 1.9V^{0.16}H^{0.83}$. Similar equation as "log (H/L) = - 0.105 log V - 0.012" also found in another paper (Corominas 1996).

Parameters including the height drop, slope angles and horizontal distance about the debris flow event have been recorded by calculating the GPS data. Based on the traveling distance L and height drop H, the volume could be estimated through the empirical equations. And it has been shown that empirical relationships can be established between the peak discharge, Q_p, of a debris flow and the debris-flow volume (Hungr 1984). The corresponding equations have the following form: $Q = 0.1\ V^{0.833}$ (Rickenmann 1999), $Q = 0.135\ V^{0.780}$ for granular debris flows, and $Q = 0.0188\ V^{0.790}$ for muddy debris flow (Mizuyama 1992).

Based on the formula mentioned above, the estimation of volume and peak discharge shows below:

Event	Volume (m^3)	Peak discharge (m^3/s)
Solhjem	860	28
Sagdalen	101860	170

6.4 The role of human activity in mechanisms

As mentioned, during the field observation of Solhjem, liquefaction phenomenon was found in the soil cover along the transport path, which leading to the mechanisms of yield stress over the strength due to the ascending pore pressure. Ascending pore pressure could be explained by the intensive rainfall. However, which the intensive rainfall could not explain was the gradually deepened channel along the road formed in the start zone. It would be more likely interpreted by erosion due to the hydrodynamic shear force of the flow. One fact worthy to noticing was the flow path sign found in the location exactly corresponding to roads' direction. One explanation could be made: due to slope cutting by the roads, the function of drainage in the slope was changed from following the slope's vertical declination to the roads' trend; along the roads' trend more and more rainfall was gathered by the drainage channels; then the channel-bed failure occurred.

Therefore, for the mechanisms of the Solhjem, it could be said that the triggering mechanisms was channel-bed failure caused by drainage due the slope cutting of human road. And developing along the path, slope failure caused by pore pressure was also contributing to the event. Assuming without human aspects in the event, it may occur debris flow in the area during the day, however, less chance for it occurring in this location and this scale.

For the location of Solhjem, same situation could happen again, when it faces to another extremely rainfall, based on the reasons showing below. Along the track, no mitigation measurement was found in the start zone and transport path. Only one defense fence was built between the barn house and the track. It reduced the risk, not hazard. The track was not cleaned afterwards. Several extremely dangerous woods dams holding boulders were found. And after the debris flow, the drainage channel had been deepened by erosion and entrainment, which meaning strengthen capability for gathering and conducting the surface water.

For Sagdalen, two bridges were totally destroyed in the gentle slope. No sign about slope failure were found. Through the map study, we have been known that the path of stream is located in the bottom of the catchment area about 12 km^2. Quite a lot of the rainfall staying as surface flow gathered to the stream due to terrain and high groundwater level, while the drainage pipes buried under the first bridge was blocked and too small, and the drainage pipes under the second bridge was totally blocked even through with bigger pipes. When the failure occurred, the bridges acted like dams, and destroyed by the powerful hydrodynamic force of the flow. The hydrodynamic force led to the mechanisms of channel-bed failure. For the reason of the second drainage pipes, with 1 m diameter, being blocked, would be due to the dumped soapstone by locals in the upper stream. It would be appropriate to suggest that the soapstone contributed to the formation of the "dam".

Hence, the mechanisms for Sagdalen event would be interpreted by the channel-bed failure and dam effect. So, without human aspects contribution such as the bridges built over the stream or dumped boulders source, it may be one flood event instead of debris flow.

About the future risk of Sagdalen, the first bridge was repaired and replaced by larger drainage pipes, while the second one was left over. The drainage cross-section in the second bridge location was enlarged, meaning more capability for flow going through. And one pool for slowing down the flow and depositing the entrained debris was built in the downstream. The measurements reduce the risk and hazard, even through the dumped soapstone has not been removed. When it faced the similar precipitation, it is unlikely the same possibility for triggering the similar debris flow.

6.5 Risk estimation under climate changing

Table showing below is the precipitation data getting from station Høvringen, with statistics about rainy days, total volume, average and maximum precipitation per day in every five years. Since debris flow normally is more possible triggered by extreme events, information about maximum would be representative. Clearly increasing trend could be read from figure showing below. The fact that increasing risk under climate changing due to the more extremely events occurrence is indisputable

data	Total rainy days	Total volume (mm)	Average (mm)	Maximum (mm)
02.06.1972-31.12.1974	428	1209.5	2.83	27.8
01.01.1975-31.12.1979	713	2040.1	2.86	34
01.01.1980-31.12.1984	663	2263.5	3.41	49
01.01.1985-31.12.1989	665	2357.5	3.55	41.5
01.01.1990-31.12.1994	690	2242.9	3.25	46.1
01.01.1995-31.12.1999	624	2126.9	3.4	26.9
01.01.2000-31.12..2004	747	2342.5	3.14	35.7
01.01.2005-31.12.2009	959	2287.6	2.39	45
01.01.2010-19.09.2012	560	1594.1	2.85	52.6

Table 6.5.1 Precipitation data read from Høvringen station in every five years since 1972, taken from www.senorge.no.

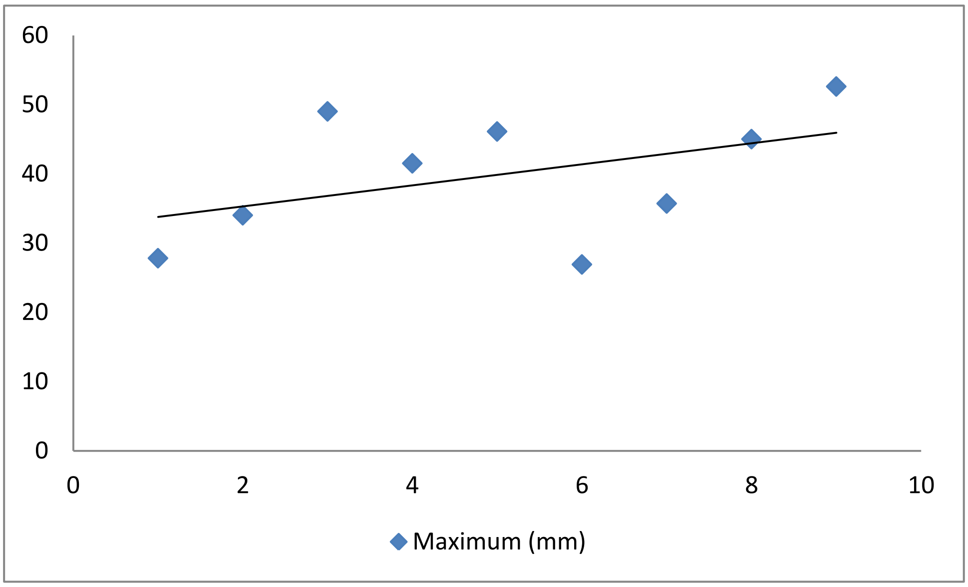


Figure 6.5.2 Tendency of maximum precipitation in every five years since 1972.

Figure showing below is presenting the modeling results of shallow landslides in Otta area under 69 mm/d precipitation with a return period of 100 years. And assuming an increase of 20% in rainfall, the comparison between present condition and future scenario is shown in b) as difference in probability of failure (Jaedicke 2008).

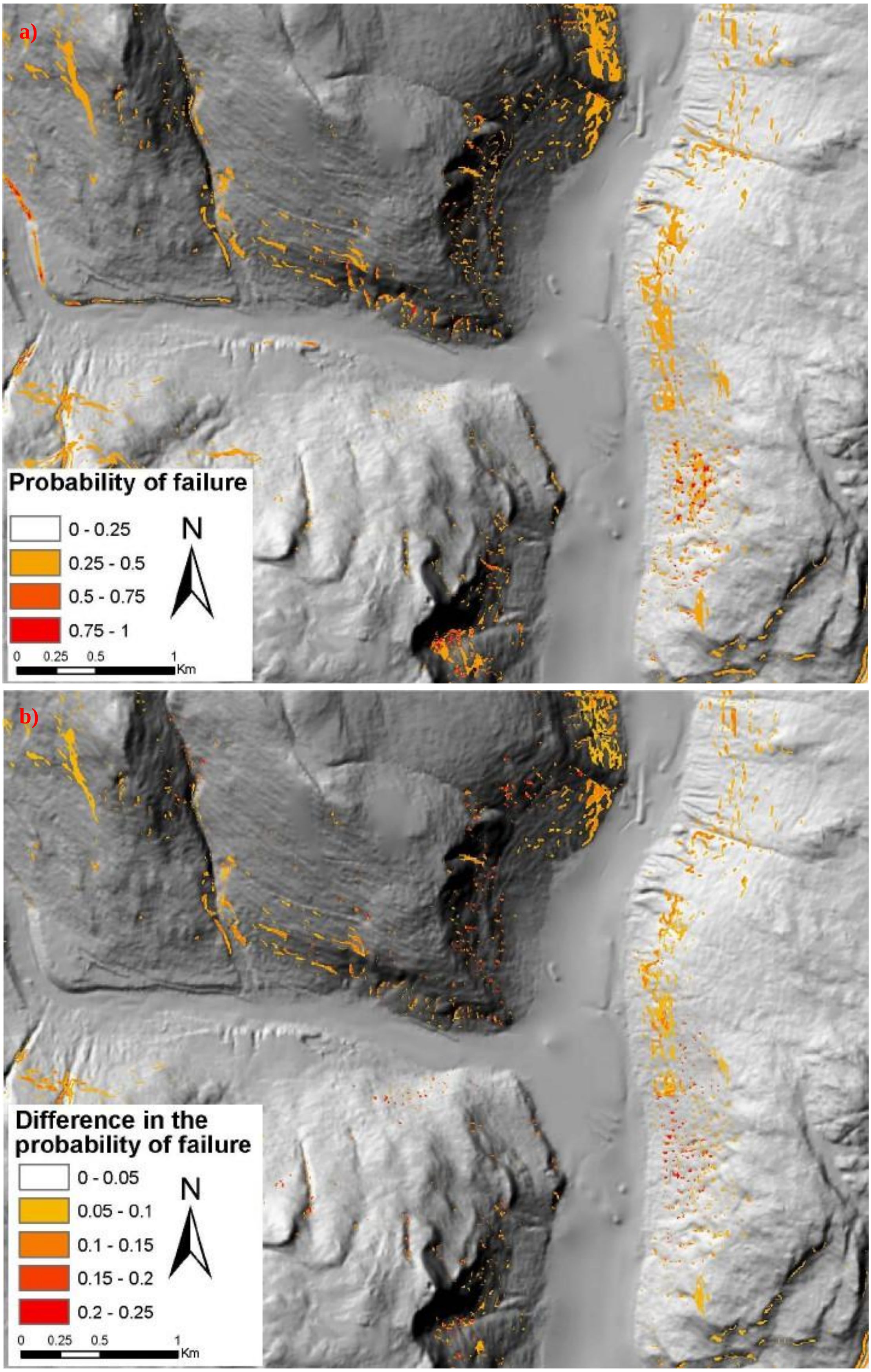


Figure 6.5.3 a) Modelling of the present stability conditions for shallow landslides in Otta area; the probability of

failure is calculated for 69 mm/d precipitation with a return period of 100 years. b) An increase of 20% in the precipitation intensity is assumed. The results are visualized as the difference between the probability of failure at the present precipitation conditions a) and the probability of failure at the modeled future conditions. Areas showing decreased probability of failure were not detected in the study area (Jaedicke 2008).

7 Conclusion

Detailed information of the process of the two events including witness observation and field observation have been documented. Parameters including the slope characteristics, runoff distance, deposit thickness, boulder sizes and erosion depth has been recorded and calculated. Simple models of the slopes are presented.

By means of the hourly precipitation data study, threshold of the rainfall for triggering has been set up. And then, based on the ratio of height drop and horizontal distance, we could estimate the volume and peak charge of the debris flows by the empirical formulas.

Through the study above, we got all the parameters of the location slope and events. Mechanisms have been interpreted to be the combination. For the first event in Solhjem, it is the combination of the channel-bed failure and the slope oversaturated failure, former of which is caused by roads' slope-cutting and reconducting of the drainage, while the other one is introduced by intense rainfall. The roads and its drainage channel are identified as the human contributes to the formation of the event.

For the second one in Sagdalen, it is the combination of the channel-bed faulure and dam failure. The latter one is due to the bridges' drainage pipes being blocked by the boulders compared to the former one caused by excessive surface flow from the intensive rainfall. The bridges and the dumped soapstone are identified as the human aspects in the event.

Climate change in the topic is viewed as the indirectly effect from human activities. Extremely rainfall event is showing an increasing trend during the data collected from last century, thereby posing increasing throat on the locals. Therefore, the unreasonable drainage channels distributions need to be improved. And also, to make sure the drainage channels being functional by through once or twice a years' exmination and blocking boulders romoval is very important.

The relationship of human activities, climate change and debris flow in this paper is clarified as human activities affect the climate change and the local environments. Some of the unnaturally activities aggravate the danger of the failure occurrence, in other words, lower the triggering threshold. Meanwhile, the climate change under human's effect poses more extremely events to the locals. Estimation about the future's precipitation is raising about 20 percents. More extremely events meet lower threshold for triggering debris flow, thereby posing more risk on the locals for the future. Therefore, the next project for the entire area, to update the detailed hazards map and relocating the locals exposed to 100 years event is essential to be done.

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Appendix A: Historical event information in Otta area, taken from www.ngu.no

POINT NO.	LANDSLIDES TYPE	DATE	LOCATION	CAUSUALTIES	DURATION	SPECIFICATION LOCATION	PREMOVEMENT BEFORE EVENTS	FALL HEIGHT	VOLUME	WITENESS	REGISTERED BY	DESCRIPTION
1	Rock falls and avalanche	15.05. 1884	Kringlia	0	Unknown	Unknown	No	Unknown	Unknown	Ivar Teigum, Trygve Odd Randheim	NGU, Astor Furseth	In Sel Kringen, at 15 May 1984 a landslide occurred from Blekalia. It hited and destroyed a house near E6, when the mom and daughter was inside. Luckily, nobody was injury. Another one was at risk too. Then the houses were removed for safety.
2		13.06. 1972	Blekalia	0	Unknown	Unknown	No	Unknown	Unknown	Per Bakke	NGU, Astor Furseth	In Otta, at 13 June 1972 a landslide flushed down Blekalia towards housing area in Plassjordet. It run down from the top of Blekalia next to E6 at 750m high to the hillside with volume several hundred m^3. One heavy stone around 12-1300kg roll down to the house of Oline and Birger Løvseth in Olav Kringensvei. Forest blocked lots of the landslide, while the stone came down to the river. the houses in the area were evacuated in a few days. Here was unexpected place for landslide. But in May 1975, a new landslide developed in the hillside of Plassjordet. Later one protection embankment built here.
3		18.04. 1897	Endrestad	1	Unknown	Endrestad	No	Unknown	Unknown	Marit Romsås, Knut Bryn, Per Bakke	NGU, Astor Furseth	In Sel Endrestad, south to Otta under Pilarguritoppen(852m oh). Rock falls occurred in the Easter, when was 21.30 in 18th April 1897. Søre Endrestad located in Endrestad and Jordet was hitted. The rock falls came towards the house. The wife, Gjøa Endrestad, barely managed to save a small kid, however, a big

												stone come through the roof and crushed one of the room beside the living room, and a boy died, one adolescent lying on the bed. The fall starts at the mountainside right under Pillarguritoppen. The stones falls down passing the place Havn which is located in Jordet, just above Baksidevegen north to Selsjorg. The stone was one square meter big and 40cm thick, which hit through the wall and killed the 30 year old instantaneous.
4		04.02. 1904	Søre Lien	0	Unknown	Lien	No	Unknown	Unknown	Jørgen Espelund	NGU, Astor Furseth	In Sel Otta Lien, one landslide occurred in evening of 4th February 1904 in Gråberget of Otta.People who lived under there, Rasmus Lien in Søre Lien, heard the first stones coming and escaped away. He was almost hit by it. The stones took down the storing building, the other houses only got minor damage, but there was a big forest damaging, and the stones came all the way down to Kleivrudjordet. The valley was full of debris. The yard/farmyard was moved to a safer place. A big stone lies on the mud boarder. See year 1906. Idnr. 5132.
5		15.02. 1906	Rasmuslia	0	16 days earlier or later	Lien	No	Unknown	Unknown	-	NGU, Astor Furseth	One big rock fall hitted the yards Nyhus and Kleivrud in February 1906, where were located 400 meters from each other under a tall mountain. On the location, Rasmuslia the house of who was located higher, seek shelter in the neighbors. The rocks fell down between the houses, crushing the storage room, causing huge damages on houses. However, luckily there was no injury reported. Forest damage was made. One huge block around 40 ton stopped right above the yard. Also see 1904 in Lien, Idnr.05130.
6		18.04. 1853	Hole	1	Unknown	Hole	No	Unknown	Unknown	Jørgen Espelund	NGU, Astor Furseth	Sel. In Hole (Holet) north for Otta, on the west side of a valley by village road, under Holepiggen. A steep area with danger of rock falls. A 8 year old boy, Per Jonsson Holet, died in 1853 because he got a stone over him in the April.

7		08.02. 1868	Sandbu	2	Unknown	Vågå	Unknown	500m	Unknown	Jørgen Espelund	NGU, Astor Furseth	Tthe 8th of February 1868, a rock fall destroyed a croft house in the yard Sandbu in Våge prestegjeld (near Vågåmo). A big stone falls down from the mountain to Sandbu and crushed the small house in Rudi and two people died, Dorte Andersdotter Rudistugum 70 year old, a child Ola Jakobsen 5 year old. Helland wrote that this was a avalanche (snowslide), but this is the correct information/details.
a	Unspecific landslides	15.07. 1739	Einangen	0	16 days earlier or later	Unknown	Unknown	Unknown	Unknown	-	NGU, Astor Furseth	Over the yard Einangen in Sel, a big landslide happened in the year 1739. Unclear about the extent of damage. There were many high streamflow many places in south of Norway in late summer this year, so this in Otta must have happened around the month july.
b		21.07. 1789	Berget	0	Unknown	Unknown	Unknown	Unknown	Unknown	Jørgen Espelund, Tor O. Bergum	NGU, Astor Furseth	In Heidal, during the flood between 21st and 23rd of July 1789, below the yard Horgen was the place Bergum or Berget. They lost their 5 houses, 4 acres field, but no one died, one lady got hurt. "A place Bergum lost 5 houses and 4 acres field and a mill, it would cost 40 rigsdaler (Rigsdaler is a unit of currency) to rebuild it." The place was later rebuild almost like today's Bergum, located a little bit below and south where an old building for wood and two new building stands. But it also have existed an "upper Bergum" which is unsure where it was located. It has been told that when the fall happened, the river to Otta was closed/stopped and afterwards the result of the river is like the one we see today.
c		23.07. 1789	Ofsen	68	Unknown	100000m closer or further	Unknown	Unknown	Unknown	-	NGI, Øyvind Høydal	-
d		30.04. 2008	Steindalsvegen	0	Unknown	Unknown	No	Unknown	Unknown	Per Bakke, Ola Næprud	NGU, Astor Furseth	In Sel Otta Steindalsvegen, at 30th april 2008, a big snow melting resulted one landslide from Tuesday 29th april 2008 in Solhjemslia and Nedre Dahle. However on 30th april, it came

												with bigger stone and landslide by Steindalsvegen. The inhibitants here were evacuated. By geological investigation they could have moved earlier. On the same day, 30.april, there was a another fall over a highway/road 15 around 1km west for Åsårbrua in Ottadalen. Map reference (Steindalsvegen) by Ola Næprud, tekn. Chief.
e		02.05. 2008	Bekken	0	Unknown	Unknown	No	Unknown	Unknown	Per Bakke, Ola Næprud	NGU, Astor Furseth	In Sel Otta Bekken/Svelstadjordet, there happened many landslides in Sel-area between 28 April-6th May, after a snow melting. At 3 o'clock in the night to 2nd May 2008, a big and later a smaller landslide and rock falls through a subdivision south in area Bekken gnr 231, north for Otta. The landslide was 50-60 meter wide and 300 meter long. Kongsvegen which was below the houses was hit. A outhouse, a barbecue house and a car was destroyed, and two subdivisions was damaged, and in total 120 people evacuated. The landslide came all the way down to E6 (the road) which was closed. No people got hurt. Mostly of the 40 households in subdivision Bekken and Svelstad could moved back earlier to their houses the same night, but 8 of them must be waited. Everyone could move back after 15th May. A landslide also happened by Rondanevegen and Einangen. The yard Åsåren was evacuated. The day after (3rd May) a mudslide blocked Bulivegen between Sjoa and Otta, and it comes smaller mudslides by Søre Steinfinnsbø and by Skjerdalen in Heidal. This day also another landslide happened over Pillagurivegen in Otta. Map reference subdivision by Ola Næprud, tekn. Chief.
f		29.04. 2008	Nedre Dahle	0	Unknown	Unknown	No	Unknown	Unknown	Per Bakke, Ola Næprud	NGU, Astor Furseth	In Sel Nedre Dahle, after a big snow melting, smaller landslides in Otta area occurred tuesday 29.april 2008 in Solhjemslia, also between Breden and Mælhum. The same day, a debris flow ran down towards the farm Nedre Dahle, north to the river Otta and beside riksvei 15. The landslide started from high up from,

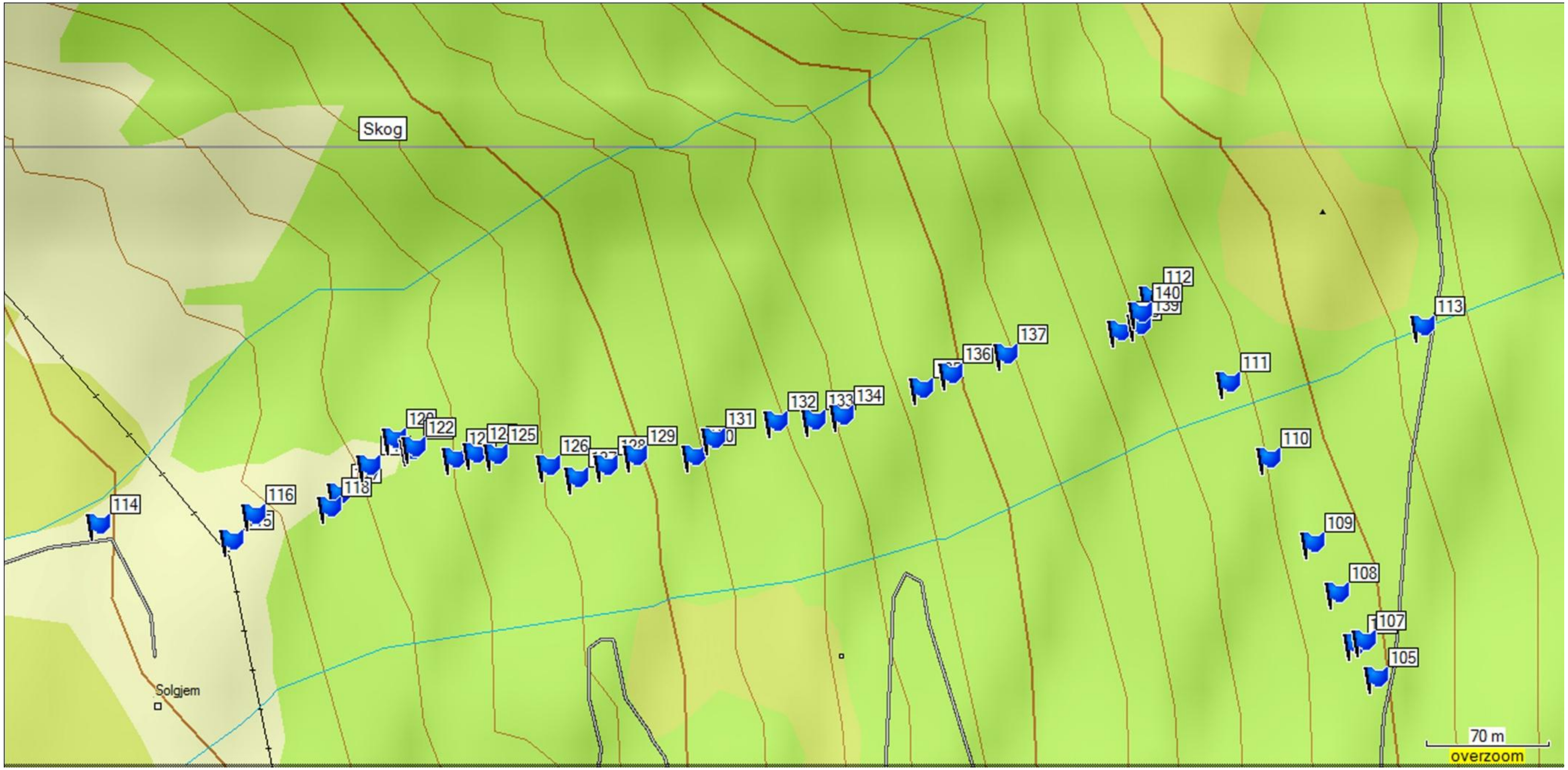
												closely below Rakstad. Also See idnr. 5260. Map reference (Nedre Dahle) by Ola Næprud, tekn. Chief.
g		15.04. 1989	Nedre Dahle	0	Unknown	Unknown	No	Unknown	Unknown	Ivar Teigum, Steinar Grønn	NGU, Astor Furseth	In Sel Otta Nedre Dale, one hundred meter west from Dalekleiva it was located a farm Nedre Dale under a steep hillside. A landslide came down the whole hillside night to 15.april 1989. The fall did some damage on its way down, but not on the houses. The fall came over the farm, from eastern part of Rakstad and down towards the farmyard in Nedre Dale, with earth, stone and mud. It has happened many smaller stone and landslides from this hillside all time, without any big damage. Late 1900s it was planted spruce (grantre) on the hillside for preventing landslides.
h		06.05. 2008	Leiren	0	Unknown	Unknown	Yes	550m	Unknown	Per Bakke, Ola Næprud	NGU, Astor Furseth	In Sel Leiren, after a big snow melting, at 6th of May 2008 one big landslide happened in Otta area, just four days after the landslide in Bekken yard. It came down Dale (Dahle) over the houses on the farm Leiren and down towards Dale å. A dwelling house was destroyed by the earth which crushed the wall. It came relatively slow. In all 10 houses and 33 persons in the subdivision on the two yards Øvre and Midtre Dahle were evacuated. Also Hegglund kindergarten was closed for several days. Leiren gnr. 218 brn. 2 was located quite high over the valley (550m) some km west from Otta, and with Dahle å close to there. There were many cracks in the ground which cause the evacuation to maintain. The cracks in Dahle was monitored for many days by HV-soldiers. The evacuees could moved back 15th May. Some day before, 29.4.2008, see idnr. 05258, a landslide came down towards Nedre Dahle. It was told that in Leiren, a landslide also happened in 1938, when 50 sheafs and parts of the earth disappeared/vanished. Map reference by Ola Næprud, tekn. Chief.

i		22.07. 1789	Åsåren	0	Unknown	Unknown	No	Unknown	Unknown	Randi Sæther	NGU, Astor Furseth	In Sel Ofsen Åsåren between 21st and 23rd July 1789, the farm of Aasaaren Nedre was hit by a landslide and all the houses, mainhouse and a storehouse were taken down to river. Both houses stand on the farm today. People escaped up to the mountain crag, and sat there seeing the animals, houses and tools were being taken down to the river. Helland: "In Aasaaren many houses were destroyed." One small boy died. They forgot him when they evacuted, while he was sleeping behind the fireplace. In the church there is a support with text about him. On the second floor in the big living room from 1604, there was a man called Pål. He did not want to come out. "My house will stand", he said. And above the house, the fall was divided and continued on both sides of that living room, so that house and the storeroom below still stand there. One guy called Christen was later owner of that farm, but much of the earth has been taken away, so he sold it in 1795.
j		21.07. 1789	Veggum	0	Unknown	Unknown	No	Unknown	Unknown	Ivar Teigium, Pål Veggum	NGU, Astor Furseth	In Sel Veggum in Ottadalen, between 21st and 23rd July 1789, on the two farms in Veggum, northern and southern parts, a big landslide happened. Also in the place Flåten (Veggumsflåten) , some hundred meters south to Søre Veggum. The landslide came from the ridge and all the way down. On Vegumgardene, all the houses flushed away, except a livingroom in Søre Veggum. People gathered on a birch grove by Nordre Veggum. Lost of animals totally ruined, as it was told. A lot of forest damaged. The houses which stood there have been rebuild today. There they just found a closet in the earth almost intact. Map reference is located in the middle area for both Veggumsgardene.
k		21.07. 1790	Sørlie	0	Unknown	Unknown	No	Unknown	Unknown	Pål Veggum	NGU, Astor Furseth	In Vågå between 21st and 23rd July 1789, Sørlie was the best farm in Ottadalen. The landslide destroyed all the houses, and left a lot of dirt and stones over the whole area. Here they lost all

												their animals.
l		18.06.1860	Sel	0	Unknown	Unknown	Unknown	Unknown	Unknown	-	NGU, Astor Furseth	In Sel, between 17th and 19th June 1860, there were two peasants who lost their houses after one landslide. No human damage, but it destroyed the farm and the houses. Unclear location. Local historian Jørgen Espelund could not find out. Map reference is located randomly/arbitrary in Sel.
m		14.05.1975	Ultungen	0	Unknown	Unknown	No	Unknown	Unknown	-	NGU, Astor Furseth	In Sel Uldalen, the 14th of May 1975, a big landslide started up in Ultungen in Uldalen at Mysuseter. Stone and earth took down two houses, forest and the earth were taken down towards the river Ula.
A	Snow avalanche	15.07.1829	Kvernhussletta	1	Unknown	Unknown	No	Unknown	Unknown	Per Erling Bakke	NGU, Astor Furseth	In Sel Kverhussletta (Kvernhussletten), one place which was located west for Solhjemsæ, 725m oh. One guy called Fredrik, nickname Frik, was taken down by a avalanche (snowslide). One winterday in 1829, he was on his way back from the mountain with loads on a sledge he pulled. On the steep Smukksjølia, with a lot of loose snow, he was taken down by the avalanche and died. When he was found, he was laying beside a stone, this stone afterwards was called Frikstone. The owner of this Kvernhusplassen is gone. Map reference location is approximated.
B		15.07.1981	Dalekleiva	0	Unknown	Unknown	No	Unknown	Unknown	Ivar Teigum, Steinar Grønn	NGU, Astor Furseth	In Sel Nedre Dale, Nedst in Ottadalen, a big avalanche (snowslide) occurred in 1981 at Dalekleiva. The slide came over riksveg 15 and out to the river. Road damaged. It had been many smaller avalanche here. Came near to some subdivision. It was later builded a avalanche protection here.
z	Flomskred	02.05.2008	Sjoa-Otta	-	07:00am 30 minutes earlier or later	Unknown	Unknown	Unknown	0.25		Jernbaneverket	-

y	Isnedfall	23.01. 1986	Otta-Sel	-	12 hours earlier or later	Unknown	Unknown	Unknown	Unknown		Jernbaneverke t	-

Appendix B: Field observation records of Solhjem, GPS points map and comments.



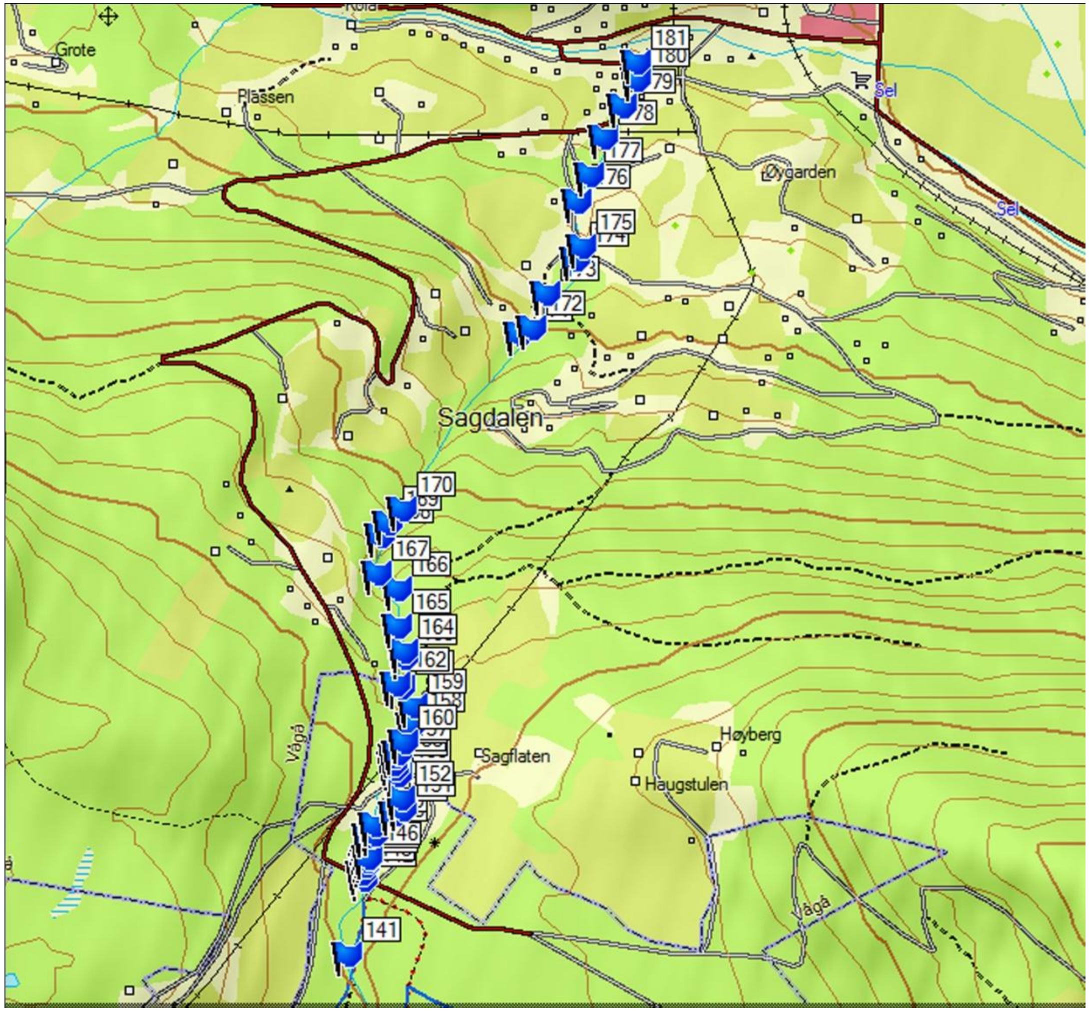
Point No.	GPS N	GPS N degree	GPS E	GPS E degree	ASL (m)	C	Distance (m)	Highness (m)	Slope (degree)	Notes
105	N61 44.811	61.44811	E9 34.381	9.34381	648					Start point. Rainfall flow collected from the up road and turned right to the lower part. Here has one drainage channel. Very fragile sharp flat mineral shall. Flushed channel showing on the old road.
106	N61 44.822	61.44822	E9 34.367	9.34367	618	1	14.32	30	64.5212	Like 10m away from the start point. The flow divided to two parts. Most of the flows follow the track keep running down, some of it turning left fun as the slope.
107	N61 44.823	61.44823	E9 34.373	9.34373	617	1	3.38	1	16.5117	Like 15m lower than the last point. In here, most of the rest running down the slope, less flow keep going this way due to the channel blocked by the debris. However, sign left from overflow showed here.
108	N61 44.838	61.44838	E9 34.356	9.34356	612	1	18.97	5	14.7743	
109	N61 44.853	61.44853	E9 34.340	9.34340	606	1	18.72	6	17.7788	
110	N61 44.879	61.44879	E9 34.311	9.34311	598	1	32.76	8	13.7291	Merge point for one cross stream on the right way, which may have flow once or twice a year. Not so much erosion found before this point. the fine material flushed away and vegetation being damaged, still haven't cleaned up.
111	N61 44.902	61.44902	E9 34.285	9.34285	591	1	29.07	7	13.5464	From all the way coming down this point, clearly twice times depth of erosion compared before the merge point, more than 15cm-25cm. Some parts showing two or more than two erosion tracks, till and rock were sediment on the road. The loose materials covered on the road were taken away by the surface flow during the strong rainfall. The inclination gets deeper and deeper. Boulders showing.
112	N61 44.929	61.44929	E9 34.234	9.34234	577	1	40.45	14	19.1020	Turning point at 537m, the end of the old road. Also one joint with another little track of road. The failure of the slope happened exactly here with big

										boulders around. Even after one year, the track of the channel get erosion in the debris flow still clearly showed.
113	N61 44.920	61.44920	E9 34.412	9.34412	630					
140	N61 44.924	61.44924	E9 34.228	9.34228	572	1	6.42	5	37.9462	Failure point, this was clearly the start of the slope failure. Showing the failure material starts running down from narrow to wide. And a small angle turning in this area. Deep track reaching to 2 meters.
139	N61 44.920	61.44920	E9 34.227	9.34227	569	1	4.48	3	33.8008	Some part is very steep with 40 degree. Loose material cover without vegetation. Very easy to flushed. Clearly showing the sign of the start zone.
138	N61 44.918	61.44918	E9 34.214	9.34214	562	1	7.27	7	43.9534	Woods dam.
137	N61 44.911	61.44911	E9 34.140	9.34140	525	1	40.13	37	42.6945	Small tree dam showing here, by several trees.
136	N61 44.905	61.44905	E9 34.104	9.34104	508	1	20.28	17	39.9857	Shallow and deep. Strong erosion, the narrow to 1m width. Very deep.
135	N61 44.900	61.44900	E9 34.085	9.34085	498	1	11.54	10	40.9313	The steepest part of the slope about 45-55 degree, strong erosion and loose material showing. Part of the track could see the bedrock. The track gets widen since this point, but not so deep, around 1-2m.
134	N61 44.892	61.44892	E9 34.033	9.34033	470	1	29.06	28	43.9538	Huge bedrock showing, size about 8 m high. Some part of slope reached to 80-90 degree.
133	N61 44.891	61.44891	E9 34.014	9.34014	461	1	10.17	9	41.5287	No huge boulders showing here, and trees were flushed away. Some part of the slope showing the sliding status.
132	N61 44.890	61.44890	E9 33.990	9.33990	449	1	12.82	12	43.1350	Many trees make up of another dam showing here. Huge boulders were trapped inside with huge dangerousity.
131	N61 44.885	61.44885	E9 33.949	9.33949	432	1	22.51	17	37.0764	One part with 6 m highness difference, like cliff. Upper there, the boulders and woods deposited there.
130	N61 44.880	61.44880	E9 33.936	9.33936	427	1	8.88	5	29.4023	Large amount of loose material, mostly are the small particles. And the deepest inclination reached to 70-80 degree.

129	N61 44.880	61.44880	E9 33.898	9.33898	408	1	20.22	19	43.2434	4-5 m depth of erosion found in this pot. Huge amount of woods left over. Boulders up to 2 meters size. Sleep angle around 40-50 degree.
128	N61 44.877	61.44877	E9 33.879	9.33879	402	1	10.65	6	29.4193	Damaged woods dam was built by 6-10 trees. And with a large amount of soil and stone filling inside.
127	N61 44.873	61.44873	E9 33.860	9.33860	395	1	11.05	7	32.3791	Big rock blocked the track, with the woods, rocks and till concentrated together. And the width of the track got narrowed. Giant boulders vacant on the slope with huge possibility of failure.
126	N61 44.877	61.44877	E9 33.841	9.33841	390	1	11.05	5	24.3661	The widen track, amount of loose rock varying from mm- cm. The deposited soil showing clearly being flushed. Also could read the same sign from the roots of the trees.
125	N61 44.880	61.44880	E9 33.808	9.33808	375	1	17.87	15	40.0265	From this point to point 123, strong flow entrainment the top cover material. The bedrock was left over, showing fragile mineral shale.
124	N61 44.881	61.44881	E9 33.793	9.33793	368	1	8.06	7	41.0003	Merging point showing another stream joint here. Bunch of loose material including till, leaves, stones, were found in this point. Very easy to be flushed away. Dangerous sauce zone for future events.
123	N61 44.879	61.44879	E9 33.780	9.33780	363	1	7.27	5	34.5478	3-4m depth erosion found, tons of boulders next to right, trees were moved left of the track.
122	N61 44.882	61.44882	E9 33.753	9.33753	352	1	14.75	11	36.7365	One depositional area around 3*3m, size of the rock varying from mm-30cm due to 20-30degree's inclination. Lots of debris deposited.
121	N61 44.882	61.44882	E9 33.752	9.33752	352	1	0.52	0	0.0000	Some of debris blocked and deposited.
120	N61 44.885	61.44885	E9 33.741	9.33741	345	1	6.74	7	46.1163	Deep erosion showing here.
119	N61 44.877	61.44877	E9 33.724	9.33724	341	1	12.69	4	17.4999	The point, due to the entrainment, the track is widening up to around 10 m. steep slopes from this point to point 117, around 70 degree. Strong erosion with over 1 m. trees were flushed with the roots showing out.
118	N61 44.864	61.44864	E9 33.699	9.33699	330	1	19.66	11	29.2477	

117	N61 44.868	61.44868	E9 33.705	9.33705	328	1	5.48	2	20.0647	Very steep from this point to the lower turning point, bedrock showing. Strong erosion and clearly debris left over in this location including tons of boulders, woods and till.
116	N61 44.861	61.44861	E9 33.650	9.33650	315	1	30.28	13	23.2453	The turning point of the debris flow, luckily the flow turns right from this point and only hit one barnhouse. Otherwise it would cause more damage or even causality if it run over the slope. Lower the slope; there were houses located and one farming field.
115	N61 44.854	61.44854	E9 33.635	9.33635	316	1	11.15	-1	-5.1255	The boundary of the fence which was built afterwards, next to the barnhouse destroyed in the event. The fence is made up with boulders and soil, which being compacted. The cross section showing trapezoid sharp with width base, around the track of the stream like a' J'. The track of the debris flow in this area being resettled with huge boulders. Little stream showing. This point was next to the electricity pole.
114	N61 44.859	61.44859	E9 33.548	9.33548	303	1	46.62	13	15.5885	The yard of the locals, under the fence, belongs to depositional zone. The inclination is gentle, and next to the other stream channel. When the debris flow occurred, it flushed away the pipe and the bridge built over the stream. The locals were trying to recover it in June 2012.

Appendix C: Field observation records in Sagdalen, GPS map and comments



Point No.	GPS N	GPS N Degree	GPS E	GPS E Degree	ASL(M)	Distance	Highness	Slope (degree)	Notes
141	N61 49.544	61.49544	E9 23.592	9.23592	608				Start point, there is one small woods on the right side of the stream which is heading from south to north. The slope of the area was very gentle; the ground soil was very saturated. The stream located in one catchment. The stream was shallow and narrow, about 1 m width, with lots of boulders saving in the bottom of the river. One wooden made bridge cross over, with 2.5 m high over the water and 2 m width.
142	N61 49.622	61.49622	E9 23.626	9.23626	585	88.69	23	14.54	There was sign showing being flooded.
143	N61 49.629	61.49629	E9 23.621	9.23621	586	8.23	-1	-6.93	The bridge was destroyed. Right now it has already been repaired. The concrete drainage pipes have been replace by iron pipe. And the diameter enlarged from 40cm to 100cm. The old pipe was flushed to the other side with some other debris, including boulders up to 30cm, depositing in the large area. The channel enlarged behind the bridge to 7 m width. however, boulders have already found in the new pipe varying from 20cm- 30cm.
144	N61 49.638	61.49638	E9 23.629	9.23629	587	10.88	-1	-5.25	4 pipes were flushed to the west side of the stream while 1 pipe was flushed to the east side. We could clearly see the debris deposited in this zone, around 5m*8m.
145	N61 49.642	61.49642	E9 23.631	9.23631	587	4.58	0	0.00	tube 2
146	N61 49.645	61.49645	E9 23.635	9.23635	587	3.96	0	0.00	tube 3

147	N61 49.668	61.49668	E9 23.636	9.23636	587	25.61	0	0.00	The width of the stream narrows down to 1-2m again. Erosion on the bank could be seen. One huge bolder about 1.5m high located in the middle of the river and divided the stream into 2 parts. Like a dam. One side was about 60cm width with most the flow and 50 cm widths in other side.
148	N61 49.670	61.4967	E9 23.648	9.23648	589	6.75	-2	-16.50	More erosion showing, the deepest reach 1.5m-2.5m. And there is off-white gypsum-like waste dumped in the right side of the bank.
149	N61 49.679	61.49679	E9 23.649	9.23649	590	10.03	-1	-5.69	We could see 10 m deposition zone in the east side while erosion in the west side.
150	N61 49.690	61.4969	E9 23.694	9.23694	590	26.86	0	0.00	A large amount of soap stone located in both sides of the river, varying from mm-cm. The size in east side was bigger.
151	N61 49.696	61.49696	E9 23.710	9.2371	589	10.81	1	5.29	1m erosion showing in the bank, the woods' roots were flushed out. Boulders found in the sides, about 100-200 square m. the steam divided into several parts, clearly great gradient showing in the merging point.
152	N61 49.706	61.49706	E9 23.706	9.23706	588	11.33	1	5.04	Great damaging showing in the bank, the sign showing the water depth was reaching to 1m. Eastern side was very deep with 60 degree slope.
153	N61 49.731	61.49731	E9 23.700	9.237	584	28.01	4	8.13	The velocity of the stream clearly speeds up in this area with increasing capacity of entrainment. Second destroyed bridge showing here, with 5 pipes, 1m diameter, leaving there. One side of the pipes was totally blocked by the boulders.
154	N61 49.738	61.49738	E9 23.693	9.23693	584	8.63	0	0.00	Flushed tube.
155	N61 49.743	61.49743	E9 23.691	9.23691	582	5.67	2	19.44	Flushed tube two, the road was totally destroyed with 12 m length road missing. The width of destroyed reached 10m. One huge bolder with size of 1 m removed by the flow.

156	N61 49.751	61.49751	E9 23.692	9.23692	582	8.92	0	0.00	One concrete pipe was removed by 10 m. Two pipes blocked and leaving in the track like a dam. Small boulders could be seen around.
157	N61 49.754	61.49754	E9 23.700	9.237	582	5.40	0	0.00	Another tube showing away from the last one about 20m. Further part the stream turned with clearly gradient about 20 degrees. Another depositional zone, the debris slope up to 75degree to 80 degree with boulders and woods saving in. Potential dam deposition.
158	N61 49.782	61.49782	E9 23.730	9.2373	582	35.01	0	0.00	Depositional zone, woods and boulders varying from mm to 1m left in the track, blocking more than half of the channel.
159	N61 49.802	61.49802	E9 23.734	9.23734	577	22.37	5	12.60	Turning point, wooden dam, and the trees blocking the stones.
160	N61 49.765	61.49765	E9 23.714	9.23714	575	42.54	2	2.69	The river was blocked almost 80 percents with boulders and flat rock. 20-30m downstream there was another deposit zone.
161	N61 49.821	61.49821	E9 23.708	9.23708	565	62.42	10	9.10	Many trees were flushed down by the debris flow, blocking the huge rock and debris. Above the river about 4-5m, 80 percents channel was blocked.
162	N61 49.825	61.49825	E9 23.698	9.23698	563	6.93	2	16.10	High elevation difference. Blocked by the tube and broke tree. The soil in the bank was very loose.
163	N61 49.853	61.49853	E9 23.713	9.23713	559	32.17	4	7.09	The velocity was slowing down due to the gentle slope. The bridge was not destroyed. Deposits were found in some area with 20-40cm boulders.
164	N61 49.858	61.49858	E9 23.713	9.23713	558	5.57	1	10.19	Open field in the track, small debris material compared to upper point. Mostly was flattery. Fewer rounds found.
165	N61 49.885	61.49885	E9 23.701	9.23701	554	30.72	4	7.42	In this pot, 2 m elevation difference like cliff with huge rock in the track. Could see the downstream with deeper slope. Bedrock

									showing.
166	N61 49.923	61.49923	E9 23.700	9.237	544	42.30	10	13.30	Hierarchical gradient showing with total gradient about 30 degrees, a large amount of boulders leaving between points 165 to 166.
167	N61 49.940	61.4994	E9 23.657	9.23657	537	29.66	7	13.28	Small water fall. Another small stream merged in. Huge boulders could found.
168	N61 49.978	61.49978	E9 23.662	9.23662	525	42.38	12	15.81	Another water fall.
169	N61 49.991	61.49991	E9 23.678	9.23678	515	16.78	10	30.79	One cliff in western side, huge high difference. The bedrock could be seen in shale. The stream turned with debris flow seen. Bank failure in down parts and the debris deposit found. Trees were flushed down to the river forming a dam.
170	N61 50.005	61.50005	E9 23.712	9.23712	517	23.85	-2	-4.79	Rock fall in the channel, blocking some debris. Taking the 80 percents of the cross section.
171	N61 50.186	61.50186	E9 23.966	9.23966	415	242.49	102	22.81	Slope failure found in this location, with 1 m rock rolling into water. Debris deposit found in both sides.
172	N61 50.194	61.50194	E9 23.995	9.23995	408	17.79	7	21.48	
173	N61 50.229	61.50229	E9 24.026	9.24026	402	42.30	6	8.07	Deposit of woods and rocks.
174	N61 50.265	61.50265	E9 24.090	9.2409	387	52.55	15	15.93	Channel got fixed.
175	N61 50.278	61.50278	E9 24.106	9.24106	379	16.78	8	25.49	1.8m drainage pipe buried under the bridge, erosion showing in the bank with 1-2 m depth.
176	N61 50.325	61.50325	E9 24.094	9.24094	368	52.71	11	11.79	Joint with another drainage pipe with diameter 25cm. Sign showing strong entrainment, the upper cover being taken away. Could see the bedrock.

177	N61 50.352	61.50352	E9 24.121	9.24121	360	33.30	8	13.51	The bridge was damaged. The road in upstream has been repaired with debris deposited. The fence in the bridge was clearly new.
178	N61 50.390	61.5039	E9 24.152	9.24152	351	45.39	9	11.21	Round pool being built over 10m diameters, for saving the debris flow.
179	N61 50.424	61.50424	E9 24.194	9.24194	341	43.93	10	12.82	Another bridge, the same situation with 177.
180	N61 50.451	61.50451	E9 24.225	9.24225	336	34.27	5	8.30	Bridge damaging.
181	N61 50.468	61.50468	E9 24.196	9.24196	333	24.40	3	7.01	End point, the flow flushed the iron fence of the bridge. And the flow over flowed the bank and reach two yards and houses of the inhabitants with thick debris deposited.