Effect of the DEMs resolution on landslide runout models

Analyses of three flow-like landslides in South of Norway

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Abstract

Dynamical runout models are essential tools in landslide hazard and risk assessment, because they allow us to simulate the motion of past landslides and to predict the motion of future landslides. Runout distances obtained from these models, combined with expert-knowledge, are used to delineate the landslide hazards zones and consequently create hazard maps. Digital Elevation Models (DEM) are widely used in landslide runout models. The accuracy of the models depends on the source and resolution of the DEM data.

By assessing the DEMs ability to interpret the terrain, and the DEM resolutions’ effect on the runout models, it will be possible to evaluate the influence of the DEM resolutions. To evaluate how DEM resolution influences results from numerical runout models, three case studies of flow-type landslides that occurred in Norway in distinct slope typologies were back-analysed with the runout models RAMMS and DAN3D by applying DEMs with 1m and 10m resolution.

The results of this study showed that the DEM resolution influence the behaviour of the runout models. By increasing the resolution of the DEMs from 10m to 1m resolution, the accuracy of the runout increased. It was shown that 1m DEMs generally provided the most accurate shape and runout length that were the most identical to the real event. This was also the case for the flow height and velocity, where the 1m DEMs provided the most accurate results. However, DAN3D obtains more varied results compared to the results obtained from RAMMS, which better complies with the real events. It was also noticed that the 10m DEMs required higher friction parameters to back-analyse debris avalanches, but there was no clear trend for the debris flows.
Acknowledgements

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1 Introduction

The economic and human losses caused by landslides around the world are high. Europe is exposed to a large number of landslides every year that results in casualties and economical losses (Nadim et al., 2006, Smith, 2013, Haque et al., 2016). Few official estimations of this exist for Norway. According to Jaedicke et al. (2008), Jaedicke et al. (2009), approximately 2000 people have been killed by different types of landslides during the last 150 years. Among them, flow-like landslides and in particular debris flows and debris avalanches, are among the most catastrophic landslide types and represent a substantial hazard all over the world that cause severe damage to infrastructure and loss of human life (Pastor et al., 2009, Dowling and Santi, 2014). The combination of high flow velocity, impact force, long runout and poor temporal predictability make debris flows and debris avalanches some of the most dangerous and destructible landslide types (Jakob and Hungr, 2005).

In Norway, debris flow (called “flomskred”) and debris avalanches (called “jordskred”) are a significant threat to communities and infrastructure. They have caused directly severe destruction of infrastructure and properties and have indirectly lead to isolation of communities in several occasions because their masses have blocked roads and railway, impeding the traffic. On rare occasions these landslide types have caused losses of lives in Norway and recent estimates from NVE indicate that 5 people died in the period 1995–2016 due to debris flows (Namork et al., 2014, Haque et al., 2016).

In the last decade there have been several debris flow and debris avalanche incidents in Norway, caused by heavy precipitation in combination with snowmelt, due to rising temperatures and ground saturation (Colleuille and Engen, 2009). With climate changes due to global warming, it is expected that Norway will have more intense and heavy extreme precipitation events, and this will increase the risk of such of landslides (Wieczorek and Glade, 2005, Bargel et al., 2011, Myrabø et al., 2016).

To reduce the costs of economic losses and the number of fatalities and to prevent future catastrophic events, quantitative risk analysis (QRA) is essential to identify the frequency or probability of hazard events (Corominas et al., 2014). By applying numerical models to QRA, it is possible to reproduce the material distribution, intensity and impact zones (Quan Luna et al., 2011). This requires accurate predictions of the runout behavior, which includes prediction of the total runout distance, velocity, flow pressures, depth of the moving mass, width and depth
of deposited masses (Hungr, 1995). Therefore, several techniques have been developed to assist landslide experts in the analysis and the understanding of the complex behavior of a failing mass down a slope.

One of the most applied approaches are numerical methods, which include 1D, 2D and 3D models. The numerical models are widely used in landslide hazard assessment and hazard mapping and the outputs can be used to generate vulnerability curves (Hürlimann et al., 2008, Hungr and McDougall, 2009, Quan Luna, 2012). Many numerical models, like RAMMS, DAN3D and FLO-2D among others (Christen et al., 2010, McDougall, 2006, O'Brien et al., 1993) are used to compute the direction and movement of a flow from its initiation area to the deposition. These models also compute other flow parameters like velocity, height and pressure (Quan Luna, 2012). However, to run such numerical models, a topographic file is required to define the terrain where the simulation will take place. This is conducted by using a Digital Elevation Model (DEM) as input data with a given resolution. A DEM is a spatially georeferenced dataset of the topography (Hutchinson and Gallant, 2000).

It has been noticed that to obtain reasonable simulation results, the quality of the DEM is essential (Rickenmann et al., 2006). Hussin (2011) and Hussin et al. (2012) observed that with decreased DEM accuracy, the runout models might misinterpret the terrain, resulting in inaccurate results. Also (McDougall, 2016) pointed out that the runout models sensitivity to DEM resolution is one of the key challenges for more accurate runout modelling. Therefore, by assessing the DEMs ability to interpret the terrain and the DEM resolutions’ effect on landslide runout models, it will be possible to evaluate the influence of the DEM resolutions

1.1 Objectives of the study

This study has the main objective to evaluate how DEM resolution influences results from numerical runout models by performing back-analyses of three selected flow-type landslides that occurred in Norway. For this purpose, the cases were representative of distinct slope typologies (from open slope, to partly channelized and to channelized typology). They were back-analysed with two runout models, RAMMS and DAN3D, by applying DEMs with 1m and 10m resolution.
To achieve the main objective, the following specific objectives have been defined:

- Selection of case studies occurred in slopes with distinct typologies and collection of landslide parameters from previous works and reports.

- Accessing and downloading DEMs and processing the DEMs to the required format.

- Back-analyses of the three selected cases with the models RAMMS and DAN3D.

- Evaluation of the applied DEMs and evaluation of results of back-analysed case studies.
2 Landslides

In mountainous areas such as Norway, mass movements, i.e. landslides and snow avalanches (referred as “skred” in Norwegian), are the most common natural hazards in the country. A “skred” is defined as the mass movements of rock, soil, snow or ice due to gravity down a slope (Kristensen et al., 2015). In this thesis, only landslides are the focus of this research, i.e. the downslope movement of soil, rock and organic materials under the force of gravity and the landform that results from such movement (Highland and Bobrowsky, 2008).

Identification and classification of landslides are typically conducted by examining several criteria. According to Varnes (1978) the most common criteria include; material type, type of moment, geometry of the release area and deposit, degree of disruption and state of activity.

Baltzer (1875) appears to be the first to classify the basic modes of landslide motion by defining fall, slide and flow. Today, the most used and accepted classification system is the Varnes Classifications System from 1978, which is based on the framework of the tri-dimensional classification system developed by Sharpe (1938) in the USA (Hungr et al., 2014). Sharpe (1938) applied the three criteria (movement, material and movement velocity) to identify and classify landslides and he was the first to separate between debris flow (channelized) and debris avalanche (open-slope). Later Varnes (1958) expanded the classification system by considering other types of material and movement. Creep, toppling failure and spreading movements were later added to the classification system (Varnes, 1978). The Varnes classification system was recently updated by Hungr et al. (2014), due to new knowledges in landslide science (Table 2.1).
Table 2.1. The updated Varnes classification system, landslide types defined by type of movement and material type (Hungr et al., 2014).

<table>
<thead>
<tr>
<th>Type of movement</th>
<th>Rock</th>
<th>Soil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fall</td>
<td>1. Rock/ice fall&lt;sup&gt;a&lt;/sup&gt;</td>
<td>2. Boulder/debris/silt fall&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>3. Rock block topple&lt;sup&gt;a&lt;/sup&gt;</td>
<td>5. Gravel/sand/silt topple&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>4. Rock flexural topple</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7. Rock planar slide&lt;sup&gt;a&lt;/sup&gt;</td>
<td>12. Clay/silt planar slide</td>
</tr>
<tr>
<td></td>
<td>8. Rock wedge slide&lt;sup&gt;a&lt;/sup&gt;</td>
<td>13. Gravel/sand/debris slide&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>10. Rock irregular slide&lt;sup&gt;a&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Slide</td>
<td>15. Rock slope spread</td>
<td>16. Sand/silt liquefaction spread&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>17. Sensitive clay spread&lt;sup&gt;a&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>18. Rock/ice avalanche&lt;sup&gt;a&lt;/sup&gt;</td>
<td>19. Sand/silt/debris dry flow</td>
</tr>
<tr>
<td></td>
<td>20. Sand/silt/debris flowslide&lt;sup&gt;a&lt;/sup&gt;</td>
<td>21. Sensitive clay flowslide&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>22. Debris flow&lt;sup&gt;a&lt;/sup&gt;</td>
<td>23. Mud flow&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>24. Debris flood</td>
<td>25. Debris avalanche&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>26. Earthflow</td>
<td>27. Peat flow</td>
</tr>
<tr>
<td>Spread</td>
<td>28. Mountain slope deformation</td>
<td>30. Soil slope deformation</td>
</tr>
<tr>
<td></td>
<td>29. Rock slope deformation</td>
<td>31. Soil creep</td>
</tr>
<tr>
<td></td>
<td>32. Solifluxion</td>
<td></td>
</tr>
</tbody>
</table>

2.1 Flow-like landslides

This thesis focuses on the analysis of flow-like landslides. Flow-like landslides are defined as the motion of a fluid material over a rigid bed and they have been studied and classified by Hungr et al. (2001). Flow-like landslides are initiated as a slide by forming a rupture surface and continue moving over a long distance (Hungr et al., 2001).

This study focuses in particular on the analysis of two types of flows: debris flows and debris avalanches (Figure 2.1). These two categories have been described and studied by many authors (Hungr, 1995, Iverson, 2005, Takahashi, 2014). They both involve the downslope movement of debris material. The word debris was described by Varnes (1978) and Hungr et al. (2014) as a mixture of sand, gravel, cobbles and boulders, with varying proportions of silt and clay that might include a significant proportion of organic materials.
Figure 2.1. Examples of flow-like landslides. A) Debris flow (GEO, 2012) B) partly channelized debris flow (Colleuille et al., 2013), C) debris avalanche (Photo: Takuto Kaneko/AP/TT).

2.1.1 Debris avalanches

According to Hungr et al. (2001), a debris avalanche is defined as “very rapid to extremely rapid shallow flow of partially or fully saturated debris on a steep slope, without confinement in an established channel.Occurs at all scales”. In Norway the term “jordskred” is applied for debris avalanches (Kristensen et al., 2015).

A debris avalanche occurs typical on open slopes and initiates as a shallow planar or rotational sliding failure. In the initiation stage, a debris avalanche can be referred to as a debris slide, before it is exposed to internal distortion and develop into flow-like properties. As the slope levels out, the debris avalanche will begin to deposit materials and in the deposition area the debris avalanche develops a laterally unconstrained colluvial apron and a coarse front with poorly longitudinal sorting (Hungr et al., 2001). In some cases as the flow moves downslope,
Debris avalanches might follow existing gullies and channels, making the debris avalanche partly channelized (Jakob and Hungr, 2005) or in some case transforming into a debris flow (Hungr et al., 2001).

Debris avalanches occur as a result of steep unstable slopes, covered by loose unconsolidated and/or weathered deposits. In Norway they are triggered by intense precipitation and intense snow melting. They can also be triggered by disintegration of bedrock during a high velocity slide-type landslide downslope, that can transform the mass into a debris avalanche (Highland and Bobrowsky, 2008). Debris avalanches can also be triggered by impact from rock fall or rock slide on soil-covered slopes, due to the rapid undrained loading process (Hungr et al., 2014).

### 2.1.2 Debris flows

Debris flow is defined as "very rapid to extremely rapid surging flow of saturated debris in a steep channel.” (Hungr et al., 2014). In Norway the term “flomskred” is used for debris flow (Kristensen et al., 2015).

A debris flow initiate periodically on already established gullies or drainage channels within steep slopes, making it reoccur in the same established paths and deposition area (Hungr et al., 2014). The flow is a mixture of sediments and water and behaves as a flow of continuous fluid driven by gravity. If materials begin to move down a channelized slope, the bed becomes subjected to undrained loading. This might result in a significant increase in pore pressure and liquefy the exposed materials (Hungr et al., 2014). Debris flows are characterized by a strong entrainment of materials and water down the flow path (Hungr et al., 2014). Debris flows are commonly described as a succession of surges (Zanuttigh and Lamberti, 2007) that entrains the bed material as it surges downslope. This leads to a bulking of the flow where the material is mainly obtained through entrainment of the saturated soil and surface water in the channel (Hungr et al., 2014).

The debris flow is released in the initiation zone, where the mass starts to accelerate. Here the magnitude of the slide may be only a few cubic meters, but due to entrainment in the channels the debris surge might increase to a large debris flow. The deposition zone mainly ends in a developed fan and deposition of materials is initiated as a combination of slope reduction and loss of confinement (Jakob and Hungr, 2005). The deposition is initiated with the deposition of
the frontal boulders that rapidly deposits as levees or abandoned boulder fronts. The finer and more dilute material continue to flow further downslope and eventually might convert into debris flood surges (Hungr et al., 2014).

The debris flow can initiate in three possible ways: a) by surface-water runoff that erode and entrain material from the channel and hillside, b) by a slide in the hillside that enter in the channel and transform to debris flow or c) by a combination of surface-water runoff and the occurrence of slide in the side of the channel that erode and entrain more material. If the debris flow starts as a slide, the magnitude of the slide might be only a few cubic meters, but due to entrainment in the channels the debris surge might increase to a large debris flow. The deposition zone mainly ends in a developed fan and deposition of materials is initiated as a combination of slope reduction and loss of confinement (Jakob and Hungr, 2005). The deposition is initiated with the deposition of the frontal boulders that rapidly deposits as levees or abandoned boulder fronts. The finer and more dilute material continue to flow further downslope and eventually might convert into debris flood surges (Hungr et al., 2014). For the definition of debris flood consult Hungr et al, 2014.

Debris flow deposits can be classified based on the type of sediment concentration, grain size distributions, flow front speeds, shear strengths and shear rates (Iverson, 1997). A rheologic classification of sediment-water flows can also be applied to classify the different debris flow phases. This classification is based on mean flow velocity and sediment concentration. Based on that a debris flow can be divided into three main phases:

1. Debris flow consists of a mixture of poorly sorted sediments and water, and with a sediment concentration between 60 and 80% in volume (Pierson and Costa, 1987).
2. Hyperconcentrated streamflow is defined as a flowing mixture of water and sediment that has a measurable yield strength and appears to flow like a liquid (Pierson and Costa, 1987), with sediment concentrations between 20% to 60% in volume (Beverage and Culbertson, 1964).
3. Stream flow is defined as flowing water with sufficiently small sediment concentration that is unaffected by sediment transport (Pierson and Costa, 1987).

The main triggering mechanisms for debris flows are heavy precipitation and/or rapid snowmelt that result in erosion and mobilization of loose materials in steep slopes (Highland and
Bobrowsky, 2008). The water fills the pore space above less permeable bedrock, increasing the pore pressure and initiating a sliding sequence (Hyndman and Hyndman, 2016). Numerous debris flows start usually as intense surface water flow runoff from heavy precipitation and or rapid snowmelt. In other cases, the debris flow may mobilize from other related landslide types that occur on steep slopes, that are typical dominated by silt-sand size materials and nearly saturated, e.g. debris slides, debris avalanches (Highland and Bobrowsky, 2008). In Norway debris flows can initiate also as slush flows and jökulhlaup (Colleuille et al., 2013).

2.1.3 Slope typology

In general, the distinction between debris avalanches and debris flows is made based on the fact that debris flows occur in steep channel, while debris avalanches occur in steep open (or not channelized) slopes. Field observations demonstrate that sometimes there is a gradual transition from debris avalanches to debris flows, also in apparently “open slopes”. Di Crescenzo and Santo (2005) showed that the occurrence of a debris flow or debris avalanche is strongly dependent on the slope typology and which can mainly be divided into: a) regular slope differentiated in convex, concave, and planar; b) slope with no hierarchized drainage basin; c) slope with lowly hierarchized drainage basin and d) slope with highly hierarchized drainage basin. The distinct slope typologies largely influence the type of failure mechanism and the behaviour of the flow.

From these observations from literature and observation from cases in Norway, it can be indicated that debris avalanches, which are also called in literature as unchannelized debris flows, occurs mainly in regular slopes and in particular in planar and convex slopes. When the regular slope has some concavities, debris avalanches might move into these depressions and becoming partly channelized or if the erosion is consistent might evolve into a debris flow after a few meters. At slopes with low gradient and no hierarchized drainage basin, observations indicate that debris flows usually initiate as a slide (in soil or debris). At slopes with lowly hierarchized drainage basin and slope with highly hierarchized drainage basin it is observed that only debris flows may develop. Usually in these case most of the them are initiated as surface water-runoff, or a combination of surface water-runoff and small slides (Di Crescenzo and Santo, 2005);

In this study, three flow-like landslides were selected that occurred in distinct slope typologies as previously described:
1. The Aurdal case is a debris avalanche that starts in regular slope as a small planar slide, before moving as a debris avalanche, and finishing as a stream watery flow.

2. The Nesbyen case is a typical example of debris flow in a slope with no hierarchized drainage basin. The debris flow starts as two separate planar slides that converged further down the slope and moved in the channel as debris flow.

3. The Mjåland case is a typical case of debris flows in slope with lowly hierarchized drainage basin. It started as a combination of surface water-runoff and a shallow slide at the hillslope in the upper part and later moves as the typical debris flow with coarse deposit.

2.1.4 Flow Dynamics

Debris flows are distinguished physically from other types of landslides by its interaction between solid and fluid forces. In general, debris flows are driven by gravity driven motion of a finite but changing mass of poorly sorted, water saturated sediments that deform irreversible and maintain a free surface. When the sliding is initiated the sediment water-mixture transform to a flowing, liquid like state, before it transforms to a rigid deposit (Iverson, 1997). Consequently, debris flows are commonly treated as a fluid, hence fluid dynamic laws are applied. Today several models have been developed to interpret the transport of momentum in debris flows, where the conservation of momentum, Newton`s second law found the basic of these models (Breien, 2005).

The forces acting on a debris flow are illustrated in Figure 2.2. If the mass is mobilized due to an increase in gravity compared to friction force, then the retarding and accelerating force will influence the mobilized mass. The accelerating forces are controlled by the effect of gravity due to mass, and the retarding force are controlled by friction components (Norem and Sandersen, 2012).
Figure 2.2. Illustration of the forces acting on a mass moving down a slope. P is the accelerating force, \( \rho \) is the density of the mass, g is the gravitational force, h the height, \( \alpha \) slope angle. F is the total friction force, consisting of the velocity independent friction \( F_c \) and the velocity dependent friction \( F_d \) (Norem and Sandersen, 2012).

The magnitude of a debris flow can be defined as the total volume of materials moved during an event from the source (initiation zone) to the deposition area. This volume is rarely determined by the volume of the failing mass. In most cases the bulk of the involved volume is contributed through entrainment of materials along the propagation direction of the mass (Jakob et al., 2005). According to Iverson (2012), the entrainment process in debris flows can be described as incorporation of solid and fluid boundary material that does not influence the bulk composition of the flow, and can result from erosion of bed material or collapse of channel banks. In the case of entrainment, the volume will increase until the flow reaches the deposition zone and materials start to deposit due to decreased velocity and steepness.
3 Case studies

The three flow-like case studies selected for this study occurred in south of Norway in the counties of Oppland, Buskerud and Rogaland (Figure 3.1). They occurred in steep valley sides, respectively at the valleys of Begnadalen, Hallingdalen and Øvstabødalen. These are steep, u-shaped valleys formed by glacier during the last ice age. All cases were triggered by intense rainfall. Two of them occurred under the same rainfall and snowmelt episode in May 2013 that triggered not only a lot of landslides but also large flood in these regions. The third case occurred in June 2016 after a short and very localized intense rainfall, which is typical in the summer. The events caused damages to buildings and roads, leading to evacuation of the local population and closure of the road for many days. The case studies were selected based on:

- Importance in terms of damage to infrastructure and residents
- Topographic conditions
- Landslide types and slope typology
- Available information from previous studies and observations
- Available topographic information (DEM)

![Map of south Norway showing the locations of the three study areas; 1.) Aurdal case in Oppland, 2.) Nesbyen case in Buskerud and 3.) Mjåland case in Rogaland (Norgeskart, 2018).](image)

**Figure 3.1.** Map of south Norway showing the locations of the three study areas; 1.) Aurdal case in Oppland, 2.) Nesbyen case in Buskerud and 3.) Mjåland case in Rogaland (Norgeskart, 2018).
3.1 Case 1: Aurdal debris avalanche

The first event analysed, and herein called Aurdal, occurred the 22nd of May 2013 at 19.30 at Svenskeplassen, a housing estate in Nord-Aurdal municipality. The event caused major damage to three houses and a garage, before it proceeded down to the main road (E16) and blocked it for several hours.

Nord-Aurdal is a municipality in Oppland county and is a part of the Valdres valley, located by the river Begna which flows through the center of the valley. The area is characterized by large mountains and deep valleys. The region has a typical continental climate, with great temperature differences between winter and summer and low annually precipitation, with peaks during the summer and fall.

The occurrence of the event was described immediately after by several national and local newspapers (Avisa Valdres (Valdres, 2013), Oppland Arbeiderblad (oa.no, 2013) and VG (Mjaaland, 2013)). Later, the event was described in a report by Kronholm and Snilsberg (2013) to assess the landslide hazard in the area. The event was also described in a master thesis by Bekkevoll (2015) as part of the characterization of landslides in Begnadalen. The area has been exposed to two landslides earlier. The first occurred at the 22nd of July 1789 and the other occurred in October 1963 (Kronholm and Snilsberg, 2013).

In the days before the event, the Valdres valley was exposed to heavy precipitation and snowmelt, which resulted in the triggering of several landslides in addition to the described event (Bekkevoll, 2015) and flood in the area. During the day of the event, it was estimated a total water supply of about 53mm from the grid closes to the event (Figure 3.2) (xgeo.no, 2018).
Figure 3.2. Total water supply, including precipitation and snow melt at the location of the event, Svenskeplassen, in the days before and after the event (xgeo.no, 2018).

The event originated from a headland, downslope of a field below Kolsrud farm, 600 meters from the city center of North-Aurdal. The source area is located at 6766402 N and 198463 E, at 632 m. a. sl. on the southwest-facing slope.

The bedrock in the area consists of sandstone, fine-grained conglomerate, shale, clayey shale and gneiss, the bedrock is covered by a thick and badly sorted till cover, which was deposited by glaciers and might be from 0.5 to tens of meters thick. In some of the steeper areas, the till layer is less than 0.5 m (NGU, 2018b) and (NGU, 2018a) (Figure 3.3).
The event is classified as a debris avalanche, which comply with earlier studies conducted by Bekkevoll (2015) and Kronholm and Snilsberg (2013), however the classification of the landslide typology of this event is not straightforward, due to change in the dynamic behavior while the mass was moving downslope. It initiated as a slide is a regular open slope, that is characteristic for debris avalanches, however the final part was somewhat channelized, and the event finished as stream watery-flow (usually observed in debris flows events). Figure 3.4 shows the characteristic traits of the event.
Figure 3.4. Characteristic slide typology of the Aurdal event at different stages.

A large amount of the deposition was deposited around the first houses in the path, where the deposits consisted mainly of large boulders and trees. The remaining materials, consisting of mainly fine debris and water, were deposited at the end of the path.

From a field survey conducted by Bekkevoll (2015), it was observed that the source of the landslide was in the transition zone between topsoil, humus and a thin moraine layer. Further down in the landslide path, the depth of the moraine layer increases. The depth of the soil varies from 0.15 meters in the source area to more than 1.0 meter along the track of the landslide, excluding the landslide deposits (Bekkevoll, 2015).

Following the erosion of materials, the deposition of materials in the central part of the path consists of coarser materials and debris such as trees, boards etc. The larger materials, consisting of boulders and trees (Figure 3.5), were deposited in the central part of the path, with more fine-grained deposit further down the slope, before the final deposition dominated by fine sediments (e.g. clay and silt) and water. The flow stopped 5-10 meters on the west side of the road. Most of the debris was deposited next to the damaged buildings in the central part of the path, and some of the fine-grained sediments were deposited on the main road.
Figure 3.5. Particular of the deposit of the debris avalanche in Aurdal (Photo: Jon Bratrud).

Figure 3.6 shows a summary of the main physical characteristics of this event, obtained from analysis of images and from previous work (Kronholm and Snilsberg, 2013, Bekkevoll, 2015). The remaining parameters were acquired with different methods described in Chapter 4.

![Figure 3.6 showing a summary of landslide parameters and location of calibration point.](image)

**Figure 3.6.** Summary of landslide parameters and location of calibration point. Polygon (white, dotted line) marking the shape of the event, with obtained landslide parameters and calibration point (red point) used to back-analyse the event.

There were multiple factors contributing to instability of soil, which resulted in the release of the debris avalanche. One factor is that the bedrock in the area is corrugated, resulting
in inconsistent thickness of the till layer. Furthermore, there are three joint sets that create loose blocks which results in an unstable slope (Bekkevoll, 2015).

One of the main reasons for the instability resulting in the event is a headland, located between the farmland and treeline, mainly consisting of humus separated from the underlying till layer. This is described by Kronholm and Snilsberg (2013) and Bekkevoll (2015) as one of the main reasons for the instability of the soil, combined with the steep slope along the headland. In general, the slope along the headland is approximately 30°, but the steepest parts are over 45°. Another important factor is the forest road on the upper side of the Kolsrud farm, which has culverts that leads the water to the field above the release area. These factors and a combination of thawing and precipitation resulted in a fully saturated soil (Kronholm and Snilsberg, 2013). This caused an increased pore pressure and probably triggered the initiation of the event.

3.2 Case 2: Nesbyen debris flow

The second event, herein called Nesbyen, occurred on 23th of May 2013 around 02.55 at Lysverkboligen, a housing estate in Nes municipality. The event caused damage to two houses and one caravan, and 21 residents were evacuated from the area. The event also caused the road Alfarveien, a road parallel to Riksvei 7, to be blocked for several hours.

Nes is a municipality in Buskerud county and is a part of Hallingdalen valley, located by the river Hallingdalselva. The area is dominated by high mountains and deep valleys. The region has a typical continental climate, with great temperature differences between summer to winter and low annually precipitation, with peaks during the summer.

The event was described shortly after by several local and national newspapers (Hallingdølen (Hallingdolen, 2013), NRK Buskerud (Solli et al., 2013, Karstensen and Grimstveit, 2013), VG (Gallefoss, 2013) and TV2 (Pedersen, 2013)). Later on, the event was described in a report by NVE (Bargel and Lund, 2016) and a report by NGI (Domaas, 2013). The event was also mentioned in a master thesis by Lund (2013).

At the time of the event, it was not reported any other landslide in the area, however, there were several landslides in the regions and other previous landslide occurred in these slopes in 2007 and 2011 triggered by heavy precipitation.
One week before the landslide, it was heavy precipitation in the area, especially on the 16th and 17th of May where approximately 50 mm of precipitation fell over the area. During May 22nd and 23rd, it was measured 28 mm precipitation at the gauging station in Nesbyen. The last eight days before the event, it was measured 95 mm precipitation, which is double of the monthly mean precipitation for May in Nesbyen (Domaas, 2013). The heavy precipitation over several days increased the pore pressure, which made the ground saturated. At the night before the event it was registered a total water supply, including precipitation and snowmelt, of approximately 28 mm from the grid closest to event (Figure 3.7) (xgeo.no, 2018).

![Figure 3.7](image_url) Total water supply, including precipitation and snowmelt at the location of the event, Lysverkboligen, in the days before and after the event (xgeo.no, 2018).

The event originated as small slides close to an old forest road in the valley side, above the housing estate at N6731630 and E175631, at 381 m and 390 m. a. sl., on the east-facing slope.

The bedrock in the area consists of migmatite, gneiss and gneiss with granite and granite pegmatite, in addition to areas with quartzite, gabbro and amphibolite, the bedrock is covered by a thick and badly sorted till cover, which was deposited by glaciers and can be from 0.5 to tens of meters thick. By the river, the soil is dominated by glacifluvial and fluvial deposits, (NGU, 2018b) (NGU, 2018a) (Figure 3.8).
Figure 3.8. Geology of the area. A) Bedrock geology of Nesbyen (NGU, 2018a). B) Quaternary deposits in Nesbyen (NGU, 2018b). The red square marks the location of the event.

The Nesbyen case is a typical example of debris flow in a slope with no hierarchized drainage basin. The debris flow starts as two separate planar slides in moraine material, that downslope converged and moved in the channel as a debris flow. The debris flow follows the gullies down towards Lysverkboligen, south of a bank constructed after a landslide in 2007 (Bargel and Lund, 2016). The debris flow did not develop clear margins along the propagation direction, making the flow partly channelized. The debris flow settled as a small fan (Figure 3.9).
Figure 3.9. Characteristic slide typology of the Nesbyen event at different stages.

The event occurred on loose materials that mainly consist of till and top soil. The till layer is several meters deep and have been exposed to heavy erosion in the flow path. In some of the steeper areas the layer is less than 0.5 meter. The till layer covers the entire valley side, all the way down to the road Alfarvegen, from there, the soil transformed to glacifluvial and fluvial materials.

The deposition is divided in two parts. In the upper part, the deposit consists of large debris, such as trees and boulders. These materials were deposited shortly after the slope began to level out. Most of the materials were deposited by the first house and caravan impacted by the debris flow. The water and fine-grained materials, such as mud, clay and silt, continued to flow before it was deposited around the last house.

A number of different landslide parameters were collected and estimated for the case study. These parameters are provided in Figure 3.10. Most of the landslide parameters were obtained from images and from previous work (Domaas, 2013, Bargel and Lund, 2016). The remaining parameters were acquired with different methods described in Chapter 4.
Figure 3.10. Summary of landslide parameters and location of the calibration point. Polygon (white dotted line) marking the shape of the event, with the obtained landslide parameters and calibration point (red point) used to back-analyse the event.

The condition leading to the initiation of the debris flow was a combination of steep slope in proximity of the forest road and the poor drainage system. The hillside has a slope of approximately 28 – 31˚ and are partly covered with deposits from ravines and earlier landslides (Lund, 2013). In the forest road, culverts had been constructed to lead the stream under the road, but they were blocked. The combination of rainfall, blocked culverts along the road and the fully saturated ground, lead to the stream flooding over the road and made the road waterlogged (Domaas, 2013).

3.3 Case 3: Mjåland debris flow

The third event, herein called Mjåland, occurred on Sunday the 2nd of June 2016 between 14.30 and 16:00, at Mjåland in Gjesdal municipality. The area is relative remote with few inhabitants and it was only reported minor damage on a power line, and the state highway fv.45 into Mjålandslona, approximately 7 km north of Byrkjedal, was blocked by debris and closed for several days (Figure 3.11).

The occurrence of the event was described by several national and local newspapers (Stavanger Aftenbladet (Bie and Fosse, 2016), Fædrelandsvennen (Ihme, 2016) and TV2 (NTB, 2016)). Later, the event was described in a report by Multiconsult (Rese, 2016) and in a master thesis by Bayissa (2017).
Gjesdal is a municipality in Rogaland county and is a part of Øvstabødalen valley. The area is characterized by large mountains and deep valleys but also maritime areas. The climate in the region of Rogaland is maritime with large differences between coastal areas and the elevated inland valleys. The inland have a cooler climate compared to the coastal areas, which is mild and moist (NorskKlimaservicesenter, 2017). The precipitation is highest in the fall and winter, and lowest during late spring and summer.

![Image](image.jpg)

**Figure 3.11.** Mjåland event (Rese, 2016)

The precipitation event that triggered the debris flow was very local, making the interpolated rainfall observations from rain gauges inaccurate. By using radar, it was estimated a total precipitation of up to 45 mm, and the rain lasted approximately 2 hours from 14.30 to 16.30. During the intense rainfall period, another debris flow occurred in the other side of the mountain (Devoli et al., 2017). The data obtained from radar provided more accurate precipitation estimation compared to the data obtained from the grid closest to the event, that was estimated to be 24 mm (Figure 3.12) (xgeo.no, 2018).
The debris flow was released from a south-east facing slope with the source area located at 6551736 N and 4130 E, at 430 m. a. sl.

The bedrock in the area mainly consists of different variations of gneiss, such as diorithic and granitic gneiss, in addition to fine to medium grained quartz and feldspar rich gneiss and migmatite. In the upper part of the mountainside the bedrock is visible, but some areas are covered by a thin layer of till. The thickness and spread of the till layer increases down the mountainside. Further down, the soil transforms from till material to a thick layer of old landslide deposits. By the river, the soil is dominated by glacifluvial deposits that varies from fine grained sand to pebbles and large blocks, (NGU, 2018b, NGU, 2018a) (Figure 3.13).
Figure 3.13. Geology of the area: upper) Bedrock geology of Mjäland (NGU, 2018a), lower) Quaternary deposits in Mjäland (NGU, 2018b). The red square marks the location of the event.

The event can be characterized as a fully channelized debris flow with a lowly hierarchized drainage basin (Figure 3.14). The event started as surface water-runoff in the upper part of the plateau. At an elevation of about 670 m the slope angle changed and the accumulation of water from the small streams converged, provoking the erosion and a shallow soil slide started. This slide, moved in a retrogressive way and at the same time moved downwards as a debris flow, eroding and entrained more material. Through entrainment, the volume increased drastically, from an initiation volume of only tens of cubic meters to a final volume of thousands of cubic meters. The flow was channelized with high velocity, developing clear margins along the propagation direction before settling as a large fan, covering a large portion of the river and valley side.
The event occurred on loose materials that primarily consists of old landslide deposits and some till. The till layer covers the upper part of the path, with a depth of less than 0.5 m due to the steep slope. Most of the path is covered by old landslide deposits that are thicker than 0.5 m, and images from the area indicate that the layer in some areas are thicker than 3 meters.

Most of the materials are deposited at the road and the river. The deposition consists mainly of blocks of different sizes, but also finer materials such as mud and silt. The eroded materials are mainly old landslide deposit, but there are also some till materials from the upper part of the slope. The soil partly covering the mountainside mainly consists of till materials.

Figure 3.15 present a summary of the parameters collected from this case from different sources. The parameters were estimated and collected from images and previous work (Rese, 2016, Bayissa, 2017). The remaining parameters were acquired with different methods described in Chapter 4.
Figure 3.15. Summary of landslide parameters collected and location of the calibration point. Polygon (white dotted line) marking the shape of the event, with the obtained landslide parameters and calibration point (red point) used to back-analyse the event.

The area is located in a valley with steep slopes. The first 100 meters up the hillside have a slope at 20°, followed by a slope at 20-30° before it reaches 30-40° for the upper part of the hillside (Rese, 2016). The release area is located almost at the top of the mountain at approximately 40° inclination. This area is only partly covered by a thin layer of soil, which is quickly saturated when exposed to intense and heavy precipitation. The combination of a thin soil layer, steep slope (40°) and heavy and intense precipitation were the causes of the debris flow.
4 Data acquisition and methodology used

This chapter gives an account of the data, methods and tools used to complete the aim of the master thesis. RAMMS and DAN3D are the 2D numerical runout models applied in this study on the three selected case studies. They require several types of input data, that need to be acquired and generated. The data processing and models are described in the following section. A general overview of the required data and methods is also provided below.

Data:
- DEM/path topography
- Release area polygons/source depth
- Release volume
- Erosion polygons
- Erosion rate/erosion parameters
- Friction parameters

Methods:
- Literature review
- Data acquisition for the selected case studies
- Downloading and pre-processing of DEMs
- DEM evaluation
- Building the models
- Run-simulation (back-analysis)
- Indexing and evaluation process

4.1 Topographic data and Digital elevation models (DEM)

To run the numerical runout models, input files that define the topography are required. One of the most used topographic input data applied to runout models are digital elevation models (DEM). Digital elevation models are digital representations of Earth’s relief and are a source of elevation data used in geoscientific applications (Toutin, 2008). DEMs are described as a spatially geo-referenced dataset where the topographic have been encoded. They are used to carry out different types of geomatics and geoscientific analysis. DEMs are typical used in hazard and risk assessment to conduct runout modelling, calculation of mass balance on glaciers and modeling watershed. The use of topographic information in various processes, such as construction, exploration, mapping etc. has made them more effective and accurate (Toutin, 2008).
DEMIs are derived from topographic data by using contour data (Hutchinson & Gallant, 2000), Laser (e.g. LiDAR), from stereo and ground control point (GCP) collection, radar, etc. by using four main approaches (Kääb, 2005):

1. Terrestrial methods include, combined distance and angle measurements, terrestrial laserscanning, terrestrial photogrammetry and optical levelling. Terrestrial methods require direct access to the measuring points to obtain the geometry.

2. Airborne methods include, photogrammetry, laserscanning and synthetic aperture radar. The airborne methods work for different platform types, such as airplanes and helicopters.

3. Spaceborne methods include, satellite stereo imagery, interferometric SAR, LiDAR altimetry and RADAR altimetry. By using image matching techniques, applying optical imagery can provide spatial image resolution as high as 0.6 m (Quickbird).

Photogrammetric and LiDAR are described more in detail since the DEMs applied to the study have been prepared from photogrammetry and LiDAR based data.

Photogrammetry is a method to obtain geometry based on processing of images that mainly creates product such as digital terrain models (DTM), digital surface models (DSM), 2D and 3D reconstruction and classification of objects for mapping, and visualization of maps (Baltsavias, 1999). Airborne photogrammetry has been used to generate DEMs since the 1960s and calculates the surface elevation by using two different looking angles within the visible or near-infrared part of the electromagnetic spectrum. Today optical digital scanners are more commonly used to generate DEMs (Bühler et al., 2011).

Airborne DEM acquisition methods using photogrammetry include several approaches, such as analogue and analytical photogrammetry based on hardcopy photography, digital photogrammetry based on digital cameras or digitized photography/frame imagery and digital photogrammetry based on other digital sensors (Kääb, 2005).

LiDAR (Light Detection And Ranging) scanners become the most common approach in the generation of accurate terrain models (Reutebuch et al., 2005). By using data obtained from terrestrial laser measurements, or from airborne laserscanning by sampling a large number of points to acquire 3D representation of the topography of an area to produce terrain models.
Compared to photogrammetric methods, LiDAR uses active methods (Kääb, 2005), which means that it provide its own source of light to obtain the measurements.

Terrestrial laser scanning (TLS) or ground based LiDAR are based on the time-flight distance measurements of an infrared laser pulse to obtain a point cloud representing the topography of an area. The infrared laser pulse is scattered when it reaches an object such as the ground surface, vegetation and buildings, and a portion of the laser pulse are reflected back to the scanner. By measuring the time flight of the pulse, the scanner calculates the distance. This is conducted for a larger area to obtain a 3D-map of the topography (Oppikofer, 2015).

Airborne LiDAR scanning is based on the principles that the travel time of a laser impulse sent from an aircraft sensor, reflected at the terrain surface and received again at the aircraft sensor, can be used to estimate the distance between sensor and terrain surface (Kääb, 2005). The laser footprint is approximately circular and varies with the surface topography and the scan angle. Airborne laser uses active, high-power, collimated and monochromatic sensors, and generally point sensors with polar geometry, direct acquisition or encoding of 3D coordinates, pointwise sampling, and airborne laser have no imaging or monochromatic images of inferior quality (Baltsavias, 1999).

LiDAR based data can be applied to a wide range of applications and tools. The laserscanning provides a DSM (Digital surface models) with a resolution from cm to meters. The data can be used to generate DEM, different types of surveying, e.g. glacier in arctic environments (Kääb, 2005), unstable rock slopes and rock fall areas to detect changes in topography (Oppikofer, 2015) and forest and vegetation monitoring (Reutebuch et al., 2005), etc.

DEM’s are mainly characterized by their spatial resolution (point density), point distribution and horizontal and vertical accuracy (Kääb, 2005). DEMs can be generated with different spatial resolutions, thus affecting the accuracy and their ability to interpreted topographical features. The accuracy of DEM and DEM-derived products is influenced by several factors, including the source of the elevation data, the horizontal resolution and vertical precision of the represent elevation data, the methods used to generate DEMs from the elevation data, the structure of the elevation data and the topographic complexity of the represent landscape (Thompson et al., 2001). To characterize the spatial resolution, the terms high resolution (< 5 m pixel dimension), medium resolution (5-100 m pixel dimension), low resolution (100-1000 m) and very-low resolution systems (> 1000) m can be applied (Kääb, 2005).
4.1.1 DEM acquisition and processing

The applied DEMs were downloaded from the two webpages Høydedata.no and Geonorge.no, developed and operated by the Norwegian Mapping Authorities (Kartverket).

The webpage Høydedata.no was developed to provide free and easy access to topographic elevation data for Norway from the National Detailed Elevation Model project. The project is using LiDAR data to cover Norway with highly detailed topographic information. The object of the project is to develop a nationwide detailed DEM with a resolution of 1x1 m by the end of 2022 (Kartverket, 2017). The webpage also provides the possibility to access and download elevation data from specific projects conducted at different time and places. In addition, DEMs were also accessed and downloaded from Geonorge.no, a webpage that include a catalog of all the public map data in Norway. In contrary to Høydedata.no the webpage not only include elevation models, but also a wide range of different maps (e.g. topographic, road maps, railway maps) developed by different public services and departments for public utility.

The following required elevation data were downloaded from the previous mentioned webpages for each of the three case studies:

a) prepared DEMs with resolution of 1m and 10m based on LiDAR data (called herein Høydedata);

b) point clouds from LiDAR (called herein Generated)

c) DEMs with a resolution of 10m based on contours and elevation points (called herein Geonorge).

An overview of the downloaded data and DEMs applied to the models is provided in Figure 4.1.
The dataset *Høydedata* is from the National Detailed Elevation Model project, based on LiDAR data and processed by the Norwegian Mapping Authorities with Triangulation and then filled in with nearest neighbour interpolation to generate DEMs.

The dataset *Generated* was downloaded as a point clouds and processed in ArcMap by using different tools. First the tool “Create LAS Dataset” was applied, which creates a LAS dataset, which is a format for storing LiDAR data, referencing the LAS files (Esri, 2018a). Later the, “Make LAS Dataset Layer” tool was used, which creates a LAS dataset layer that filter the LiDAR data for class code 2, that represents ground measurements (Esri, 2018b). The resulting layer was used as input for the “LAS Dataset To Raster tool”, that use the elevation data stored in the LiDAR points referenced by the LAS dataset to generate a raster file (Esri, 2017). The interpolation method used in the tool was Inverse Distance Weighting (IDW). The dataset consists of DEMs with 1m and 10m grid size/resolution.
The interpolation method used in the tool was Inverse Distance Weighting (IDW), where the estimates are based on values located near the interpolated point weighted by the distance from the interpolated point. The technique applies a linearly weighted combination of a set of sample points to determine the cell values, where the weight is a function of inverse distance (Naoum and Tsanis, 2004). The dataset consists of DEMs with 1m and 10m grid size/resolution.

The dataset Geonorge was downloaded as DEMs with a 10m grid size/resolution, based on contours and elevation points generated from a hybrid DTM structure by using the software SCOP (Simple Concurrent Object Oriented Programming) (Kartverket, 2018). The dataset was resampled to 1m by using the “Resample” tool in ArcMap. The tool changes the spatial resolution of the raster dataset to 1m by applying the desired interpolation method (Esri, 2018c). In this case the Bilinear interpolation method was applied to the raster files. The interpolation method determine new cell values by estimating the weighted distance average for the four nearest input cells (Esri, 2018c).

All the DEM files datasets were then processed with the tool “Fill” in ArcMap, to remove sinks and imperfections in the datasets. Before the data can be applied to the runout models, they needed to be processed and prepared into the required format. Initially the DEM files are in raster format but are converted to ESRI ASCII grid files (asc.). This is conducted in ArcMap by applying the tool “Raster to ASCII”. The ESRI ASCII grid (Figure 4.2) is then ready to be applied to RAMMS but need further processing before applied to DAN3D.
Fi
Figure 4.2. Example of the converted ESRI ASCII grid.

The DEM files were further processed in Scripter (extension of Surfer) and Surfer 8 (by Golden Software, Inc) to generate path topography files and source topography files in the form as ASCII elevation grid files (.grd), that can be applied to DAN3D. The path topography file is defined as the topography of the sliding surface over which the slide flows, and are created from pre-landslide DEM. The source topography file is defined as the vertical depth topography of the sliding mass at the time step \( t = 0 \) (Hungr, 2010). The gridded map files need to have the same spacing and the same amount of grid nodes with maximum 1000 nodes on each axis. In the case when there is no available post-landslide DEM, the source topography file must be created from a polygon made in ArcMap. The polygons were given values based on the depth of the scarps, estimated from images and tools in ArcMap, while the area outside the polygons was given a value of 0 to blank the area. The source topography files were prepared in ArcMap for the dataset Geonorge and all source topography files used for the Mjåland case. The preparation of the grid files in this paper was prepared according to the detailed manual by Dahl (2010) to prepare grid files used in DAN3D. It is also possible to create erosion maps if the material properties changes within the location (Hungr, 2010). It was assumed that the material properties were constant for all the cases, consequently no erosion maps were prepared and
applied. The processing steps to prepare the DEM files to RAMMS and DAN3D are described in Figure 4.3.

![Flow chart of the processing of DEM to the runout models.](image)

**Figure 4.3.** Flow chart of the processing of DEM to the runout models.

### 4.2 Landslide Parameters

In addition to the DEMs the models require a range of different input data. The landslide parameters were obtained through analysis of the cases by using previous reports, papers and images describing the events. The writer did not conduct any field work, due to limited time and the maturity of the landslide, the specific parameters required for the two models are listed in Table 4.1 and the collection of them are described in the following subsections.
Table 4.1. The parameters required to conduct simulation with erosion in the 2D numerical models used.

<table>
<thead>
<tr>
<th>RAMMS</th>
<th>DAN3D</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEM</td>
<td>Path topography (DEM)</td>
</tr>
<tr>
<td>Release area polygon</td>
<td>Source depth file</td>
</tr>
<tr>
<td>Release volume</td>
<td>Internal friction angle</td>
</tr>
<tr>
<td>Erosion polygon</td>
<td>Maximum erosion depth</td>
</tr>
<tr>
<td>Erosion parameters</td>
<td>Erosion rate</td>
</tr>
<tr>
<td>Friction coefficient (Mu)</td>
<td>Friction coefficient (Mu)</td>
</tr>
<tr>
<td>Turbulence coefficient (Xi)</td>
<td>Turbulence coefficient (Xi)</td>
</tr>
</tbody>
</table>

Preparation of landslide polygons

The polygons of the landslides and the associated release areas were defined based on preliminary polygons of the case studies provided by NVE. The polygons were modified based on images and satellite photos taken shortly after the events. Polygons of the release areas are illustrated in Figure 4.4.

Figure 4.4. The polygons of the release areas for the case studies. A) Aurdal, B) Nesbyen, C) Mjåland.

Volume estimation

The total volume and the initial released volume were estimated for all the cases, either collected from previous works or calculated in ArcMap by using the difference of pre and post DEMs.

For the Aurdal case, the volume was estimated in two previous works. In a report assessing the hazard of future landslides in the area, Kronholm and Snilsberg (2013) estimated the total volume of the landslide to be 360 m$^3$, while Bekkevoll (2015) calculated the total volume of the landslide to be approximately 2650 m$^3$ by comparing LIDAR data from before and after the event. However, this estimation from Bekkevoll (2015) only covers the area from the source to
the first house in the flow path, due to uncertainties in the lower parts of the landslide path. Because of the large uncertainties for the estimations conducted by Bekkevoll (2015) and Kronholm and Snilsberg (2013), ArcMap was used to calculate release volume and total volume. The release volume was estimated to 851 m$^3$ and the total volume to 3140 m$^3$.

For the Nesbyen case, the initial volume was assessed by Domaas (2013) to be approximately 500 m$^3$. The event began as two separate shallow slides that merged further down the slope into one debris flow. The Northern release area had a volume of 300 m$^3$ and the one located south had a release volume of 200 m$^3$. The total volume of the event was calculated in ArcMap to be 3500 m$^3$.

The Mjåland case was examined by Rese (2016) that estimated the release volume to be very low without specify, and that the total volume of the flow increased drastically due to entrainment along the flow path. In addition, Bayissa (2017) estimated the release volume to be approximately 92 m$^3$. The total volume of the event was calculated in ArcMap to be 25205 m$^3$.

**Erosion polygons and parameters**

Erosion and entrainment of material are important factors in debris flow modeling. Erosion of sediments along the flow path causes flow bulking, that highly influence the runout behavior of the debris flows (Frank et al., 2017). In the case studies erosion is an important factor and necessary to get the most accurate flow volume and thus runout behavior.

RAMMS require polygons that represent the area that are exposed to erosion. The erosion polygons are based on the existing landslide polygons and images of the cases. In addition to the polygons the model requires erosion parameters, these parameters are defined based on the geological properties of the area and values defined from images. On the contrary, DAN3D does not require any polygons, but bases the erosion on the two parameters, maximum erosion depth and an erosion rate that is defined by the initial slide volume, the final slide volume and the length of the erodible zone. The parameters were estimated in ArcMap or collected from literature, to provide a precise estimation.
4.3 Numerical modelling

Several approaches have been developed to understand and evaluate the risk related to landslides. To assess the hazards related to debris avalanches and debris flows it is important to have methods and tools that can be used to assess their dynamic behaviour and impact in different topography settings. An important method to consider this risk is modelling the runout.

To predict the runout of landslides, three different approaches can be used (Figure 4.5).

1) Analytical methods which include lumped mass and continuum mechanics models to predict the behavior of debris flows and the motion of the mass from initiation to deposition and can estimate intensity and hazard extent.

2) Empirical methods, that estimate the extent of the runout area by applying the correlations of the observational data (McDougall and Hungr, 2004).

3) Numerical methods, that are applied in this thesis, are mainly based on continuum fluid mechanics, that utilize the conservation equation of mass, momentum and energy to describe the dynamic motion of debris. It also use a rheological model that describe the involved materials behavior during the flow (Quan Luna et al., 2014). Regarding the classification of the different types of runout prediction, numerical methods are in some cases regarded as individual class of methods (Quan Luna, 2012) or as an subdivision of analytical methods (Fell et al., 2005).
Figure 4.5. An overview of the different runout prediction approaches. The approach followed in this thesis are represent with arrows and white boxes.

**Numerical models**

Numerical simulation models are physical based, deterministic approaches, based on depth-average flow equations and simple flow resistance terms. Numerical methods are widely used to study the relations between driving forces and resisting forces within a slope and its interaction with the soil/rock mass and external factors (Fell et al., 2005). Numerical runout models make it possible to predict runout distance, flow velocities and impact pressures for different landslide types. Several types of runout models have been developed to provide more accurate tools to predict landslide behavior in three-dimensional terrain (Christen et al., 2010). This make it essential to select the appropriate model parameters. Back-analyses of well documented debris flow is the preferred method for model parameterization in engineering applications (Schraml et al., 2015). An overview of a selection of numerical runout models are listed in Table 4.2.
### Table 4.2. List of numerical runout models.

<table>
<thead>
<tr>
<th>Model</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>DAN</td>
<td>Hungr (1995)</td>
</tr>
<tr>
<td>DAN3-D</td>
<td>McDougall (2006)</td>
</tr>
<tr>
<td>FLO-2 D</td>
<td>O'Brien et al. (1993)</td>
</tr>
<tr>
<td>D-CLAW</td>
<td>George and Iverson (2014)</td>
</tr>
<tr>
<td>MassMove2D</td>
<td>Beguería et al. (2009)</td>
</tr>
<tr>
<td>RAMMS</td>
<td>Christen et al. (2010)</td>
</tr>
</tbody>
</table>

The models use the concept of equivalent fluid and assume constant density and incompressibility of the flowing material, in addition to the shallow water approximation (Schraml et al., 2015). Foremost numerical dynamical models are based on continuum fluid mechanics. Continuum fluid mechanics apply the conservation equation of mass, momentum and energy to describe the dynamical motion of the landslide mass, in addition to a rheological model to describe the material property of debris (Quan Luna, 2012). Thus, the methods have the ability to model the flow path of the debris and related characteristics (e.g. flow velocity, flow height, acceleration, impact pressure, runout distance) by using equations with a selected rheological model capable of describing the properties of the flow (Chen and Lee, 2000).

**The continuum depth average method**

The continuum mechanical theory was first developed by Savage and Hutter (1989). This theory manages to describe the dynamics of motion of a finite mass down an incline surface. Numerical models based on continuum mechanics consider a heterogenous and multiphase sliding mass of a flow as continuum, thus indicate that the depth and the length of the flow is larger compared to the dimension of the individual particles in the flow. The dynamics of debris flows can then be modelled by applying an equivalent fluid, where the rheological properties are of a such character that the simulated flowing masses bulk behavior have approximately the expected bulk behavior of the real two-phase mixture (Pirulli and Sorbino, 2008). The equivalent fluids dynamical behavior can be described by the conservations laws of mass and momentum given by:
\[ \nabla v = 0 \]  

\[ \rho \left( \frac{\partial v}{\partial t} + v \nabla v \right) = -\nabla \sigma + \rho g \]

where \( v(x, y, z, t) = (v_x, v_y, v_z) \) is the velocity vector of the moving mass in a three-dimensional \((x, y, z)\) reference system, \( \sigma(x, y, z, t) \) is the Cauchy stress tensor, \( \rho \) the density of the mass, and \( g(x, y, z) = (g_x, g_y, g_z) \) is the gravitational acceleration vector. Assuming the flow is incompressible and that the depth of the debris flow is much smaller than the length, by integration in depth direction of Equation 1 and 2 it is possible to obtain the depth-average equation of motion (Savage and Hutter, 1989).

\[ \frac{\partial h}{\partial t} + \frac{\partial h v_x}{\partial x} + \frac{\partial h v_y}{\partial y} = 0 \]  

\[ \rho \left( \frac{\partial v_x h}{\partial t} + \frac{\partial h v_x^2}{\partial x} + \frac{\partial h v_x v_y}{\partial y} \right) = \frac{\partial (\sigma_{xx} h)}{\partial x} - \tau_{zx} + \rho g_x h \]  

\[ \rho \left( \frac{\partial v_y h}{\partial t} + \frac{\partial h v_x v_y}{\partial x} + \frac{\partial h v_y^2}{\partial y} \right) = \frac{\partial (\sigma_{yy} h)}{\partial y} - \tau_{zy} + \rho g_y h \]

Where \((v_x, v_y)\) is the depth-average velocity in \((x, y)\) directions, \( h \) is the flow depth, \((\tau_{zx}, \tau_{zy})\) is the shear resistance stress, \((\sigma_{xx}, \sigma_{yy})\) is the depth average normal stress, and \((g_x, g_y)\) is the gravitational acceleration (Savage and Hutter, 1989). Equation 3, 4 and 5 are the governing equations of the numerical models and are solved by different formulations of solution reference frames. The models are based on two dimensional equations, simulated over a three-dimensional terrain (Breien, 2005).

The solution reference frames applied to the models are classified as Eulerian or Lagrangian. Eulerian reference frame is the conventional method in computational fluid dynamics. The reference frame is fixed in space, analogous to an observer standing still as the flow passes. It requires the solution of more complex equations using a dense fixed computational grid. The Lagrangian reference frame moves with the local velocity, analogous to an observer on top of
the flow in motion. This approach simplify the governing equations and do not waste time and resources in void zones (Quan Luna, 2012).

**Rheology**

When applying numerical runout models that are based on continuum mechanics the models require a rheological model to describe the materials characteristic of the flow. The rheology of the flow can be described as the resistance force working within the flow and at the interface between the flow and the bed path. This resistance force is expressed with the term basal rheology (Quan Luna, 2012). The rheological models applied to debris flows use the concept of equivalent fluid to model the behaviour of the flowing masses. This is conducted by relating the motion of the flow and the stress states to obtain the conservation of mass and momentum (Breien, 2005).

There are several rheological models, with some of the most common flow resistance terms applied to dynamic runout models being: 1) Bingham rheology, were resistance is a function of flow depth, velocity, constant yield strength ($T_c$) and dynamic viscosity ($\eta$) (Coussot, 1997), 2) Frictional rheology, were resistance is based on the pore fluid pressure and the relation between the effective bed and normal stress at the base (Hungr and McDougall, 2009), 3) Quadratic rheology, were the resistance that applies the viscous term defined in Bingham equation and incorporates a turbulent contribution to the yield (O'Brien et al., 1993), 4) Voellmy rheology, were resistance features a velocity-squared resistance term (turbulent coefficient) and a Coulomb-like friction (apparent friction coefficient) (Voellmy, 1955).

The two selected dynamical numerical runout models used in this thesis, use the Voellmy model, because several studies have found that the Voellmy model provides good results in debris flow back-analyses (Hungr and McDougall, 2009, Hussin et al., 2012, Pirulli and Sorbino, 2008).

**RAMMS**

RAMMS (RApid Mass Movements Simulation) is a numerical simulation model used to calculate the motion of geophysical mass movements such as snow avalanches, debris flows and rock falls from initiation to runout in three-dimensional terrain (Bartelt et al., 2013). The model is used by landslide experts to provide understanding of the dynamics of geophysical mass movements in complex terrains for mitigation measures and hazard mapping. RAMMS
was developed at the WSL Institute for Snow and Avalanche Research SLF in Switzerland and originally designed to provide a tool to model snow avalanches but was later updated to include the possibility to model debris flows and rockfalls. The model includes 3 modules: RAMMS: Avalanche, RAMMS: Rockfall and RAMMS: Debris flows. The calibration and validation of the modules were conducted at the full-scale test sites at St. Léonard/Walenstadt for rockfall and mitigation measures, Vallée de la Sionne for snow avalanches and Illgraben for debris flows (Bartelt et al., 2017).

The RAMMS: Debris flow module is designed to model fast flowing flows that consist of rocks, where the interstitial fluid is mud. It uses the depth-average equation applied to a fixed Eulerian coordinate system and estimate the slope-parallel velocities and flow heights (Bartelt et al., 2013). The advantage with RAMMS is its ability to predict the runout path, velocity, flow height and impact pressure in a two and three-dimensional environment (Hussin et al., 2012). It applies the Voellmy-Salm fluid flow continuum model (Salm, 1993), which is based on the Voellmy-fluid flow law and characterize the debris flow as a hydraulic-based depth average continuum model (Quan Luna et al., 2014).

The release area is defined by the user as a polygon, and the model provides two different options for characterization of the release area, block release or hydrograph. In the case of block release the release height is determined by the user, and the volume is calculated. The other possibility is to use a hydrograph which require the knowledge of the amount of material that flow past a specific location in the channel. Bartelt et al. (2017) recommend using block release for small unchannelized debris flow and hydrograph for channelized debris flows.

RAMMS use the momentum as a stopping mechanism, which is the product of mass and velocity for an object. It summed up the momenta for all grid cells at each dumb step and compare it with the sum of the maximum momentum. The simulation is aborted, and the flow is stopped when the percentage is below the user-defined threshold (Bartelt et al., 2017).

The new version of RAMMS: Debris flow (v1.7.0) have been updated with a new entrainment model. The newly introduced entrainment model will increase the accuracy of the runout of debris flows. The algorithm used in the new model predicts the depth and erosion rate as a function of basal shear stress and are based on analysis of erosion measurements conducted at the Illgraben catchment in Switzerland (Frank et al., 2015). The key features of the model are given in Table 4.3.
DAN3D

The DAN3D model was developed at the University of British Columbia in Canada to provide a 3D extension to the already existing 2D model DAN, proposed by Hungr (1995), (McDougall, 2006). The model applies a semi-empirical approach based on the concept of equivalent fluid defined by Hungr (1995). Landslide materials are complex and heterogeneous, thus DAN3D model them as a hypothetical material governed by the rheological relationship between internal and basal rheology. The model applies a Lagrangian numerical method modified from Smooth Particle Hydrodynamics (SPH) to solve the depth-average equations of motion for an equivalent fluid (McDougall, 2006). The model also has the ability to model several types of rheology, e.g. Frictional, Plastic, Newtonian, Bingham and Voellmy. DAN3D use a source topography file, defined as the vertical depth topography of the sliding mass at the time step $t = 0$, to express the release area (Hungr, 2010).

To confine the internal stress states in DAN3D the internal friction angle was introduced (McDougall, 2006). The internal friction angle defines the amount of internal friction within a material. The angle of friction varies between 25 – 35° for till deposits according to a study conducted in England by Bell (2002). DAN3D applies a user defined stopping criteria, that make it stop after a predetermined duration of maximum 1000 seconds or be stopped manually by the user during the simulation (Schraml et al., 2015).

In DAN3D the erosion factor is based on an erosion rate and is defined as the bed-normal depth eroded per unit flow depth and unit displacement (Hungr, 2010). The erosion rate is based on the input parameters initial slide volume, final slide volume and length of erodible zone. DAN3D uses an empirical approach based on the user -prescribed erosion velocity ($E$), that express the bed-normal depth eroded per unit flow depth and unit displacement. Entrainment is limited by a user defined maximum erosion depth, defined within the entrainment zone (Hungr and McDougall, 2009). The key features of the model are given in Table 4.3.
4.3.1 Building the numerical Models

The model RAMMS requires topographic input in the format ESRI ASCII (txt.) files. The source area was defined by a polygon made in ArcMap and imported to RAMMS. There are two possible methods to define the release area/volume, either Block release or input hydrograph. The choice depends on type of debris flow and available data. Bartelt et al. (2017) recommend using block release with a given initial depth in the case of small unchannelized debris flows, and input hydrograph in the case of channelized debris flows. In this paper the release areas will be defined as block release for all the cases, due to the lack of available data to construct input hydrographs (see Chapter 4.3.3).

RAMMS provides several default values for different parameters in the simulation window. The default value for density (2000 kg/m3) was kept, which is recommended if there is no available information on the debris flow material. The active-passive earth pressure coefficient, lambda was kept at its recommended default value at 1. If the value is changed it may lead to numerical instabilities. The stop parameter which is defined as percentage of total momentum was kept at its default value at 5%.

The model DAN3D requires the topographic input files to be in the form of an ASCII elevation grid file (.grd). The control parameters used in DAN3D include number of particles simulated, the erosion rate, and number of materials to be simulated. It is possible to choose between five different rheologies: Frictional, Plastic, Newtonian, Bingham and Voellmy. The selected rheology requires input for material properties. The preferred rheology was Voellmy as used in

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<table>
<thead>
<tr>
<th></th>
<th>RAMMS</th>
<th>DAN3D</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Rheology:</strong></td>
<td>Voellmy</td>
<td>Frictional, Voellmy and Bingham</td>
</tr>
<tr>
<td><strong>Solution Approach</strong></td>
<td>Continuum Integrated</td>
<td>Continuum Integrated</td>
</tr>
<tr>
<td><strong>Numerical scheme</strong></td>
<td>Finite difference</td>
<td>SPH</td>
</tr>
<tr>
<td><strong>Reference frame</strong></td>
<td>Eularian</td>
<td>Lagrangian meshless</td>
</tr>
<tr>
<td><strong>Grid</strong></td>
<td>Fixed</td>
<td>Affiliated to the flow</td>
</tr>
<tr>
<td><strong>Source</strong></td>
<td>Block release and hydrograph</td>
<td>Block release</td>
</tr>
<tr>
<td><strong>Stopping criteria</strong></td>
<td>Percentage of momentum</td>
<td>User defined duration</td>
</tr>
<tr>
<td><strong>Pressure term</strong></td>
<td>Dynamic $k_{up}$</td>
<td>$k_a = k_b = 1$</td>
</tr>
<tr>
<td><strong>Variation of rheology</strong></td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Entrainment rate</strong></td>
<td>Process based and defined</td>
<td>Defined</td>
</tr>
</tbody>
</table>
RAMMS and recommended by McDougall (2006) to be used in DAN3D for wet and saturated flows. The unit weight was kept on the default value (20 kN/m³), that corresponds to the material density recommended to use in RAMMS (2000 kg/m³). The friction coefficient ($\mu$) and the turbulence coefficient ($\xi$) was calibrated to fit observations of the cases, together with the internal friction angle. The internal friction angle had a default value of 35°, which is appropriate for a dry fragmented rock (Hungr, 2010). DAN3D applies a user defined stopping criteria, that make it stop after a predetermined duration of maximum 1000 seconds or be stopped manually by the user during the simulation (Schraml et al., 2015). Manually stopping criteria may be decreased velocities far away from significant values (Frekhaug, 2015), when the flow front visually come to a halt (Schraml et al., 2015), or when most of the slide materials were deposited (McDougall, 2006). For these cases the simulations were stopped when the center of the mass visually came to a halt or the flow front visually halt. The student version of the numerical model, DAN3D was kindly provided by Prof. Oldrich Hungr.

### 4.3.2 Back-analysis

Back-analysis is an important tool to assess the applicability and flexibility of the models to examine how well they match past-events (Frekhaug, 2015). Back-analysis is performed by changing the key input parameters, in order to get a close match with the field indicators (Quan Luna et al., 2014). When performing a back analysis, it is essential that the final simulation results are close to the estimated calibration values.

The back-analysis was conducted by calibrating the input parameters in RAMMS and DAN3D in the three case studies. The calibrated input parameters were the friction parameters ($\mu$ and $\xi$), which were changed until the desired runout length and calibration point values were obtained. The rest of the input parameters were kept constant. When the input parameters, used in the calibration of the models are continuous variables, it may result in a wide range of possibilities, therefore the principle of equifinality must be considered (Hussin et al., 2012).
4.3.3 Applying input parameters

To conduct simulations, it is necessary to apply a number of input parameters. The required input parameters depend on the applied models and the selected rheology. The required input parameters are listed in Table 4.1 in chapter 4.2.

Topographic data

As described in section 4.1.1 the applied DEMs had a resolution of 1 and 10 meters and were obtained from different sources, generated with various techniques.

Release Volume

The absence of available data to generated hydrograph, resulted in the use of block release for all the cases. The release height was set to the estimated release volumes (Chapter 4.1.2). In DAN3D the release area is defined as a source depth file that have a defined volume, and it is not possible to change the volume directly in DAN3D.

The application of different DEMs into the models, result in small differences in the release volume between simulations. The reasons for this is that in RAMMS the release height will change slightly between the applied DEMs, thus the height is changed to match the release volume, but the limits of decimals will result in small variations. In DAN3D it is the generation process of the depth source file, that require the user to define the release area with a polygon and calculate the release volume based on that. Making it difficult to get the exact release volume.

Erosion

In RAMMS erosion polygons and several erosion parameters are added, while in DAN3D an erosion rate and a maximum depth of erodible materials were added. The erosion parameters and polygons were defined for each case study.

Friction parameters/Flow parameters

The input parameters were calibrated until the best combination of accurate runout and the associated calibration values (velocity and flow height) were estimated. It requires two input parameters and is widely used as a rheology model to simulate debris flows. The rheology was applied to DAN3D, which have access to several rheology models, compared to RAMMS were
the Voellmy model is integrated. The Voellmy model divide the frictional resistance into two part: a dry-Coulomb friction coefficient, proportional to the normal stress represent as $\mu$ and a velocity dependent turbulent friction coefficient expressed as $\xi$ (Christen et al., 2010).

In the case of insufficient information about the flow in RAMMS, Bartelt et al. (2017) recommend to begin calibration with $\mu=0.2$ for the Dry-Coulumb type friction and $\xi=200$ for the Viscous-turbulent friction in the case where the type of flow is not known. The Voellmy friction coefficients was changed with steps of +/- 1 for the Dry-coulomb and +/-100 for Viscous-Turbulence, until the simulation matched the data from field observations and images from the locations. In most cases the values of $\mu$ range between 0.05 and 0.4. Regarding the viscous-turbulent friction ($\xi$) the parameter is in the range of 100-200 for granular flows and 200-1000 for muddy flows (Bartelt et al., 2017). The models were run until the parameters was optimized and provided the best possible runout and associated values. The optimized parameters were then applied to DAN3D and calibrated.

### 4.3.4 Evaluating the output values

The evaluation of the back-analysed cases is based on both qualitative and quantitative assessment. Where the qualitative assessment is based on the perception of the simulation, a visual interpretation of the runout length and the out-put data. For the quantitative assessment an index to evaluate the obtained results, grading the data with a defined value to assess which of the DEMs that interpret the events and the slope typology/debris slide typology most accurate, of the different resolutions, datasets and models.

#### Evaluation index

The index evaluates the results collected at the calibration points, max flow height and max flow velocity, and the runout length of the back-analysed case studies. The index used to classify and rate the obtained data can be described as follow: All the obtained results (Max flow height, flow velocities, runout length) are calculated to an index value (Equation 6), this index value are defined from the estimated values at the calibration point, or the runout length of the real event, which are defined as 100. The index values are then rated based on its value and placement within a defined range that are given a value ranking from 1 to 3, were 1 is a good match, while 3 is a bad match (Table 4.4). Finally, the DEMs used in the back-analyses are evaluated based on their score and compared to each other. The index calculation is based
on Equation 6, where $X_t$ is the initial data value, $X_0$ is the estimation conducted before the simulations and $\hat{X}_t$ is the new index value of the variable (Federal Reserve Bank of Dallas, 2013).

$$\hat{X}_t = \frac{X_t}{X_0} \times 100$$  \hspace{1cm} \text{Equation 6}$$

The index intervals were defined based on the real estimated values obtained from reports and images for the individual index criteria. The rating system also apply a colour, to each class to make it clear. The intervals are presented in Table 4.4.

**Table 4.4.** Index to rate the obtained data and evaluate the back-analysed case studies.

<table>
<thead>
<tr>
<th>Rating Value</th>
<th>Def. Of rating value</th>
<th>Index range Max Flow height</th>
<th>Index range Max Flow velocity</th>
<th>Run-out extension/distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Good</td>
<td>(80, 120)</td>
<td>(94, 106)</td>
<td>(99, 101)</td>
</tr>
<tr>
<td>2</td>
<td>Medium</td>
<td>(40, 80), (120, 160)</td>
<td>(88, 94), (106, 113)</td>
<td>(99, 97), (101, 103)</td>
</tr>
<tr>
<td>3</td>
<td>Bad</td>
<td>$40 &gt; X &gt; 160$</td>
<td>$88 &gt; X &gt; 113$</td>
<td>$97 &gt; X &gt; 103$</td>
</tr>
</tbody>
</table>

**Calibration Points**

There is little available information about the maximum flow height for the cases, but from images taken right after the events it is possible to estimate flow heights in some areas. These areas were used as calibration points, to provide the most accurate runout simulations for the cases. The estimated flow height varies from case and are based on visual analyses of images and estimations from reports. The estimated calibration values are described further in the result chapter. For all the cases there are no available information about the maximum velocities. By using the estimated flow heights at the calibration points, the flows impact velocities were estimated using a simple velocity equation (Equation 7). Where $h$ is the height of the flow, $g$ is the gravitational constant and $V$ is the impact velocity of the flow (Devoli, 2018).
These estimations were used as calibrations points during the simulations, and work as a reference. It is important to notice that these values have a high degree of uncertainty, due to the estimations are mainly based on images and the velocity equation is simple and do not consider all factors influencing flow velocity. Making the main calibration point evaluation criteria the flow height.

**Runout length**

To evaluate if a simulation is accurate to the real event, one of the key evaluation criteria is the runout length. The runout length is defined as the horizontal distance from the upper boundary of the release area to the lower boundary of the deposition area (Anfinnsen, 2017). The content of the deposit may vary from large blocks and granular materials to fine mud and silt with a high-water content. Materials with small size and high-water content may have a longer runout length compared to more granular materials. This transition is in some circumstances unclear in the simulated runout, which make it difficult to distinguish the deposited mass from muddy-rich waters (Frekhaug, 2015).

**DEM evaluation**

To evaluate the DEM resolution, the slope angle was the preferred factor, due to the fact that it is an important condition of landslides and control the behavior of landslide dynamics. The evaluation was conducted for all three cases, described in Chapter 3, by selecting DEMs from one dataset of each case with a resolution of 1m and 10m. The DEMs were then applied into the geoprocessing tool Slope in ArcMap to generate slope angle maps, followed by the generation of slope profiles and cross sections.

\[
V = \sqrt{(h \times g \times 2)}
\]

*Equation 7*
5 Results

This chapter presents the results obtained with the methods described in the previous chapter. This chapter focus on the evaluation of the prepared DEMs by assessing the slope characteristics, assessment of the back-analysed case studies with distinct slope typology and the influence of the DEMs resolution, dataset properties and applied runout models. Finally, the results are summarized and compared in three main parts:

- Evaluation of the DEMs with slope angle maps, profiles and cross sections
- Evaluation of the back-analysed case studies and the applied DEMs
- Comparison of the back-analysed case studies and applied DEMs

It is important to notice that only a selection of the back-analysed simulations are described in detail in this chapter, due to the large number of calibrations. For each case study the results are illustrated with flow heights from the DEMs with a resolution of 1m and 10m for both runout models, as well as profiles and cross sections of the deposition. The results obtained at the calibration points and the runout lengths are rated with an index to quantify the results and are presented for all case studies, together with box plots of the results and plots of the friction parameters.

The remaining results are illustrated with flow height figures in Appendix 1 and tables with the output data in Appendix 2.

5.1 Evaluation of DEMs

A selection of the applied DEMs are evaluated by assessing slope angle maps and the corresponding profiles and cross sections. In total two DEMs with different resolution were selected and evaluated for each case study.

5.1.1 Aurdal

For the Aurdal case the dataset Høydedata has a maximum slope of 50° for the 1m DEM, while the 10m DEM has a maximum slope of approximatly 35° (Figure 5.1). In general, the steepest part of the path is steeper with the 1m DEM, but the area with high inclination is smaller.
compared to the 10m DEM. For Aurdal, the 1m DEM provides a higher level of details compared to the 10m DEM, as expected, but both of them express the topography of the slope similarly, where the steepest parts are located in the same areas. The first noticeable difference is that the steep parts cover a larger area for the 10m DEM compared to the 1m DEM. This makes the 10m DEM to underestimate the impact of changes in slope compared to the 1m DEM. This is noticeable at the roads which are misinterpreted largely due to the 10m DEM cell size.

Figure 5.1. Aurdal case. Slope angle map generated from the dataset Høydedata with A) 1m and B) 10m resolution. The black line is the landslide boundary, the grey dotted line is the slope longitudinal profile, the grey line is the cross section.
By plotting the slope angle along the selected topographic profiles, the difference in the level of details and smaller inclinations in the terrain are noticeable (Figure 5.2). In general, they indicate the same slope angle trend, except that the 10m DEM ignore large deviations in slope angles within short distances.

![Slope profiles](image1)

**Figure 5.2.** Aurdal case. The 1m and 10m DEMs slope along the landslide path, from the a.) source to b.) final deposition from the dataset Høydedata.

Following the cross section of the slope, it is possible to see the large differences in detail between the resolutions (Figure 5.3). Where the 1m DEM provides large variations in slope angles, while the 10m DEM only provides a smooth line. The 1m DEM generally provides a higher slope angle.

![Cross sections](image2)

**Figure 5.3.** Cross section of slope angles for 1m and 10m DEMs from the dataset Høydedata.
5.1.2 Nesbyen

For the Nesbyen case the dataset Høydedata the maximum slope has an inclination of 69° for the 1m DEM and 40° for the 10m DEM (Figure 5.4). The steepest parts of the path are located at the same areas in both DEMs, which is also the case for the flatter areas. The difference is that the areas are much larger for the 10m DEM, thus a larger part of the path have a steep slope. Another noticeable feature in the slope angle maps is that the roads are not considered to the same extent in the 10m DEM and is not represented as an important terrain feature.

Figure 5.4. Nesbyen case. Slope angle map generated from the dataset Høydedata with A) 1m and B) 10m resolution. The black line is the landslide boundary, the grey dotted line is the slope longitudinal profile, the grey line is the cross section.
From the slope angle profiles, the difference between the resolutions are noticeable in this case as well (Figure 5.5). In general, the slope of the 10m DEM follows the slope profile of the 1m DEM, but the 1m DEM have a larger d in slope angles within small distances compared to the 10m DEM.

**Figure 5.5.** Nesbyen. The 1m and 10m DEMs slope along the landslide path, from the a.) source to b.) final deposition from the dataset Generated.

In the cross section of the slope the 1m DEM provides the largest variation in slope angles, the 10m DEM only provide a smooth line, that gradual increase along the cross section (Figure 5.6). In this case the 1m DEM has lower slope angles compared to the 10m DEM.

**Figure 5.6.** Cross section of slope angles for 1m and 10m DEMs from the dataset Generated.
5.1.3 Mjåland

In Mjåland, the dataset Høydedata has a maximum slope of 82° for the 1m DEM and 65° for the 10m DEM (Figure 5.7). The slope angle maps show no large differences in the distribution of the steepest parts in the polygon which is also the case outside of the polygon. Due to the difference in cell size, the 1m DEM considers the local differences more than the 10m DEM, thus some terrain features are more noticeable in the 1m DEM.

Figure 5.7. Mjåland. Slope angle map generated from the dataset Høydedata with A) 1m and B) 10m resolution. The black line is the landslide boundary, the grey dotted line is the slope longitudinal profile, the grey line is the cross section.

In general, the profiles follow the same trend but the slope from the 1m DEM expresses more details (Figure 5.8). The difference in slope angles vary largely for the 1m DEM compared to a smoother change in slope angles for the 10m DEM.
Figure 5.8. Mjåland. The 1m and 10m DEMs slope along the landslide path, from the a.) source to b.) final deposition from the dataset Høydedata.

For the cross sections of the slope the 1m DEM provides the largest variation in slope angles, the 10m DEM only provide a smooth line with small gradual changes (Figure 5.9). In this case the 1m DEM has the large slope angles compared to the 10m DEM.

Figure 5.9. Cross sections of slope angles for 1m and 10m DEMs from the dataset Høydedata.
5.2 Results of the back-analyses

In this chapter the results from the back-analysis are presented. For each case the obtained flow height, flow velocity and deposition distribution of the back-analysed cases are compared and illustrated with figures and graphs. The result includes all simulations conducted with the dataset Høydedata, the results from the datasets Generated and Geonorge are presented in the summary section for each case study. The results from the back-analyses with the datasets Generated and Geonorge are presented as flow height figures and tables for each case study in Appendix 1 and 2.

5.2.1 Aurdal

RAMMS

For the back-analyses with RAMMS, the most accurate simulations were provided with the friction parameters \( \mu = 0.18 \) and \( \xi = 260 \) for 1m DEM, and \( \mu = 0.24 \) and \( \xi = 800 \) for the 10m DEM (Table 5.1). For this case, a previous back-analysis was conducted by Kronholm and Snilsberg (2013) that obtained friction parameters \( \mu = 0.18 \) and \( \xi = 200 \), by applying a DEM with 1m resolution to RAMMS.

Table 5.1. Friction parameters obtained from the back-analyses of the Aurdal case with 1m and 10m DEMs from the dataset Høydedata.

<table>
<thead>
<tr>
<th></th>
<th>1m</th>
<th>10m</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Internal Friction (( \mu ))</strong></td>
<td>0.18</td>
<td>0.24</td>
</tr>
<tr>
<td><strong>Turbulence Friction (( \xi ))</strong></td>
<td>260</td>
<td>800</td>
</tr>
</tbody>
</table>

The flow height of the back-analysed 1m and 10m DEMs follow the path but overestimate the margins (Figure 5.10). This overestimation is considerable larger for the 10m DEM, while the 1m DEM provides a more compact flow. The total runout length of the event is approximately 401 m. In this case, the 1m DEM underestimate the length to be 394 m, while the 10m overestimate it to be 420 m. The flow is more influenced by the road in the 1m simulation and follows the road, in addition to estimate a thicker flow height compared to the 10m. The biggest difference between the two resolutions are the estimation of the flow heights, with a max flow height of approximately 2.8 m for the 1m DEM and 0.9 for the 10m DEM. This may be due to the large difference between the turbulence friction parameters for the simulations.
Figure 5.10. Aurdal case. Flow height distribution simulated with RAMMS using the DEMs from the dataset Høydedata. A) 1m DEM. B) 10m DEM.

The total volume of the flow was estimated to be approximately 3140 m$^3$. The volumes obtained for the back-analysed DEMs are provided in Table 5.2 and indicate that the 1m DEM provides a higher total flow volume compared to the 10m DEM. Both simulations underestimate the flow volume compared to the estimated real value, with a deviation of 216 m$^3$ and 1128 m$^3$ for the 1m DEM and 10m DEM respectively. This indicates that the erosion factor contributes almost twice as much with a higher resolution. The erosion parameters applied in back-calibrated case study are equal for all simulation.
Table 5.2. The table includes estimated real volume, total flow volume obtained from the back-analyses and deviation from the estimated volume.

<table>
<thead>
<tr>
<th></th>
<th>1m DEM</th>
<th>10m DEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimated volume (m³)</td>
<td>3140</td>
<td>3140</td>
</tr>
<tr>
<td>Total flow volume (m³)</td>
<td>2924.2</td>
<td>2011.7</td>
</tr>
<tr>
<td>Volume deviation (m³)</td>
<td>-215.8</td>
<td>-1128.3</td>
</tr>
</tbody>
</table>

The deposition profiles indicate that after approximately 100 m, material starts to deposit along the path (Figure 5.11). The deposition increases after 200 m from the source for both resolutions and the final deposit is initiated after 360 m. Both models have small deposition peaks along the path, but the 1m DEM has several large peaks before the final deposition, where the highest peaks are slightly below 0.6 m. The 10m DEM has a smoother deposition with an average deposition height slightly below 0.1 m. The final deposition for the 1m DEM consists of two large peaks between 0.8 and 1 m, while the 10m has one large deposition with a thickness of approximately 0.4 m.

![Deposition profiles](image)

**Figure 5.11.** Deposition profiles acquired from the 1m and 10m DEMs from the dataset Høydedata in the model RAMMS.

The cross section of the deposition is taken at the road covered by the final deposition. The 1m DEM estimates two separate deposition peaks with a thickness of 1 m and 0.5 m (Figure 5.12). This is not the case for the 10m DEM, where the cross section is smooth with a gradual increase of deposition thickness until it reaches the maximum thickness, and gradually decreases. In the
1m DEM, a small hill might have separated the flow. Because of the resolution of the 10m DEM, the hill is not influential enough to change the flow.

Figure 5.12. Cross section of the deposition across the road in the deposition zone for the 1m and 10m DEMs from the dataset Høydedata applied to RAMMS.

Figure 5.13 summarizes the profiles of the analysed flow parameters, flow height, velocity, and deposition. In general, the simulations follow the same trend, but the 1m DEM tend to fluctuate more along the path for all the flow parameters compared to the 10m DEM that has smoother transition for the flow parameters along the path. The flow velocities are relatively equal, but the 1m DEM has a higher max velocity, while the 10m DEM have a higher velocity along the flow path. For the flow height, the trend is the same, but the 1m estimates a higher flow height. Deposition thickness is highly influenced by the flow height, which is noticeable with deposition peaks at the same location as the flow height peaks.

Figure 5.13. A plot of the flow height, velocity, and deposition profiles along the path, for the 1m DEM (line) and 10m DEMs (dot) from the dataset Høydedata applied to RAMMS.
DAN3D

The most accurate simulations were provided with the friction parameters \( \mu = 0.19 \) and \( \xi = 250 \) for the 1m DEM and \( \mu = 0.28 \) and \( \xi = 300 \) for the 10m DEM (Table 5.3). The 10m DEM obtains the highest internal friction (\( \mu \)) and turbulence friction (\( \xi \)).

**Table 5.3.** Friction parameters obtained from the back-analyses of the Aurdal case with 1m and 10m DEMs from the dataset GeoNorge in DAN3D.

<table>
<thead>
<tr>
<th></th>
<th>1m</th>
<th>10m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal Friction (( \mu ))</td>
<td>0.19</td>
<td>0.28</td>
</tr>
<tr>
<td>Turbulence Friction (( \xi ))</td>
<td>250</td>
<td>300</td>
</tr>
</tbody>
</table>

Both simulations overestimate the extent of the margins, but only the 10m DEM overestimates the length of the runout (Figure 5.14). The 1m DEM estimated the runout length accurate to 401 m, while the 10m estimated it to be 398 m which is slightly less than the real value. In this case the flow is shifted more towards south compared to the real event, where a large portion of the flow are moving outside the polygon. The flow height is highest with the 1m DEM at almost 3.3 m and the 10m DEM estimates it to be precisely 2.2 m.
The volumes obtained from the simulations are provided in Table 5.4. DAN3D overestimates the total flow volume largely, with 4173.43 m$^3$ for the 1m DEM and 2214.14 m$^3$ for the 10m DEM. In this case the 10m DEM provide the most accurate volume estimation.
Table 5.4. The table include, estimated real volume, total flow volume obtained from the back-analyses and deviation from the estimated volume.

<table>
<thead>
<tr>
<th></th>
<th>1m DEM</th>
<th>10m DEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimated volume (m³)</td>
<td>3140</td>
<td>3140</td>
</tr>
<tr>
<td>Total flow volume (m³)</td>
<td>7313.43</td>
<td>5354.14</td>
</tr>
<tr>
<td>Volume deviation (m³)</td>
<td>+4173.43</td>
<td>+2214.14</td>
</tr>
</tbody>
</table>

The depositions take place after 180 m from the source for both DEMs (Figure 5.15). The 1m DEM consist of several deposition peaks, with the largest after 220 m, followed by several smaller peaks until the final deposition after 350 m. The 10m DEM consist of two large peaks, where the first is located after 220 m from the source and the final deposition after 350 m. The first large peak has a thickness of approximately 2 m for the 1m DEM and a thickness of 1.4 m for the 10m DEM. The final deposition has a thickness of 1.1 m for the 1m DEM and 0.7 m for the 10m DEM.

Figure 5.15. Profiles of the deposition acquired from the 1m and 10m DEMs from the dataset Høydedata in DAN3D.

The 1m DEM provided a small deposition with a max height of 0.05 m compared to the 10m DEM that provided a large deposition area, with a max height of 0.35 m (Figure 5.16). The depositions have a width of almost 40 m for the 1m DEM and 90 m for the 10m DEM.
Figure 5.16. Cross section of the deposition across the road in the deposition zone for the 1m and 10m DEM applied to DAN3D.

In Figure 5.17, where all the profiles are summarized, both resolutions provide the same characteristic trend. The flow height and deposition are similar for both DEMs, compared to the velocity where the 1m DEM estimates it to be higher than the 10m DEM.

Figure 5.17. Plot of the flow height, velocity, and deposition profiles throughout the flow, for the 1m DEM (line) and 10m DEM (dot) from DAN3D.
Summary for Aurdal

The estimated flow height is higher when applying a DEM with 1m resolution, but in some cases a DEM with 10m resolution may provide the same flow height, depending on the applied friction parameters and dataset (Figure 5.18). For DEMs with 1m resolution, the max velocity is mainly within the range 10 - 11 m/s, while DEMs with 10m resolution provides a larger range from 8 m/s and up to 11 m/s. The max velocity obtained with 1m DEMs is almost 12 m/s and the minimum at 9 m/s, the 10m DEMs have a max velocity above 11 m/s and a minimum at 8 m/s.

![Box plot of A) flow height and B) flow velocity from all back-analyses conducted with RAMMS and DAN3D with 1m and 10m resolution.](image)

**Figure 5.18.** Box plot of A) flow height and B) flow velocity from all back-analyses conducted with RAMMS and DAN3D with 1m and 10m resolution.

The total volume of all the simulations conducted for the Aurdal case study, indicates that the 10m DEMs have simulations with higher volume compared to the 1m DEM, but the average total volume is higher for the 1m DEM (Figure 5.19).

![Box plot of the total volume for all back-analysis conducted with RAMMS and DAN3D in Aurdal.](image)

**Figure 5.19.** Box plot of the total volume for all back-analysis conducted with RAMMS and DAN3D in Aurdal.
The back-analyses conducted with 1m DEMs are located within a range of 0.15 to 0.25 for the internal friction coefficient, while the turbulence friction coefficient lies in the range 250 to 400 m/s² (Figure 5.20). The back-analyses conducted with the 10m DEMs have a smaller range regarding the internal friction coefficient from 0.24 to 0.30, while the turbulence coefficient varies from 200 and up to 800 m/s².

Figure 5.20. Data dispersion of the friction parameters for the Aurdal case study with RAMMS and DAN3D.

The index provides an overview of all calibrations and their quality. From the index, the general trend is that the 1m DEMs provide the best results (Table 5.5). The 1m DEM from the dataset Høydedata applied to RAMMS obtain the best results, while the corresponding 10m DEM provide the poorest results.

Table 5.5. Index of all calibrations conducted for the case study in Aurdal.

<table>
<thead>
<tr>
<th>Case study</th>
<th>Høydedata</th>
<th>Aurdal Generated</th>
<th>GeoNorge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>RAMMS</td>
<td>DAN3D</td>
<td>RAMMS</td>
</tr>
<tr>
<td>Resolution</td>
<td>1m</td>
<td>10m</td>
<td>1m</td>
</tr>
<tr>
<td>Flow height</td>
<td>112</td>
<td>26</td>
<td>280</td>
</tr>
<tr>
<td>Flow velocity</td>
<td>103</td>
<td>144</td>
<td>138</td>
</tr>
<tr>
<td>Runout length</td>
<td>98</td>
<td>105</td>
<td>100</td>
</tr>
</tbody>
</table>
5.2.2 Nesbyen

RAMMS

The friction parameters applied to obtain the most accurate runout were $\mu = 0.07$ and $\xi = 850$ for the 1m DEM and $\mu = 0.06$ and $\xi = 800$ for the 10m DEM (Table 5.6). The only difference between the resolutions is the turbulence friction coefficient, which is $50 \text{ m/s}^2$ higher for the 10m DEM.

Table 5.6. Friction parameters obtained from the back-analyses of the Nesbyen case with 1m and 10m DEMs from the dataset Høydedata in RAMMS.

<table>
<thead>
<tr>
<th></th>
<th>1m</th>
<th>10m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal Friction ((\mu))</td>
<td>0.07</td>
<td>0.06</td>
</tr>
<tr>
<td>Turbulence Friction ((\xi))</td>
<td>850</td>
<td>800</td>
</tr>
</tbody>
</table>

Both applied resolutions match the polygon of the real event (Figure 5.21). As noticed from earlier simulations, the simulations tend to overestimate the length of the margins. In RAMMS, the 1m provides the best approximation to the real event, by evaluating the runout length. The flow height propagates from the release areas, through the transport channels until the flow materials settles in the depositional zone. However, none of the calibrations reach the maximum runout of the real event (676 m) but the 1m DEM provided a runout length of 672 m and 673 m for the 10m DEM, thus underestimating the runout distance with 4 m and 3 m compared to the observed runout distance. The maximum flow height was highest for the 1m DEM at 2.0 m, while the flow height was 0.6 m for the 10m DEM.
The total volume of the flow was estimated to be approximately 3500 m$^3$, however the calibrations underestimated the volume with -67 m$^3$ for the 1m DEM and -2291 m$^3$ for the 10m DEM. This is a large deviation from the estimated value for the 10m DEM compared to the more accurate 1m DEM. In this case the erosion factors contribution to the flow volume is almost four time as high for the calibration conducted with a 1m DEM compared to the one performed with a 10m DEM (Table 5.7).
Table 5.7. The table include, estimated real volume, total flow volume obtained from the back-analyses and deviation from the estimated volume.

<table>
<thead>
<tr>
<th></th>
<th>1m DEM</th>
<th>10m DEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimated volume (m³)</td>
<td>3500</td>
<td>3500</td>
</tr>
<tr>
<td>Total flow volume (m³)</td>
<td>3432.6</td>
<td>1209.4</td>
</tr>
<tr>
<td>Volume deviation (m³)</td>
<td>-67.4</td>
<td>-2290.6</td>
</tr>
</tbody>
</table>

Figure 5.22 illustrates the deposition of the flow for the 1m and 10m resolution DEMs. The deposition of materials initiates after 100 m from the source for both DEMs. Both DEMs deposit small amounts of materials before the final deposition after 550 m. The 1m DEM provides the largest deposition and has a few deposition peaks before the final deposition. The 1m DEM have several peaks before the final deposition, while the 10m DEM does not provide any peaks before the final stage but have a smooth gradual increased deposition height as the flow moves. The maximum thickness of the deposition is slightly above 1.1 m for the 1m DEM and slightly below 0.3 m for the 10m DEM.

![Deposition profiles](image)

Figure 5.22. Profiles of the deposition acquired from the 1m and 10m DEM from the dataset Høydedata in RAMMS.

The cross section taken at the calibration point shows that both simulations behave similar with the same peaks (Figure 5.23). The highest deposition is located in the centre and decreases with the distance. In addition, the deposition is divided into two parts: a large deposition at the centre
of the cross section and a small to the right. The 1m DEM has the largest deposition height at 1.1 m, and the 10m DEM at approximately 0.3 m.

**Cross section of deposition**

![Cross section of deposition](image)

**Figure 5.23.** Cross section of the deposition across the road in the deposition zone for the 1m and 10m DEM from the dataset Hoydedata applied to RAMMS.

Figure 5.24 summarizes the profiles of the output data along the landslide path. The interaction between the profiles from the 1m DEM shows that when the velocity decreases, the deposition increases, and the flow height follows the velocity trend in the transport channel where it decreases when the velocity decreases and vice versa. For the 10m DEM, the flow height is larger than the velocity throughout the most of path and until it reaches the deposition zone.
Figure 5.24. Plot of the flow height, velocity, and deposition profiles throughout the flow from the dataset Høydedata obtained with RAMMS. A) 1m DEM, B) 10m DEM.

**DAN3D**

The friction parameters applied to obtain the most accurate simulations were $\mu = 0.09$ and $\xi = 750$ for 1m DEM and $\mu = 0.10$ and $\xi = 500$ for 10m DEM. The turbulence friction coefficient is higher in the 1m DEM, than in the 10m DEM, but lower than the parameters applied in RAMMS. The 10m DEM have the lowest turbulence coefficient at 500 m/s$^2$ (Table 5.8).
Table 5.8. Friction parameters obtained from the back-analyses of the Nesbyen case with 1m and 10m DEMs from the dataset Høydedata.

<table>
<thead>
<tr>
<th></th>
<th>1m</th>
<th>10m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal Friction (μ)</td>
<td>0.09</td>
<td>0.10</td>
</tr>
<tr>
<td>Turbulence Friction (ξ)</td>
<td>750</td>
<td>500</td>
</tr>
</tbody>
</table>

The areas with the highest flow heights are located in the same parts of the event for both resolutions. The width of the shape is overestimated for the 1m DEM, while the 10m DEM is more accurate (Figure 5.25). The observed runout length is approximately 676 m, while the 1m and 10m DEMs obtain a runout length of 680 m and 691 m, overestimating the distance with 4 m and 15 m. The maximum flow height at the 1m DEM is 2.5 m and for 10m DEM it is 2.0 m. In DAN3D, the 10m DEM provides the most accurate runout behaviour, where the calibrated runout is approximately identical to the real event.
Figure 5.25. Aurdal case. Flow height distribution simulated with DAN3D. A) 1m DEM. B) 10m DEM.

With DAN3D, the calibrations overestimate the total flow volume with +3962 m$^3$ for the 1m DEM and +807 m$^3$ for the 10m DEM (Table 5.9). In this case the 10m DEM provided the most accurate total flow volume, while the 1m DEM compute the total flow volume to be twice of the estimated value.
Table 5.9. The table includes estimated real volume, total flow volume obtained from the back-analyses and deviation from the estimated volume.

<table>
<thead>
<tr>
<th></th>
<th>1m DEM</th>
<th>10m DEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimated volume (m³)</td>
<td>3500</td>
<td>3500</td>
</tr>
<tr>
<td>Total flow volume (m³)</td>
<td>8462.03</td>
<td>5307.23</td>
</tr>
<tr>
<td>Volume deviation (m³)</td>
<td>+3962.02</td>
<td>+807.23</td>
</tr>
</tbody>
</table>

The deposition profiles are plotted in Figure 5.26 and provides an almost identical trend between the different resolutions. Deposition of materials is initiated for both resolutions after approximately 280 m from the source, with low values until the final deposition begins. The 1m DEM provides two peaks. There is one small peak after 500 m from the source, and the last peak represents the final deposition which is initiated earlier than the 10m DEM. The 10m DEM provides a gradual increased deposition before the final deposition are initiated. The 1m DEM provides the thickest deposition at 1.6 m while the 10m DEM is 1.4 m thick.

![Deposition profiles](image)

The cross section of the deposition indicates that the thickest deposition for both resolutions are located in close proximity to each other (Figure 5.27). The 1m DEM has a larger portion of the deposition located to the left, while the 10m DEM is more located to the right. A small peak is located to the right in the 1m DEM. The 10m DEM is smoother and consist of only one large peak.

Figure 5.26. Profiles of the deposition acquired from the 1m and 10m DEM from the dataset Høydedata in DAN3D.
peak. The 1m DEM has the largest deposition thickness at 1.6 m, compared to 1.5 m for the 10m DEM.

![Cross section of deposition](image)

**Figure 5.27.** Cross section of the deposition across the road in the deposition zone for the 1m and 10m DEM from the dataset Høydedata applied to DAN3D.

Both DEMs provides the same trend, but the 1m DEM estimates the highest values for all the flow parameters (Figure 5.28). This trend applies throughout the entire path, except in the deposition area, were the 1m DEM initiate the final deposition prior to the 10m DEM. This results in a higher flow height for the 10m DEM the last 100 m.
Summary for Nesbyen

For almost all simulations the DEMs with a resolution of 1m estimate the maximum flow height and flow velocity higher than the 10m DEMs (Figure 5.29). The 1m DEMs have an average flow height of 2 m, while the 10m DEMs have it slightly below 1 m. The average max velocity for the 1m DEMs lies in the range of 12-13 m/s, and in the range of 8-9 m/s for the 10m DEMs.

Figure 5.28. Plot of the flow height, velocity, and deposition profiles throughout the flow, for the 1m DEM (line) and 10m DEM (dot) from the dataset Høydedata applied to DAN3D.

Figure 5.29. Box plot of A) flow height and B) flow velocity from all back-analyses conducted with RAMMS and DAN3D with 1m and 10m resolution.
The volumes obtained from the calibrated DEMs with 1m resolution and 10m resolution are plotted in Figure 5.30. The 1m DEM estimates in average a higher total volume compared to the 10m DEM.

![Figure 5.30](image)

Figure 5.30. Box plot of the total from all back-analyses conducted with RAMMS and DAN3D with 1m and 10m resolution.

The applied friction parameters are relatively spread (Figure 5.31). In general, all the friction parameters are located within the range of 0.12 to 0.05 for the internal friction coefficient and mainly in two groups around 300 m/s$^2$ and 800 m/s$^2$ for the turbulence friction coefficient.

![Figure 5.31](image)

Figure 5.31. Data dispersion of the friction parameters for the Nesbyen case with the numerical models RAMMS and DAN3D.
By comparing the results from the index, it is difficult to observe a general trend between the resolutions (Table 5.10). The datasets Høydedata and Generated provide good results for the flow height and runout length, while the dataset Geonorge provide bad results for most of the parameters. The 1m DEM from the dataset Høydedata applied to RAMMS obtain the best results, while the 10m DEM from Geonorge applied to RAMMS provide the poorest results.

Table 5.10. Index of all calibrations conducted for the case study in Nesbyen.

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Aurdal</th>
<th>GeoNorge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>RAMMS</td>
<td>DAN3D</td>
</tr>
<tr>
<td>Resolution</td>
<td>1m</td>
<td>10m</td>
</tr>
<tr>
<td>Flow height</td>
<td>112</td>
<td>26</td>
</tr>
<tr>
<td>Flow velocity</td>
<td>103</td>
<td>144</td>
</tr>
<tr>
<td>Runout length</td>
<td>98</td>
<td>105</td>
</tr>
</tbody>
</table>

5.2.3 Mjåland

RAMMS

The friction parameters obtained from the calibrations are \( \mu = 0.10 \) and \( \xi = 600 \) for the 1m DEM and \( \mu = 0.14 \) and \( \xi = 750 \) for the 10m DEM. In this case, the 1m DEM requires lower friction parameters compared to the 10m DEM (Table 5.11).

Table 5.11. Friction parameters obtained from the back-analyses of the Mjåland case with 1m and 10m DEMs from the dataset Høydedata with RAMMS.

<table>
<thead>
<tr>
<th></th>
<th>1m</th>
<th>10m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal Friction (( \mu ))</td>
<td>0.10</td>
<td>0.14</td>
</tr>
<tr>
<td>Turbulence Friction (( \xi ))</td>
<td>600</td>
<td>750</td>
</tr>
</tbody>
</table>

Both simulations estimated the runout length almost identical to the real event but obtains a slightly wider shape in the final part of the path and in the deposition area (Figure 5.32). Both DEMs manage to underestimate the runout length (795 m for 1m DEM and 797 m for 10m DEM) compared to the real runout length (823 m). The 1m DEM provides a much larger max flow height at 3.2 m, while the 10m DEM estimated the flow height to be approximately 1 m.
Figure 5.32. Mjåland case. Flow height distribution simulated with RAMMS. A) 1m DEM. B) 10m DEM.

With a total flow volume of approximately 25200 m$^3$, RAMMS underestimates the total volume with almost -13000 m$^3$ for 1m DEM and -22000 m$^3$ for the 10m DEM (Table 5.12). The 1m DEM computes almost three times the total flow volume of the 10m DEM, with the same erosion area and parameters.

Table 5.12. The table includes, estimated real volume, total flow volume obtained from the back-analyses and deviation from the estimated volume.

<table>
<thead>
<tr>
<th></th>
<th>1m DEM</th>
<th>10m DEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimated volume (m$^3$)</td>
<td>25205</td>
<td>25205</td>
</tr>
<tr>
<td>Total flow volume (m$^3$)</td>
<td>8320.04</td>
<td>2241.9</td>
</tr>
<tr>
<td>Volume deviation (m$^3$)</td>
<td>-15884.6</td>
<td>-21963</td>
</tr>
</tbody>
</table>
Profiles of the deposition from the simulations are illustrated in Figure 5.33. Deposition of materials begins after approximately 140 m from the source for both DEMs. The deposition for the 1m DEM consists of several peaks before the final deposit, while the 10m DEM has a smoother and gradual deposition, that is lower than the 1m DEM. In the final deposition, the 1m DEM has a high deposition rate with some inconsistence, that increase from less than 0.1 m to almost 1.1 m. The 10m DEM provides a more gradual increase until it reaches the max value slightly below 0.3 m.

![Deposition profiles](image)

**Figure 5.33.** Profiles of the deposition acquired from the 1m and 10m DEM.

A cross section of the deposition was taken along the road where the main parts of the deposition settled. The DEMs provide a similar trend, where the cross section consists of two major peaks (Figure 5.34). As noticed from earlier cases, the 1m DEM has more sudden large changes in the thickness, while the 10m DEM provides a smoother cross section with small changes along the road.
Figure 5.34. Cross section of the deposition across the road in the deposition zone for the 1m and 10m DEMs applied to RAMMS.

Figure 5.35 provide flow height, velocity and deposition profiles taken along the landslide path. Both resolutions have the same trend, but the 1m DEM have higher and more variated values during the flow. The 1m DEM provide a higher velocity compared to the 10m DEM. The flow height for the 1m DEM is higher than then 10m DEM.

Figure 5.35. Plot of the flow height, velocity, and deposition profiles throughout the flow, for the 1m DEM (line) and 10m DEM (dot) applied to RAMMS.
The preferred friction parameters were $\mu = 0.25$ and $\xi = 700$ for the 1m DEM and $\mu = 0.25$ and $\xi = 800$ for the 10m DEM (Table 5.13). The internal friction is equal for both resolutions, but the turbulence friction is slightly higher for the 10m DEM.

**Table 5.13.** Friction parameters obtained from the back-analyses of the Nesbyen case with 1m and 10m DEMs from the dataset Høydedata with DAN3D.

<table>
<thead>
<tr>
<th></th>
<th>1m</th>
<th>10m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal Friction (Mu)</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>Turbulence Friction (Xi)</td>
<td>700</td>
<td>800</td>
</tr>
</tbody>
</table>

The runout length for the simulations are similar, where both overestimate the extent of the margins. When the real event travel down the slope, the main part of the flow is located more to the left compared to the calibrated cases (Figure 5.36). For the calibrations, the main flow is shifted more to the left and the thickest layers are located almost at the left margin and past the margins of the real event. This applies to both DEMs, but the effect is more noticeable for the 10m resolution. The 1m DEM overestimates the distance in some parts of the deposition but underestimates the runout length (806 m) and the 10m DEM underestimates the length (807 m). A max flow height of 6.1 m for 1m DEM and 5.8 m for 10m DEM were obtained.
DAN3D overestimated the total flow volume with +12132 m³ for the 1m DEM and +14527 m³ for the 10m DEM (Table 5.14). The total flow volume is extremely overestimated, especially compared to the values obtained with RAMMS (Table 5.12).

Table 5.14. The table includes estimated real volume, total flow volume obtained from the back-analyses and deviation from the estimated volume.

<table>
<thead>
<tr>
<th></th>
<th>1m DEM</th>
<th>10m DEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimated volume (m³)</td>
<td>25205</td>
<td>25205</td>
</tr>
<tr>
<td>Total flow volume (m³)</td>
<td>34314.2</td>
<td>41190.9</td>
</tr>
<tr>
<td>Volume deviation (m³)</td>
<td>+12131.8</td>
<td>+14527.4</td>
</tr>
</tbody>
</table>

The deposition profiles illustrated in Figure 5.37 indicate that a small amount of materials is deposited in the area between 130 m to 170 m from the source along the landslide path for both resolutions. The deposition is then stopped before it is initiated again after 290 m with low
values. Both calibration ends with a final deposition peak. The 1m DEM has two minor peaks before the final deposition, while the 10m DEM has a constant low value until the initiation of the final deposition. The final depositions are located in the same area and end simultaneously for both resolutions. The 1m DEM has a final deposition of almost 6 m, while the 10m DEM has a thickness of 5 m.

**Figure 5.37.** Profiles of the deposition acquired from the 1m and 10m DEM from the dataset Høydedata in DAN3D.

The cross section of the depositions indicates that both simulations estimate the thickest parts in the same area (Figure 5.38). Both consist of two peaks, one small located around 50 m and one large covering most of the plot. The thickest deposition is provided by the 1m DEM at 5.5 m, while the 10m DEM thickest part of the deposition are slightly above 4 m.
Figure 5.38. Cross section of the deposition across the road in the deposition zone for the 1m and 10m DEM from the dataset Høydedata applied to DAN3D.

Figure 5.39 indicates that both DEMs follow the same trend. The 1m DEM has a lower velocity throughout the flow, but a higher flow height. For the deposition, the 1m DEM has a higher final deposition than the 10m DEM but stop to deposit after the same distance.

Figure 5.39. Plot of the flow height, velocity, and deposition profiles throughout the flow, for the 1m DEM (line) and 10m DEM (dot) from DAN3D.
Summary for Mjåland

The flow heights and velocities are estimated to be higher for the 1m DEMs than the 10m DEMs, where the 1m DEMs have an average max flow height at 3.8 m and the 10m DEMs have a max flow height at 3.3 m (Figure 5.40). The average max velocity for the 1m DEMs are approximately 13.5 m/s, and slightly less for the 10m DEMs.

Figure 5.40. Box plot of A) flow height and B) flow velocity from all back-analyses conducted with RAMMS and DAN3D with 1m and 10m resolution.

The volumes obtained from the 1m DEMs and the 10m DEMs are plotted in Figure 5.41. The total volume is estimated to be higher for the 10m DEMs with an average volume of 22000 m$^3$, compared to an average volume of 12000 m$^3$ for the 1m DEMs.

Figure 5.41. Box plot of the total volume from all back-analyses conducted with RAMMS and DAN3D with 1m and 10m resolution.
The applied friction parameters are relatively spread, when examining the dispersion between the 1m and 10m resolutions (Figure 5.42). In general, all friction parameters are located within the range of 0.1 to 0.28 for the internal friction coefficient and a turbulence friction coefficient from 400 to 800 m/s². The 1m DEMs internal friction coefficient ranges from 0.10 to 0.28, while the turbulence friction coefficient lies within the range of 400 to 700 m/s². For the 10m DEM the internal friction coefficient lies within the range of 0.12 to 0.28, while the turbulence friction ranges from 750 to 800 m/s².

![Friction parameters](image)

**Figure 5.42.** Data dispersion of the friction parameters for the Mjåland case with the numerical models RAMMS and DAN3D.

From the index, the general trend is that the 1m DEMs provide the best results but some of the 10m DEMs also provide good results (Table 5.15). For this case study the 1m DEM from the dataset Geonorge applied to DAN3D obtain the best results, while the 10m DEM from the dataset Høydedata applied to RAMMS provide the poorest results.

**Table 5.15.** Index of all calibrations conducted for the case study in Nesbyen

<table>
<thead>
<tr>
<th>Case study</th>
<th>Dataset</th>
<th>Mjåland Generated</th>
<th>GeoNorge</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hoøyedata</td>
<td>RAMMS 1m</td>
<td>DAN3D 1m</td>
</tr>
<tr>
<td>Resolution</td>
<td>1m</td>
<td>10m</td>
<td>1m</td>
</tr>
<tr>
<td>Flow height</td>
<td>99</td>
<td>25</td>
<td>66</td>
</tr>
<tr>
<td>Flow velocity</td>
<td>115</td>
<td>10</td>
<td>106</td>
</tr>
<tr>
<td>Runout length</td>
<td>97</td>
<td>97</td>
<td>98</td>
</tr>
</tbody>
</table>
6 Discussion

In this chapter, the results of the back-analyses presented in the previous chapter are discussed to determine the influence of DEM resolutions on 2D numerical runout models applied to three case studies with distinct slope typology. This is conducted by discussing the following topics:

- Collection of data and models
- Applied methodology
- Evaluation of DEM resolution
- Evaluation of the runout performance
- Index and success of the resolutions

6.1 Collection of data and models

This study makes use of a number of data to be applied to the 2D-numerical runout models to conduct the back-analyses. A literature study was conducted to localize flow-like landslides with distinct slope typology and information from open available sources. All the three selected case studies have been described in previous work in the form of reports (Kronholm and Snilsberg, 2013, Domaas, 2013, Rese, 2016) and master theses (Bekkevoll, 2015, Lund, 2013, Bayissa, 2017). No field survey was conducted for this work. There are mainly two reasons for this. First, it was considered that the amount of available information in previous reports was enough and of good quality to run reliable simulations. Second, it was considered that because of the extensive period of time passed since the events occurred, it would have been difficult to obtain better quality parameters. This of course caused some problems regarding the estimation of different landslide parameters, such as the estimations at the calibration points that are mainly based on images and on descriptions from the reports. By conducting field work, it would be possible to identify more calibration points. However, as indicated by (Bartelt et al., 2017), some parameters like flow height and velocities are difficult to collect even during field survey.

Digital elevation models or point clouds from before and after the events were available for all the cases, except for the dataset Geonorge. The combination of insufficient information about the DEM and the “low” resolution made it difficult to decide if the data were from before the
events or after. For the case study Nesbyen, it was clear that the DEM was from after the event, because the construction of an embankment after the event are visible and thus influences the runout. The DEMs from the datasets Høydedata and Generated are based on the same point clouds, but they are created with different interpolations methods. By using different interpolation methods, the methods will produce different estimates for height values for the same point. This will also result in different quantities of errors for the different DEMs (Fisher and Tate, 2006). By applying the various DEM datasets, it is possible to observe how the runout behaviour changes within the different case studies.

Two 2D numerical runout models RAMMS and DAN3D were applied to back-analyse the case studies. The two runout models were selected based on several reasons. RAMMS are widely used in Norway by consultants in assessment and mapping of landslides and avalanche hazards (Kronholm and Snilsberg, 2013, Gunne Håland et al., 2015). This makes it necessary to evaluate the performance with DEMs with different resolutions. For RAMMS, a student version of the runout model was available at the University of Oslo. DAN3D was selected because of a conversation with Prof. Hungr, which found the topic interesting. He agreed to use the student version of the model for the purpose of his work. This model has been used in previous work in Norway (Frekhaug, 2015, Anfinnsen, 2017).

### 6.2 Applied methodology

The methods used in this thesis included the collection of data and models, the building of the numerical models, the back-analysis and to the evaluation of the results. To evaluate the difference between the 1m and 10m resolution DEMs, ArcMap was used to create slope angle maps with the different resolutions, because of the importance of the slope component to determine hydrological flow paths (Veregin, 1997). This was done to provide a better understanding of how the resolution of DEMs influence the terrain. The generation of the slope angle maps provides a good visualization of how the resolution influence the terrain. Slope angle maps along with the profiles, provide an insight in how the debris flow will behave down the slopes. This can be further assessed by examining the aspect and generation of drainage network.

The 2D numerical models were prepared by adding the required parameters to conduct the simulations. RAMMS and DAN3D require different input parameters, as explained in Chapter
There are several differences between the runout models. RAMMS requires a polygon of the release area and a release height to define the release volume, and both the polygon and the release height are possible to create and modify in the model. In DAN3D, the source depth topography file, that represent the source area and the release volume, must be generated in a separate software (Surfer 8), without the possibility to modify the shape and values in the runout model. This caused some problems during the generation of the source depth file, that resulted in small variations in the release volumes. Another important difference is the erosion parameters applied to the runout models. In RAMMS, the erosion is calculated based on an erosion polygon that represents the area exposed to erosion together with a range of erosion parameters (Chapter 4), while in DAN3D, the erosion is based on an erosion rate and a max erosion height. These differences make it difficult to compare the resolution of the DEMs effect on the volume. It also provided some problems when trying to apply similar erosion parameters between the models. This problem resulted in large variation of volume, between the models for each of the case studies.

The back-analyses were conducted by calibrating the friction coefficients until the events were realistically reproduced. To decide if the simulation was successful, the flow behaviour in term of shape and length (Simoni et al., 2012) together with values at the calibration points were used as criteria. By conducting back-analyses, it is possible to reproduce the events realistically. This method resulted in simulations that manage to reproduce the different aspect of the events relatively realistic.

### 6.3 Evaluation of DEM resolution

DEMs with higher resolution provide more accurate terrain features compared to low resolution DEMs due to the increased available information within small distances, making it easier to interpret small terrain changes or features. This chapter addresses the differences between a 1m DEM and a 10m DEM by comparing the slope angles at the different case studies. The data is illustrated in slope angle maps, profiles of the slope angle along the landslide path and cross section taken at the calibration points.

As expected, the resolution influences the DEMs interpretation of the slope in all the case studies. This results in large variations of the slope angle along the path between the resolutions. This is very noticeable when comparing the profiles and cross sections, where the 10m
resolution DEMs provide smaller and more gradual changes in slope compared to the 1m resolution DEMs. These differences in terrain might lead to different results for the back-analyses and result in deviations between the applied friction parameters.

### 6.4 Evaluation of the model’s runout performance

#### 6.4.1 RAMMS

**Landslide shape and runout length**

The back-analysed cases are evaluated by considering the shape and runout length of the simulations. DEMs applied to RAMMS provided both accurate shape and length, but some of the simulations overestimated the extent of the shape and length. Generally, all the DEMs with 1m resolution applied to RAMMS provided accurate shape and length. Figure 5.10, 5.21 and 5.32 illustrate the shape and length of the 1m DEM, and the back-analyses conducted for the partly channelized debris flow in Nesbyen provided the most accurate simulation. The DEMs with a 10m DEMs tend to overestimate the shape extensively compared to the 1m DEMs. The tendency to overestimate the runout shape might be related to the interpolation process of the elevation data. According to Hussin (2011), interpolation of elevation data might result in smoothing of the cross section of the channels compared to estimations conducted in field. This effect is larger for the 10m DEMs that have a larger cell size, thus smoothing of a larger area. This effect results in a more dispersed flow for the 10m DEMs compared to the 1m DEMs.

The large cell size of the 10m DEM results in deficient expression of complex topography along the path. Small ridges and other terrain features that realistically will influence the flow behaviour, are absent or poorly expressed in the 10m DEMs compared to 1m DEMs that has a smaller cell size and manages to express these features.

**Flow height and velocity**

The flow height is considerably different between the resolutions. In Aurdal, the flow height is almost three times larger for the 1m DEM, which is also the case for the two other locations. According to Hussin (2011), the DEM’s ability to express rapid decrease of slope results in an increased flow height, making the flow height very dependent on the accuracy of the DEM. This rapid transition is illustrated in the slope profiles (Figure 5.2), where the 10m has smooth
transitions in the slope, while the 1m DEM has rapid transitions. This might explain the large difference in flow height between the resolutions. The estimated maximum flow heights provide large deviations between the resolutions. In all the back-analysed cases, the DEMs with 1 m resolution provides the highest max flow height, and in almost all cases the max flow height is twice as high for the 1m DEM compared to the 10m DEM. This is highly influenced by the large deviation of total volume between the resolution, and a larger flow volume will provide a thicker flow.

The velocity of debris flows, and debris avalanches are highly dependent on the properties of the flow. According to Hungr et al. (2001) debris flows generally have velocities in the range of 1 m/s and up to 20 m/s. Norem and Sandersen (2012) state that debris flows in most cases are reported to have a velocity in the range of 5 m/s and up to 10 m/s, but debris flows with a volume higher than 50,000 m³ are able to reach 15 m/s. Based on the range stated by Norem and Sandersen (2012) all the 1m DEMs applied to RAMMS provide high velocities, in some cases above 15 m/s. The 10m DEM provides lower estimations, but also tends to provide very high velocities. When consider the velocity, it is important to notice that the velocity can exceed 10 m/s, e.g. at the Mjåland case, where it was reported that the debris flow had a very high velocity (Rese, 2016), that might indicate velocities exceeding 10 m/s. The velocity increases with higher DEM resolution. An earlier back-analysis of the Mjåland case conducted by Bayissa (2017) estimated the max velocity to be approximately 14 m/s, which corresponds with the max velocities obtained with RAMMS in this study. The velocity is very dependent on the volume of the flow. This is observed at the Mjåland case, which has a much larger volume than the other case studies and also the highest velocities.

Volume

The back-analyses conducted in RAMMS underestimate the total flow volume for all the three case studies, independently of the DEM resolution and dataset. Even though RAMMS have recently introduced an new empirical entrainment algorithm (Frank et al., 2015), it underestimates the total volume for all simulations. The underestimation is largest for the 10m DEMs and the largest landslide, Mjåland. When comparing the volume accuracies to slope typologies, the volume accuracies decreases with increased channelization for the 10m DEMs. However, this is not the case for 1m DEMs where there is no obvious trend. This might also be connected to the release method applied in the runout model. All the back-analyses are performed with block release, but it is recommended that simulations of debris flow should be
conducted with hydrographs, especially debris flows like the Mjåland case. However, slides that occur in open slopes obtain better results from block release (Bartelt et al., 2017).

According to Deubelbeiss and McArdell (2012) the block release method, which was applied to all the cases, are the most appropriate for small to medium sized release volumes (<100m3), while discharge hydrograph are more suitable for larger release volumes (>100m3). This might explain the problems related to the simulations conducted for the Mjåland case, where the low release volume (<100 m3) did not manage to release a sufficient flow, but by increasing the release volume to 200 m³, it was possible to back-analyse the event using the 1m DEMs.

In RAMMS, the volume differences between the resolutions are smaller compared to DAN3D but are twice as large at Aurdal and almost three times as large in Nesbyen, while Mjåland is four times as large. This is also the case between the case studies, where Mjåland is the largest with a realistic value of 22 000 m³, Nesbyen with a value of 3500 m³ and Aurdal with a value 3140 m³. The velocity is highly dependent on the volume, and a higher volume corresponds to higher velocities (Schraml et al., 2015).

To reproduce erosion patterns, it is necessary with a realistic representation of the channel morphology. This requires DEMs that have a high enough quality to provide representation of the channels, that are possible for the runout models to interpret (Frank et al., 2017). The fully developed channels, combined with a narrow channel in the upper part of the path, might cause insufficient interpretation of the erosion patterns for the Mjåland case with 10m DEMs. For the other cases, the slope is partly channelized (Nesbyen) or open (Aurdal), where this effect will be smaller. This might partly explain the large differences in total flow volume for the different resolutions. Other factors that might influence the volume are incorrectly applied erosion parameters and inaccurate erosion zones.

The deposition along the path are highly influenced by the volume of the flow. The 1m DEMs provides thicker and more spread deposition than the 10m DEMs. The thickness is connected to the increased volume, thus more materials to deposit, while the spread is related to the terrain changes along the paths. This indicates that the 1m DEMs have more varied deposition along the paths, compared to the 10m DEMs that have a gradual deposition, until the final deposition.
**Friction Parameters**

The friction parameters were adjusted until the output data matched the shape and runout length of real events as close as possible. Adjusting the friction parameters until the desired runout behaviour is obtained, is a common procedure when conducting back-analysis (McDougall, 2006, Quan Luna, 2012). The parameters are adjusted for the distinct slope typologies and characteristics for each case study. The obtained friction parameters vary between resolutions and datasets at the different locations, which is dependent on the acquisition technique and applied interpolation methods to the DEMs.

In RAMMS the friction parameters for the dataset Høydedata are higher for the DEMs with 10m resolution, except at Nesbyen. It should be noticed that the internal friction coefficients obtained at Nesbyen are very low, with values down to 0.06. Evaluating the internal friction coefficient, the coefficient is relatively similar between the resolutions but with slightly lower values for the 1m DEMs in Aurdal and Mjåland. The turbulence friction coefficient (\(X_i\)) have no typical trend regarding the resolution, except that it is lower for two of the 1m DEMs. The low turbulence coefficient might be related to the DEMs ability to express terrain features, because they have a steeper slope, resulting in higher flow velocities.

### 6.4.2 DAN3D

DAN3D manages to back-analyse almost all cases with 1m and 10m resolutions, except for the 1m DEMs from the dataset Generated for Mjåland, which was not used due to an error in the path topography file that caused the nodes to provide unrealistic values. In addition, the 10m DEM from the dataset Generated at Aurdal were not evaluated, due to largely overestimated release volume.

**Landslide shape and runout length**

The back-analyses conducted with DAN3D are evaluated by considering the shape and runout length of the simulations. In general, DAN3D provides accurate shapes and length, but overestimates the shape extensively for some of the simulations. The back-analyses conducted with the 10m DEMs did not obtain more accurate shapes and runout lengths, e.g. the Aurdal case (Figure 5.14) where both simulations are relatively equal. However, the 1m DEM estimates the deposit more accurately. This is the opposite compared to Nesbyen (Figure 5.25), where the
simulation conducted with the 10m DEM provides a more accurate shape but overestimates the runout length. At Mjåland (Figure 5.36), both DEMs provide good approximations, but the 10m DEM overestimates the shape slightly more, but both underestimate the longest runout of the real event. The difference in runout between the resolutions might be connected to the same factors as discussed in the RAMMS chapter. To summarize, the 1m DEMs provide narrow and precise runout and a more accurate length compared to the 10m DEMs.

**Flow height and velocity**

The flow height is relatively larger for the simulations conducted with a 1m resolution, approximately 0.3 - 1.0 m higher than the simulations conducted with a 10m resolution. The Mjåland case, which has a very large total volume, has the highest flow height, while the two other cases have considerable lower values. In DAN3D, the flow height is not only controlled by the volume, e.g. the Nesbyen case has lower flow height than the Aurdal case, but higher volume. Thus, other factors might influence the flow height. It is known that the DEM’s ability to express the rapid transition of slope angles along the track, influences the flow height (Hussin, 2011).

The back calibrated cases provide relatively high velocities for all the simulations. This is largely influenced by the large volume for all the simulations. For all simulations conducted at Aurdal and Nesbyen, the 1m DEMs obtains the highest velocities. However, at the Mjåland case, the 10m provided the highest flow height. This is, as mentioned earlier, heavily influenced by the volume. Only in Mjåland, the 10m DEM estimates the highest volume, which results in increased velocities. Field observations and previous studies concluded that the flow was extremely rapid (Rese, 2016, Bayissa, 2017), making it plausible that the max velocity is higher than the range from Norem and Sandersen (2012). The velocity obtained from the simulations at 15 m/s is very high, but the large volume (>20 000 m³) increases the possible max velocity of the flow (Norem and Sandersen, 2012). This assumption corresponds with the back-analysed DEMs, where the 10m grid from Høydedata provided the highest volume (41 000 m³) and the highest velocity (15 m/s).

**Volume**

Debris avalanches and debris flows can obtain a large amount of their volumes by entrainment, making volume changes a dominant characteristic for debris flows and debris avalanches.
In DAN3D, the volume differences between the resolutions are noticeable for most of the simulations. In addition, DAN3D tends to overestimate the total volume drastically compared to the real values. DAN3D applies an entrainment rate, where the volume change is simulated by augmenting the particles as they override entrainable materials (McDougall and Hungr, 2004). This is calculated based on the release volume, final volume, length of the erodible zone and the erosion depth. DAN3D manages to overestimate the volumes in all the simulations, both for 1m and 10m resolutions. One of the reasons for the overestimations is the use of the erosion depth. The amount of materials obtained through entrainment is limited by the erosion depth. By decreasing the erosion depth, the amount of entrained materials will decrease, which results in a smaller volume estimation. The erosion depth was kept constant for the case, to provide the same conditions for all simulations.

The erosion parameters that control the entrainment rate were kept constant for all simulations, except for the user defined time that was adjusted for the individual simulations and the release volumes. The release volumes had small variations between the DEMs. According to Frank et al. (2017), the most important feature of the DEMs is their ability to represent the channels so the models manage to interpret the channels. Thus, a 1m DEM will provide a better representation then a 10m DEM. It may be assumed that the 1m DEM provide a better representation of the terrain and thus should result in more accurate simulations.

**Friction parameters**

In DAN3D the friction parameters vary more, with no clear trend directly between the resolutions. For the internal friction, the 10m DEMs obtain a higher value at Aurdal and Nesbyen than the 1m DEMs, while in Mjåland both DEMs have the same values. When considering the turbulence friction, the 10m DEMs require higher values than the 1m DEMs at Aurdal and Mjåland, while in Nesbyen the DEMs with 1m resolution have the highest value. The turbulence friction increases from the slope typology open slope (Aurdal) to the partly channelized (Nesbyen) and to the channelized (Mjåland). This tendency applies for both resolutions.

**6.5 Summarizing the case studies with index values**

To provide an approach to summarize the result for the distinct case studies, a normalized index was created (see Table 4.4). It is based on the flow height and velocity at the calibration points.
and on the runout length. An index can be used to evaluate the models ability to perform predictions (Simoni et al., 2012) and is used as an additional quality criteria. In this work, the results were given a value that are located within an interval to provide a grade, ranging from 1-3, where 1 is the most successful.

For the debris avalanche in Aurdal, the DEM with 1m resolution provided the highest rating (Table 5.5). The 1m DEMs manage to provide good estimation of the flow height in almost all cases, except in two of the back-calibrations conducted with DAN3D. The velocity estimation provides relatively poor results, except for the two 1m DEM that are highly accurate. This is not the case for the runout length, where almost all simulations provide good results. In this case the 1m DEM from the dataset Høydedata applied to RAMMS obtained the highest index rating, thus making it the most accurate simulations.

For the debris flow in Nesbyen, the 1m DEMs provided the highest index rating (Table 5.10). In general, all values obtained at the calibration point provided low index rating, except for two 1m DEMs applied to RAMMS with accurate flow height values and a 10m DEM applied to DAN3D with accurate flow velocity. For the runout length, most of the simulations obtained good or acceptable values, except for the simulations conducted with the dataset Geonorge in RAMMS. The DEMs are from after the event, thus the construction of embankment and partly removal of the channels influence the runout and result in poor accuracy. In this case, the 1m DEM from Høydedata applied to RAMMS provided the best simulation.

The debris flow in Mjåland had several successful simulations with both resolutions (Table 5.15). In this case, DAN3D provided the most successful simulations with good or medium rating on most of the simulations, except for flow height and velocity for the 10m DEM from the dataset Geonorge. In general, the flow height and runout length provide good or decent index values, but the velocity is underestimated for five of the simulations. In this case, the 1m DEM from Geonorge applied to DAN3D provided the most successful simulation.
7 Conclusion

In this study, the influence of DEM resolution on two dynamical runout models at three case studies with distinct slope typology was evaluated.

The evaluation was conducted by back-analysis of three case studies that occurred in south of Norway. The Aurdal event was a debris avalanche that occurred the 22nd of May 2013. It was triggered by heavy precipitation and rapid snowmelt. The event occurred in an open slope and had a total runout length of 401 m with a total volume of 3140 m$^3$. The Nesbyen event was a debris flow that occurred on 23rd of May 2013. The debris flow was triggered by precipitation and started as two separate planar slides before converging. The event occurred in a partly channelized slope with a runout length of 676 m with a total volume of 3500 m$^3$. The Mjåland event was a fully channelized debris flow that occurred on Sunday the 2nd of June 2016. It was triggered by intense and heavy precipitation and had a runout length of 823 m with a total volume of 25205 m$^3$.

The applied DEMs had a resolution of 1m and 10m and were downloaded from Høydedata.no and Geonorge.no. Point clouds were also downloaded from Høydedata.no. The point clouds were used to generate DEMs with a resolution of 1m and 10m for the dataset Generated. In total 36 different DEMs were applied to the runout models.

The two numerical models used for the back-analyses were RAMMS and DAN3D. RAMMS is a numerical simulation model used to calculate the motion of geophysical mass movements in three-dimensional terrain. The model was developed at the WSL Institute for Snow and Avalanche Research SLF in Switzerland and was originally designed to provide a tool for modeling snow avalanches, but was later updated to include the possibility to model debris flows and rockfalls (Christen et al., 2010). DAN3D is a dynamic numerical model developed to conduct runout analysis of extremely rapid, flow-like landslides. The model was developed at the University of British Columbia in Canada to provide a 3D extension to the already existing 2D model DAN (McDougall, 2006).

The methodology used in this study consisted of DEM generation and processing, estimation of landslide parameters and back-analyses. The generation and processing of the applied DEMs were conducted by using different tools in the software ArcMap and Surfer 8. Landslide parameters were collected and estimated from previous reports, images and by using ArcMap.
The back-analyses were conducted by applying the different DEMs to the runout models and changing the friction parameters until the desired runout was obtained. The effect of the DEMs resolution were evaluated by assessing the shape and length of the runout, the flow height and velocities, total volume, and friction parameters obtained from the calibrated cases. An index was also prepared to evaluate the flow height and velocities at the calibration points, and the runout length.

In general, the 1m DEMs provided the most accurate shape and runout length but this is also dependent on the applied slope typology, dataset, and runout model. When comparing the shape of the simulated cases, the 1m DEMs provided simulations that were more identical to the real events. The 1m DEMs provides better runout for the channelized debris flows, while there is no obvious trend for the case with open slope typology. The flow height and velocity data obtained from the back-analysed cases indicate that the 1m DEMs provides more accurate estimations. Generally, the 1m DEMs obtain a much higher flow height for almost all simulations, compared to the 10m DEMs. Considering the velocity, the 1m DEMs generally provides the highest velocities. The 1m DEMs estimates the largest volume for all the cases except at Mjåland. For the Mjåland case, DAN3D provided extremely large volumes for the 10m DEMs. It was also observed that DAN3D estimated larger volumes compared to simulations conducted with RAMMS. The friction parameters obtained from the back-analysis indicated no clear trend between the resolutions, when comparing all the case studies. However, it was observed that the 10m DEMs requires higher friction parameters to back-analyse debris avalanches.

The results proved that the DEM resolutions affect the results from the runout models. By increasing the resolution, both runout models obtain more accurate runout behaviour. However, DAN3D obtains more varied results compared to the results obtained from RAMMS, which better complies with the real events. To conclude, DEMs with higher resolution provides better and more accurate simulations.
7.1 Further work

- It should be noticed that when conducting field work shortly after an event, it should be standard procedure to conduct field estimations of flow height and velocity for the entire event and at certain locations where it is possible to obtain the data, in addition to estimate release volume and total volume. This makes it easier to carry out modelling and to assure the quality of hazard maps.

- The generation of a standardized national database, with recommended parameters to conduct simulations, should be considered. This should be done by providing a database with parameters that are suitable for different landslides and slope typology.

- Assessment of the model sensitivity to the DEM resolution by keeping the friction parameters constant and vary the DEM resolution for flow-like landslide with numerical models.

- RAMMS and DAN3D entrainment methods should be further assessed, by assessing how the different parameters and, for RAMMS, the shape of the erosion polygons influences the runout behaviour. This should also be assessed by consider the effect of DEM resolution.

- The simulations conducted with the high resolution DEMs takes a long time. Further development should be conducted to decrease the simulations time.

- It should be considered to improve DAN3D by making it possible to apply release area and the corresponding release volume directly in the model. By improving this, the model will be more user-friendly, and it would be possible to modify the release area and volume without using another software to process the data.
References


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Appendices

- Appendix 1: Flow height figures for the back-analysed case studies

- Appendix 2: Tables of output data from the back-analysed case studies

- Appendix 3: EGU poster
Appendix 1

Flow height figures for the back-analysed case studies.

Aurdal, RAMMS:
Aurdal, DAN3D:
Nesbyen, RAMMS:
Nesbyen, DAN3D:

1m DEM Høydedata DAN3D

10m DEM Høydedata DAN3D

1m DEM Generated DAN3D

10m DEM Generated DAN3D

1m DEM Geonorge DAN3D

10m DEM Geonorge DAN3D
Mjåland, RAMMS:
Appendix 2

Tables of output data from the back-analysed case studies

Aurdal:

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<th>Høydedata</th>
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<th>GeoNorge</th>
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<td>DAN3D</td>
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<td>Max height (m)</td>
<td>Max height (m)</td>
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<td>Max velocity (m/s)</td>
<td>Max velocity (m/s)</td>
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Appendix 3

EGU poster
EFFECT OF THE DEM’S RESOLUTION ON LANDSLIDES RUN-OUT MODELS

Martin Aleksander Michalsen1, Graziaella Devoli1,2, Byron Quan Luna3

Introduction:

Every year, landslides cause billions of dollars in damage to infrastructure and economic losses. By using different DEM resolution models, it is possible to predict their run-out distance and behavior. Multiple landslide run-out models are used today, developed for various applications and resolutions. These models are largely based on Digital Elevation Models (DEMs) that are used as input data. This study presents a comprehensive overview of the DEM’s resolution and its influence on the prediction of the run-out distance and behavior of two landslide run-out models, RAMMS (SiT) and DAN3D (Jonigk and Midogahara), for three case studies located in Southern Norway.

Case studies:

1) Årdal, Ogland (Norway)

Date of occurrence: 22nd May 2010
Type: Debris flow
Triggering parameters:
- Initial slope: 15°
- Initial water content: 10% 
- Initial temperature: 15°C
- Initial water content: 10%
- Initial temperature: 15°C

2) Nebygna, Buskerud (Norway)

Date of occurrence: 22nd May 2010
Type: Debris flow
Triggering parameters:
- Initial slope: 20°
- Initial water content: 20%
- Initial temperature: 20°C
- Initial water content: 20%
- Initial temperature: 20°C

3) Mjølland, Rogaland (Norway)

Date of occurrence: 21st June 2010 at 10:00
Type: Debris flow
Triggering parameters:
- Initial slope: 25°
- Initial water content: 30%
- Initial temperature: 30°C
- Initial water content: 30%
- Initial temperature: 30°C

Methodology:

DEM data for the locations were obtained from the Norwegian Mapping Authority and accessed at Høyden.no and Geonorge.no. In addition, DTMs were generated using point clouds downloaded from various webpages. The DEMs were named as follows:

- Høyden: 3D DEM, generated from UGM data and processed with ‘Hoydeliten’ and filled in with nearest neighbor interpretations, downloaded directly from Høyden.
- Geonorge: 2D DEM, based on contours and elevation points, downloaded from Geonorge.

Results:

The models were then compared with literature and observation for the best run-out distance and behavior of the two landslide run-out models, RAMMS (SiT) and DAN3D (Jonigk and Midogahara), for three case studies located in Southern Norway.

Example of flow velocity:

For the Årdal case, using RAMMS (SiT), the best performance is given by DAN3D, with 10% DEM resolution in the output. The 2D DEM is generated in Geonorge and compared to RAMMS in DAN3D. Thus, for the 1m DEMs RAMMS provides the best results.

Model Setup:

To conduct run-out analysis of a landslide, several parameters are required. These include the geometry of the landslide, its initial conditions, and the DEM resolution. The ideal resolution for a landslide run-out model is 1 m.

Reference: